The Gran Turismo Magazine

Beyond the Apex


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GT ACADEMY
2008-2013

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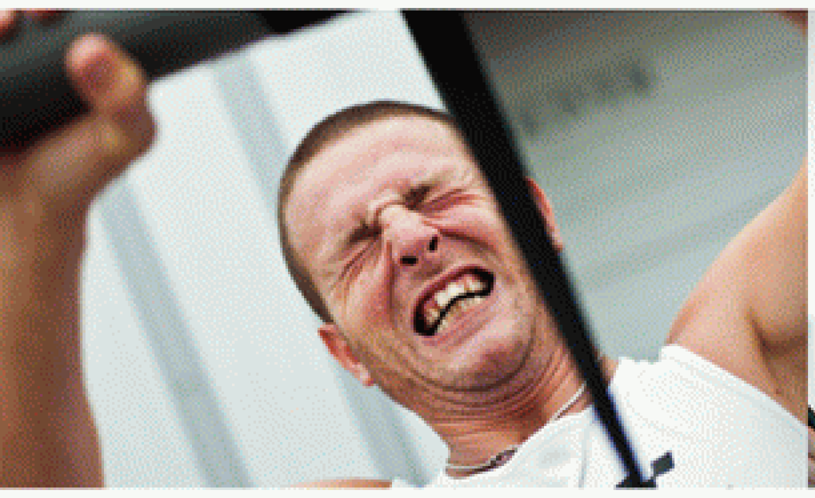
Gran Turismo: It awakens, inspires and nurtures potential driving talent.


15TH ANNIVERSARY

On one of the most sacred grounds in motorsports,



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the resolve and driving ability of a select few are tested to their limits.

Choose your own power setting or drive system, it's all up to you.
Participating in 1000 time trial events is not impossible.
In the world of driving simulators, transcending the experiences of the real world is a stark possibility.

In order to realize that seemingly improbable notion, the GT Academy was launched in 2008.
Its mission: To help those who honed their skills on Gran Turismo to realize their dreams of becoming a real race driver.

In the ensuing years, this "project" has grown and expanded dramatically. In 2012, a total of 1,400,000 gamers from Europe, America, Russia, South Africa and the Middle East participated in online qualifying stages.

So, you see, there's no reason for anyone to give up their dreams of becoming a race driver.
Someday, the one standing atop the podium at a famous racetrack, basking in the applause of tens of thousands of fans, may be you.

The true nature of one's character is exposed in its entirety.


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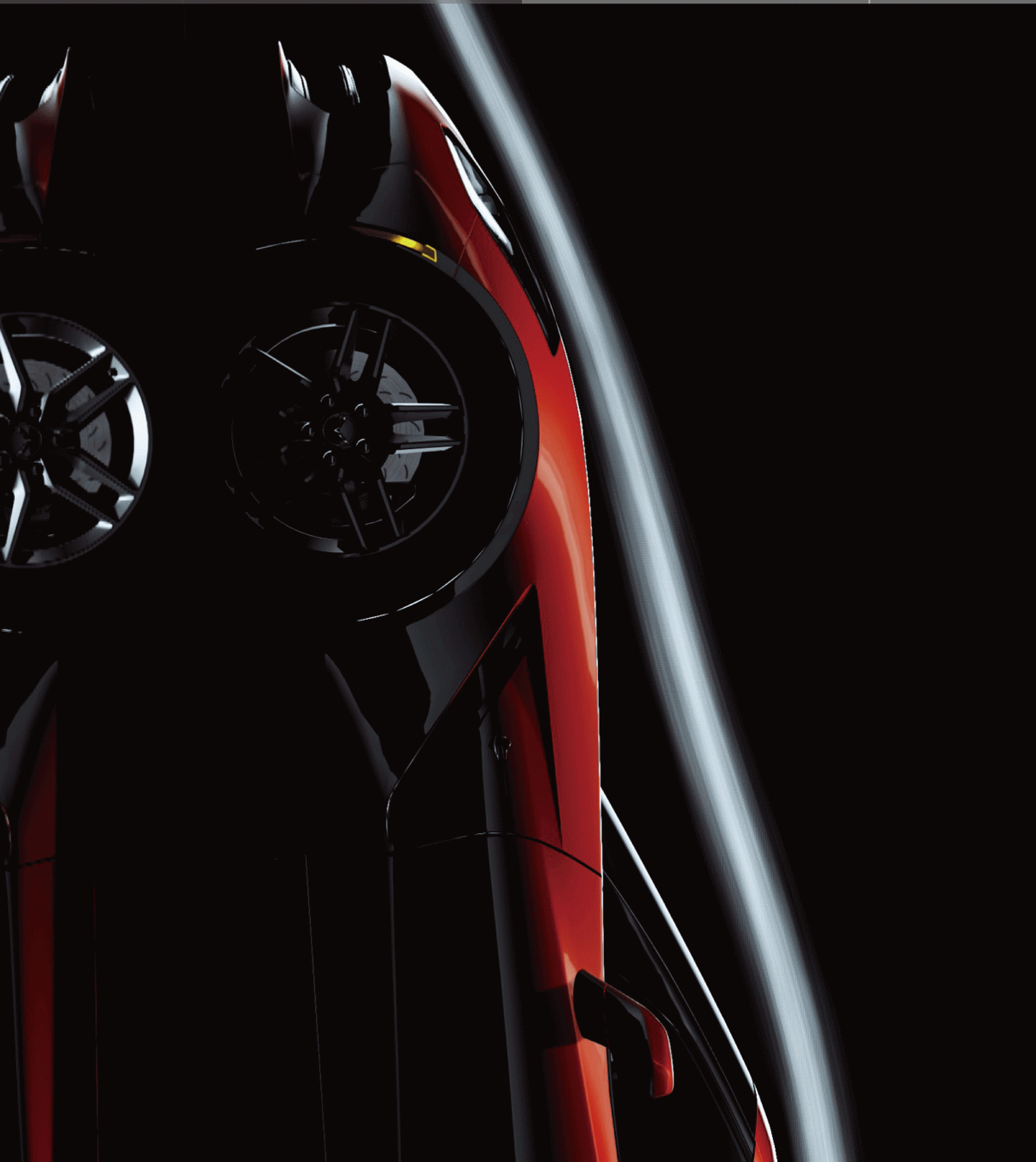


Engineering

Pre

There are many publications about automotive technology, ranging from professional textbooks to car magazines for the general public. But, there is a big difference between the professional automotive engineers and the general public when it comes to understanding the intricacies of cars and how they function. This difference is not usually known to people who lack professional expertise.

The reason for the large knowledge gap between professional engineers and the general public is due to the presence (and absence) of basic engineering knowledge. With that said, let's see if we can bridge that gap a little by sharing some of the basic engineering knowledge possessed by professional automotive engineers. In addition, we'll share some stories that even people with knowledge of professional engineering should enjoy. Hopefully, you can take the time to read these sections and come away with a better understanding of automotive engineering, and thereby gain an appreciation of the world of high-performance cars.

Chapter One will describe basic mechanics and introduce the concepts of force, moment (hereafter, torque) and energy, followed by a discussion on the theory of vibration. Force, torque and energy are fundamentals of engineering, and the theory of vibration, explained in Chapter Two, is the foundation of vehicle kinetics and suspension tuning.

Chapter Two covers vehicle kinetics and the tuning of the suspension system. Hopefully, this chapter will show you how professionals understand the concept of suspension movement and how it affects the vehicle. In particular, you'll learn about the basics of vehicle steering tests, and how the suspension can be analyzed by a seven-post rig. There is a picture of a seven-post rig, but no actual discussion of how it would be used to analyze a suspension, nor a reference to the figure.

Chapter Three will introduce the basics of statistical mechanics and thermodynamics that go into the making of an automobile engine. What kind of engine can achieve theoretical efficiency? Why does energy loss occur in an actual engine that prevents theoretical efficiency? We will explore the natural reasons why energy loss occurs by way of physical phenomena.

Chapter Four will explain aerodynamics. Bernoulli's theorem, which shows the relationship between pressure and velocity, is often used to describe the down-force of a racecar and the phenomena of lift of an airplane. It is probably not well-known outside of the normal world of fluid dynamics, but Bernoulli's theorem is merely an entry point into the complicated world of aerodynamics. We will go one step further here and explore the concept of theoretical aerodynamics.

Chapter Five will explain computational fluid dynamics (hereafter, CFD). CFD is an indispensable part of automotive development, and is a familiar term among auto racing fans as it's one of the most important tools in the development of racecars. However, the knowledge of how something is actually built using CFD is limited only to a handful of experts; therefore, we want to show you, at least briefly, the concepts of CFD theory.

The engineering theories presented here are basic knowledge for automotive engineers, but are relatively difficult for the uninitiated observer. Absorbing all of this information from beginning to end may prove challenging. If so, you can just browse the parts that seem interesting to you. We hope this will at least provide a peek into the vast world that's mostly hidden from public knowledge, reserved for the few who call themselves professional engineers.

1-1 The concepts of force and torque

▶ Let's learn the definitions and differences of the two

Various forces, including torque, are at work whenever a car is moving. Understanding these is the first step in understanding cars. So, let's first have a look at the concepts of force and torque.

The definition of force

The tires, suspension, and engine all generate force when a vehicle is moving. These forces are generated in different ways, and may seem to produce various types of power. However, those forces can all be calculated simply by using the same formula, known as the Equation of Motion: F = ma (Force = Mass x Acceleration), and there are no essential differences.

The Equation of Motion shows that force is derived from the acceleration of a mass, meaning that force is an effect which changes the speed and direction of movement of an object. Vice versa, if the speed or direction of a mass changes, there is always some form of force involved.

For instance, frictional force generated between the road surface and tires changes the speed and direction of motion of a car (a mass), and the damping force of a damper has the effect of reducing the speed of vibration of the car and tires.

Diagram 1-1-1 Even though the various forms of force acting on a car appear different, they are essentially the same from a physics standpoint

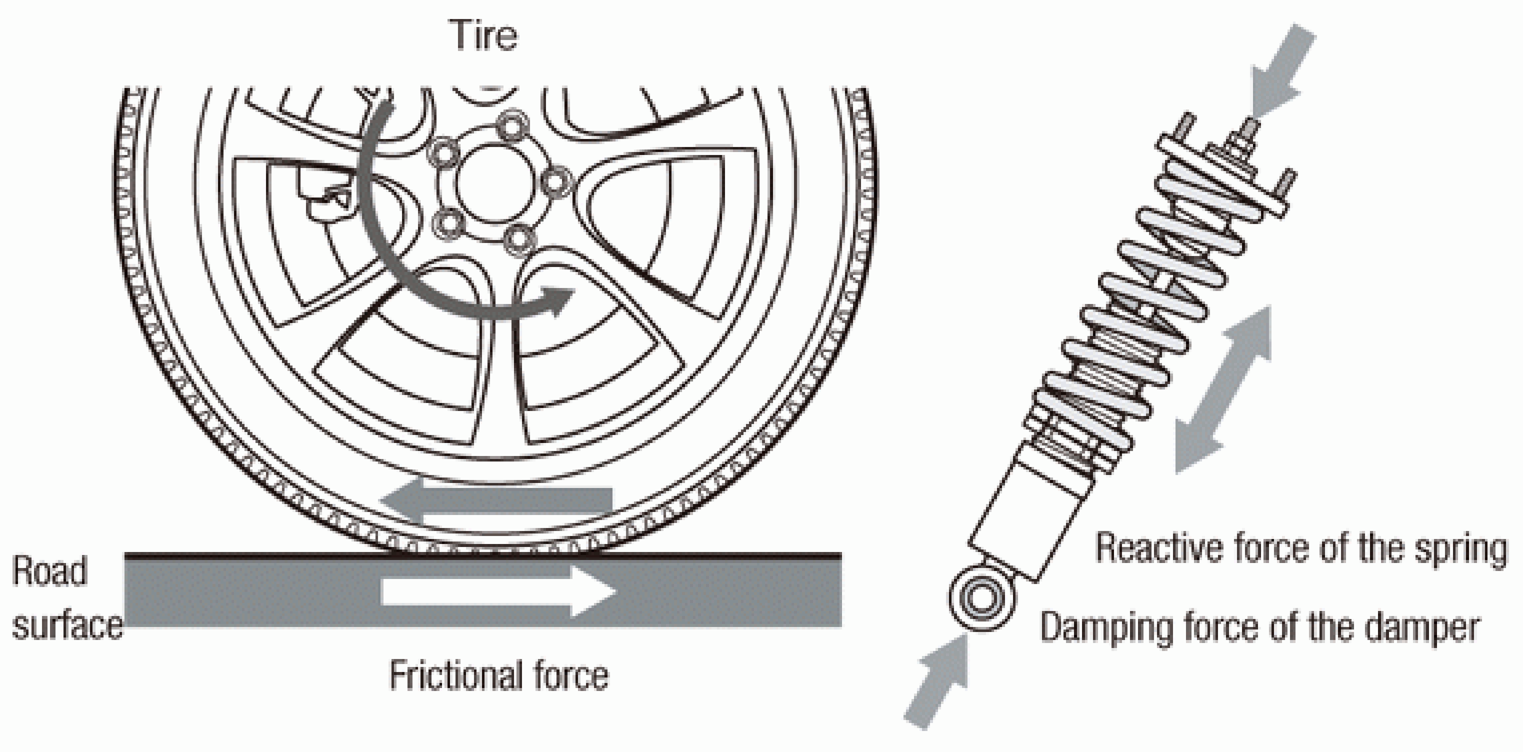
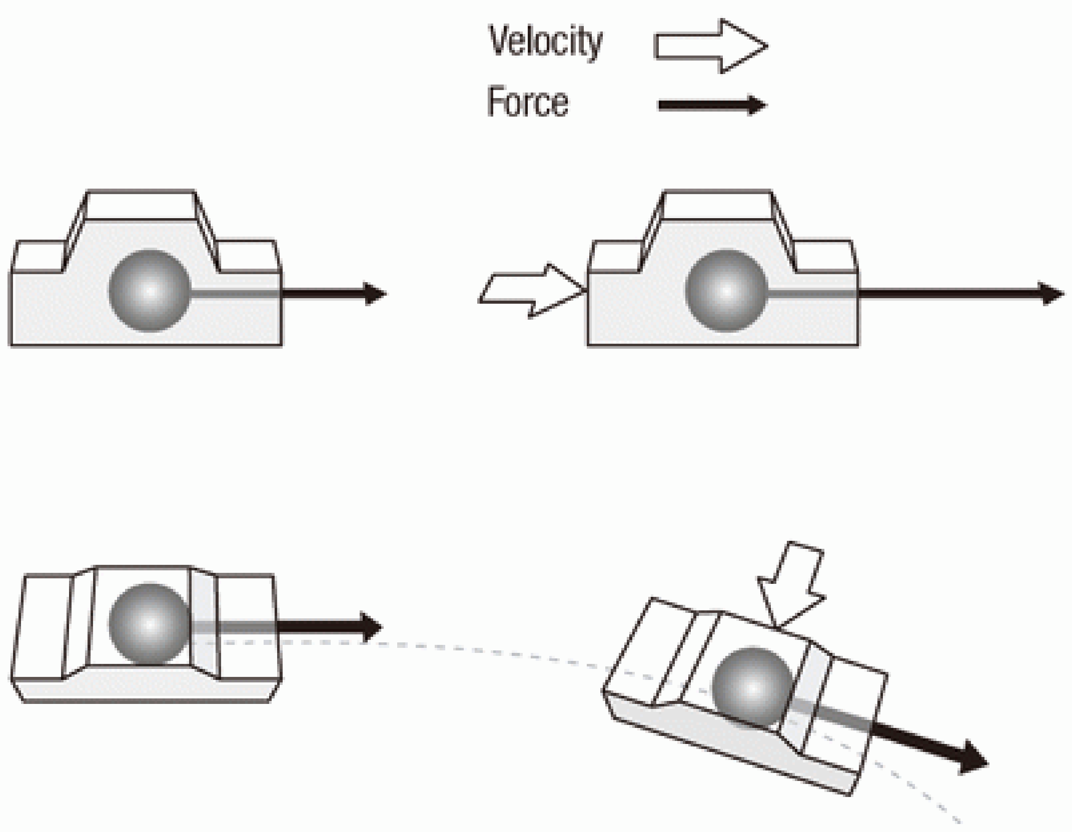


Diagram 1-1-2 Force is an effect which changes the speed and direction of movement of an object



Adding force changes the speed and direction of an object.

The various forces that a car produces can all be calculated by the equation:
F = ma (Force = Mass x Acceleration)
Force is a phenomenon that affects the speed of a mass.

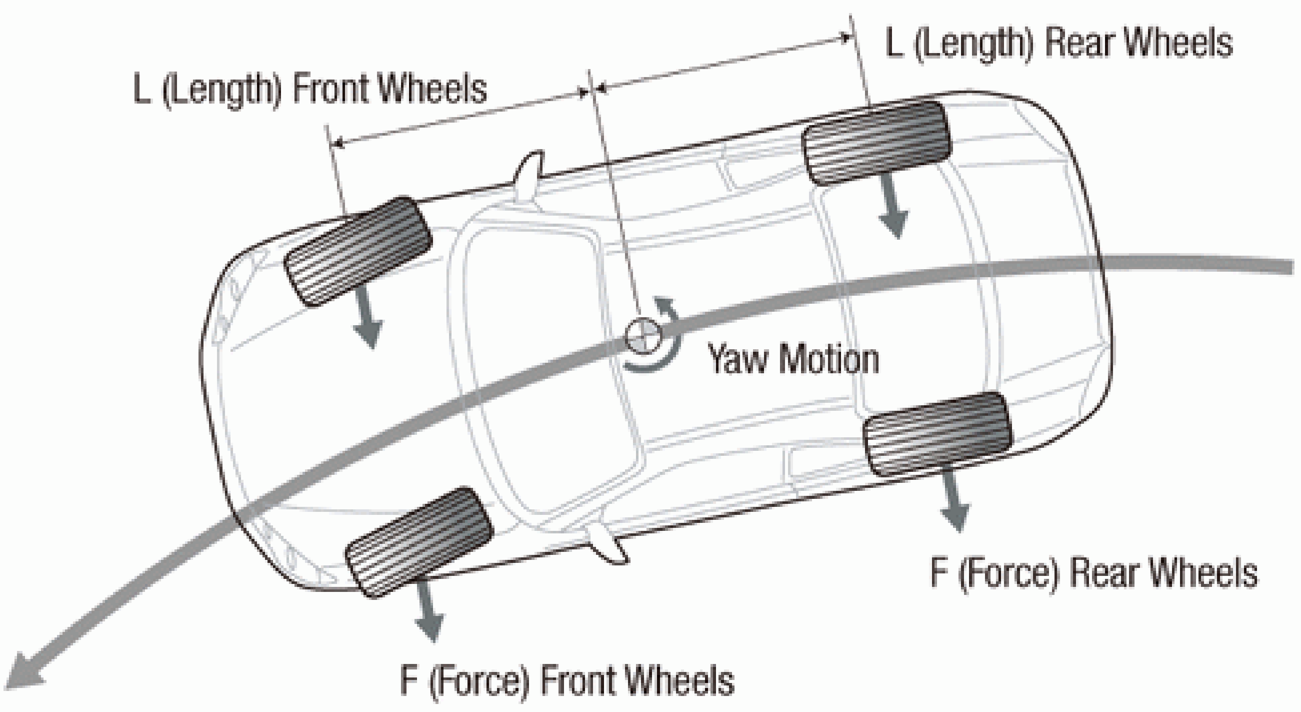
The definition of torque

When you turn the steering wheel, a car changes direction because the tire produces a force in a direction perpendicular to the line of travel. A car's rotational motion caused by such a force is called yaw. In like manner, the effect where a force causes rotational motion of an object is called torque. The amount of torque depends on the quantity of the force applied multiplied by the distance from the axis of rotation. This can be mathematically represented as M = L x F (Torque = Length from the rotational axis x Force).

Let's consider the actual torque acting upon the turning of a car. If the rotational axis is at the center of gravity of the turning vehicle, the amount of torque that the front wheels produce is determined by [the distance of the front wheels from the center of gravity] x [the lateral force produced by the front wheels]. Of course, during the turn, the rear wheels are producing torque by [the distance of the rear wheels from the center of gravity] x [the lateral force produced by the rear wheels]. This causes resistance in the opposite direction to the front wheels, thereby affecting the torque of the front wheels.

For example, during actual cornering, when you turn the steering wheel, the torque on the front wheels becomes larger than that of the rear wheels, which starts the turn of the vehicle. The torque caused by the front and rear wheels is equal near the corner's clipping point. Once that point is passed, turning the steering wheel back causes the torque on the rear wheel to be greater than that on the front wheel, which will stop the rotation.

Diagram 1-1-3 **Relationship between the torque applied to the vehicle by the front and rear wheels and rotational movement. A car starts its cornering when the torque of the front wheels is greater than that of the rear wheels.**



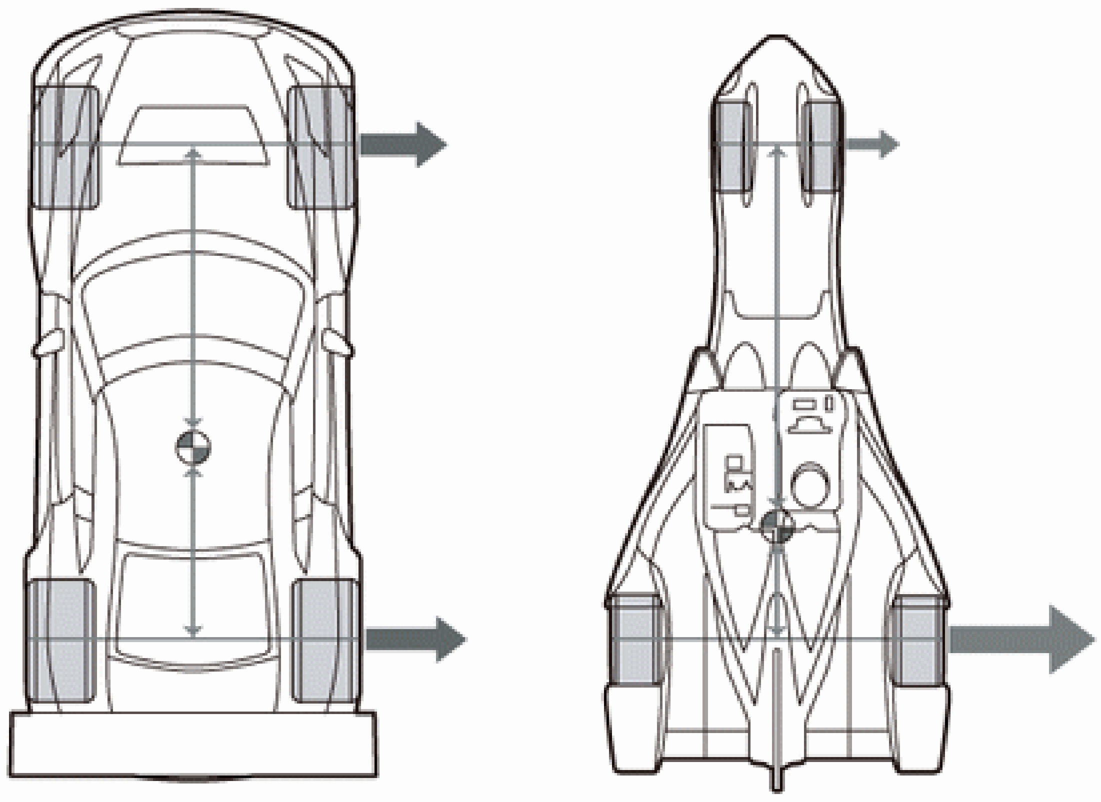
L Front Wheels x F Front Wheels > L Rear Wheels x F Rear Wheels: The yaw angle of the vehicle increases (turning in).

L Front Wheels x F Front Wheels < L Rear Wheels x F Rear Wheels: The yaw angle of the vehicle decreases (turning out).

Torque is the force that causes the rotational movement of an object.

M = L x F: Torque = Length from the rotational axis x Force.

Diagram 1-1-4



TIPS Diagram 1-1-4 shows the force generated by the front and rear wheels of a Nissan GT-R NISMO GT3 (left) and a Nissan Delta Wing (right). Let us assume that the rotational axis of the vehicle is at the center of gravity. Next, notice that the distance to the front and rear wheels from each rotational axis (center of gravity) is different. We can now see that, in order to balance the torque generated at the front and rear wheels, the force needed to be generated by the front and rear wheels are each different between the vehicles. The center of gravity of the Delta Wing is in the far rear, so the grip force required for the front and rear tires are completely different. In reality, a special tire that is only 10cm wide is used at the front of the Delta Wing. In comparison, the center of gravity in the GT-R NISMO GT3 is near the center of the body, so a roughly equivalent amount of force is required by both the front and rear tires.

1-2 The Concept of Energy

▶ Understanding Conservation of Energy

The Law of Conservation of Energy

The physical reactions in a car include kinetic, thermal, electrical, magnetic and chemical. For example, when gasoline ignites in the cylinder of an engine, the temperature in the cylinder rises and moves the piston, the result of a chemical, thermal and kinetic reaction. Aside from force, these different types of physical phenomena produce one thing in common, and that is energy. Energy can change from one form into another even among differing physical phenomena, and the total quantity of energy does not change before or after conversion and is constant. This is called the Law of Conservation of Energy.

Diagram 1-2-1 The Concept of Energy

Physical Phenomena in a Car

- Kinetic Reaction
- Thermal Reaction
- Electrical Reaction
- Magnetic Reaction
- Chemical Reaction

→ **Energy is a common physical outcome**

Braking is the act of changing kinetic energy to thermal energy.

Engine cylinder conservation

If we look at the energy created by the physical phenomenon of a moving cylinder in an engine, we'll see that the chemical energy of the gasoline is converted into thermal and kinetic energy. In other words, the gasoline engine is a device that converts chemical energy into kinetic energy, a form that is convenient for people to use. In that moment, it is guaranteed by the Law of Conservation of Energy that the amount of chemical energy converted is equal to the sum of the amounts being transferred into thermal and kinetic energy. How well an engine converts chemical energy into useful kinetic energy is what defines efficiency of an engine.

Diagram 1-2-2 **The concept of energy conversion in the cylinder of an engine**

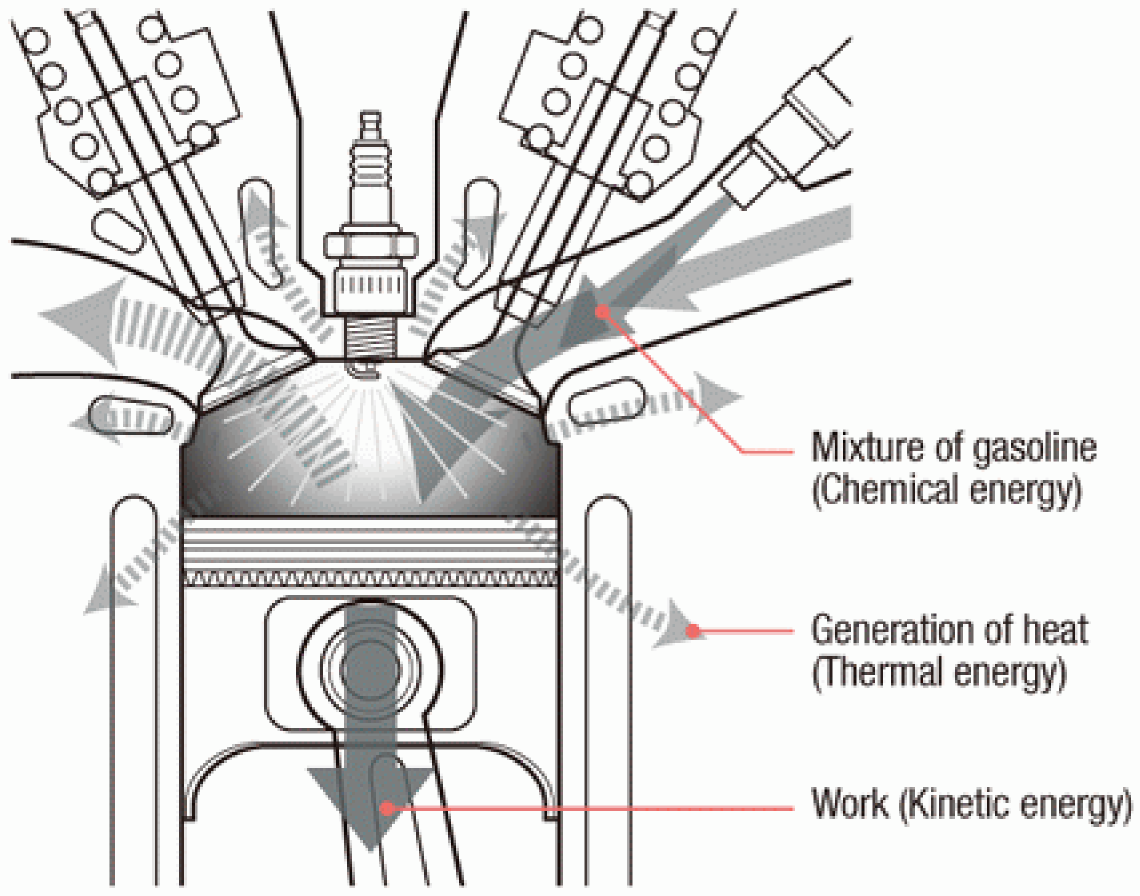
Chemical energy

↓

Thermal energy | Kinetic energy

Conversion of energy does not change the total quantity of energy.
This is called the Law of Conservation of Energy.

Diagram 1-2-3



1-3 The Mechanism of Vibration

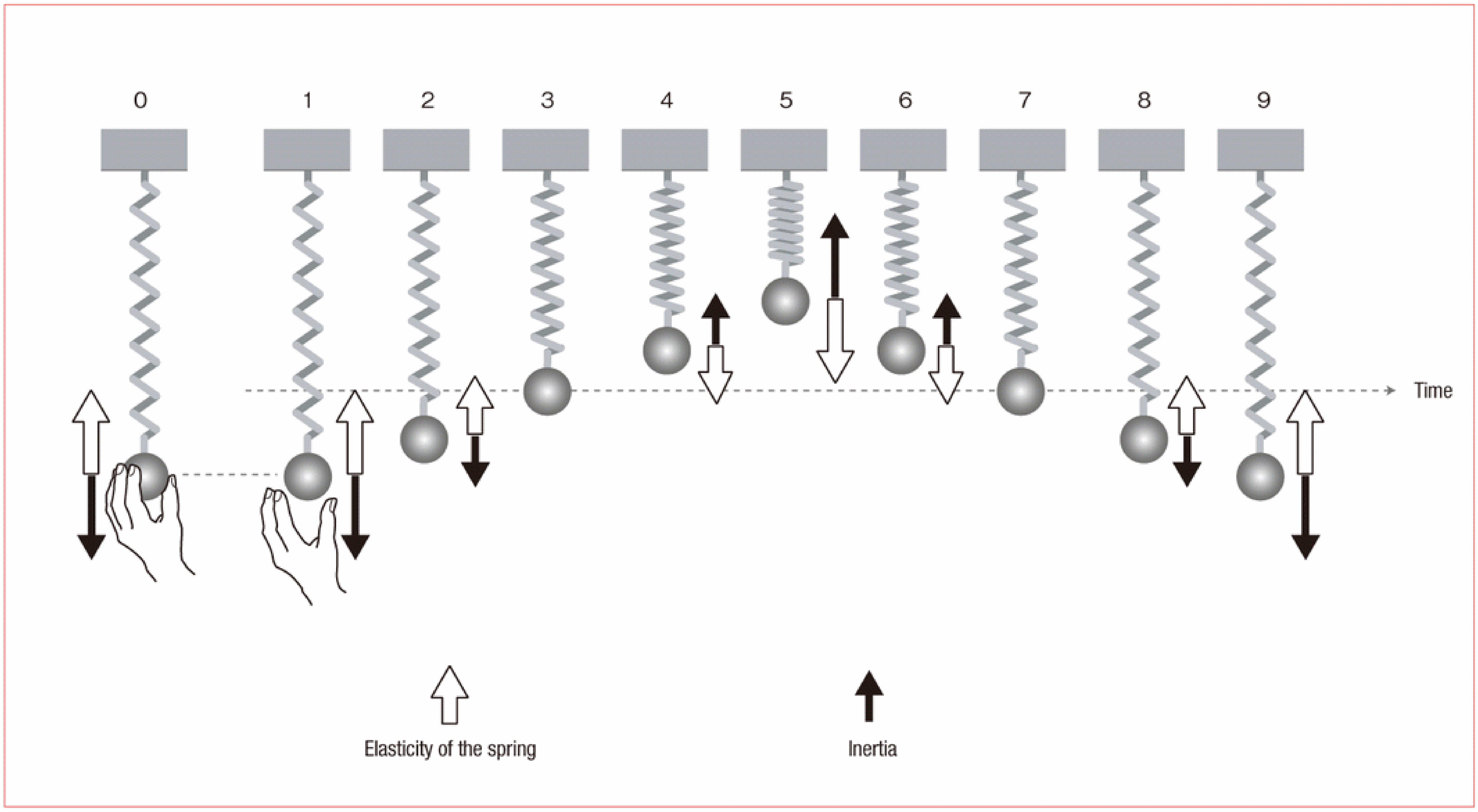
▶ Vibration is related to the mass and elasticity of an object

Vibration occurs in all car engines, suspension systems, car body etc. We will explain the details in Part 2 of how the movement of a vehicle is also a part of the phenomenon of vibration. So, what is the mechanism of vibration? Before we get into a discussion of vehicle motion, let us first clarify the concept of vibration.

Vibration viewed from the aspect of force

An easy way to conceptualize this is to think of a single spring with a weight hanging on it. Think of this as a vibration system where something causes vibration of an object (Diagram 1-3-1). When you pull the weight by hand and lengthen the spring, elasticity against that force is created (#1-2). Upon releasing the weight, the spring is going to return to its original length while pulling back the weight through its elasticity (#3). It would shorten the spring so that the spring will return to original length, and even after the elastic force reaches zero the weight tries to keep moving due to inertia (#4). The spring reaches maximum compression, and as a result, the movement of the weight slows to the point where the weight stops momentarily (#5), but the force of the weight causes it to stretch again (#6). The compressed spring exerts its elasticity and tries to return to its original form (#7). Finally, it returns to its original form, but due to the inertia from the weight, the spring tries to move again (#8). The cycle of #1 through #8 continues and steadily decreases as the spring returns to its original position. This is vibration as seen from the aspect of force. In the phenomenon of vibration, inertia and the elasticity of an object become both cause and effect.

Diagram 1-3-1 When viewed from the aspect of force, the inertial force of the weight always matches the elasticity of the spring. Note that the length of the arrows in the vertical direction of the spring are equal in each process



Vibration Seen from the Aspect of Energy

The vibration just described can be observed through the Law of Energy Conservation. If we view vibration from the aspect of energy, it can be said that it is an exchange of kinetic energy of the weight with the expansion and contraction from the elastic energy of the spring. The elastic energy of the spring is highest when the displacement of the spring is the largest (the spring is fully stretched out or fully contracted) as shown in Diagrams #1, #5 and #9. The maximum speed, and thus kinetic energy, of the and is, by the way, at the points where the spring has momentarily returned to the original length.

The maximum speed, and thus kinetic energy, of the weight can be seen at positions (#3) and (#7) and at these points the spring has momentarily returned to the original length.

Diagram 1-3-2 When seen from the aspect of energy, vibration is the exchange of the weight's kinetic energy and the spring's elastic energy

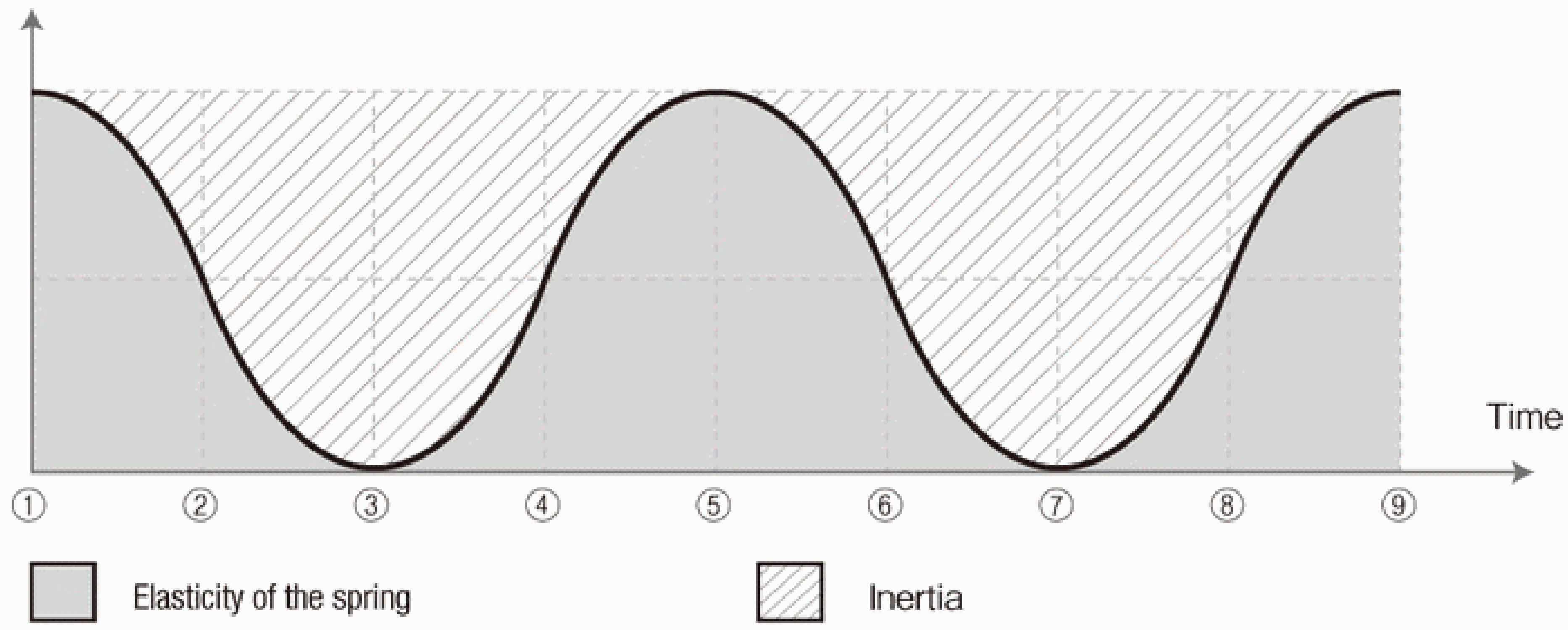
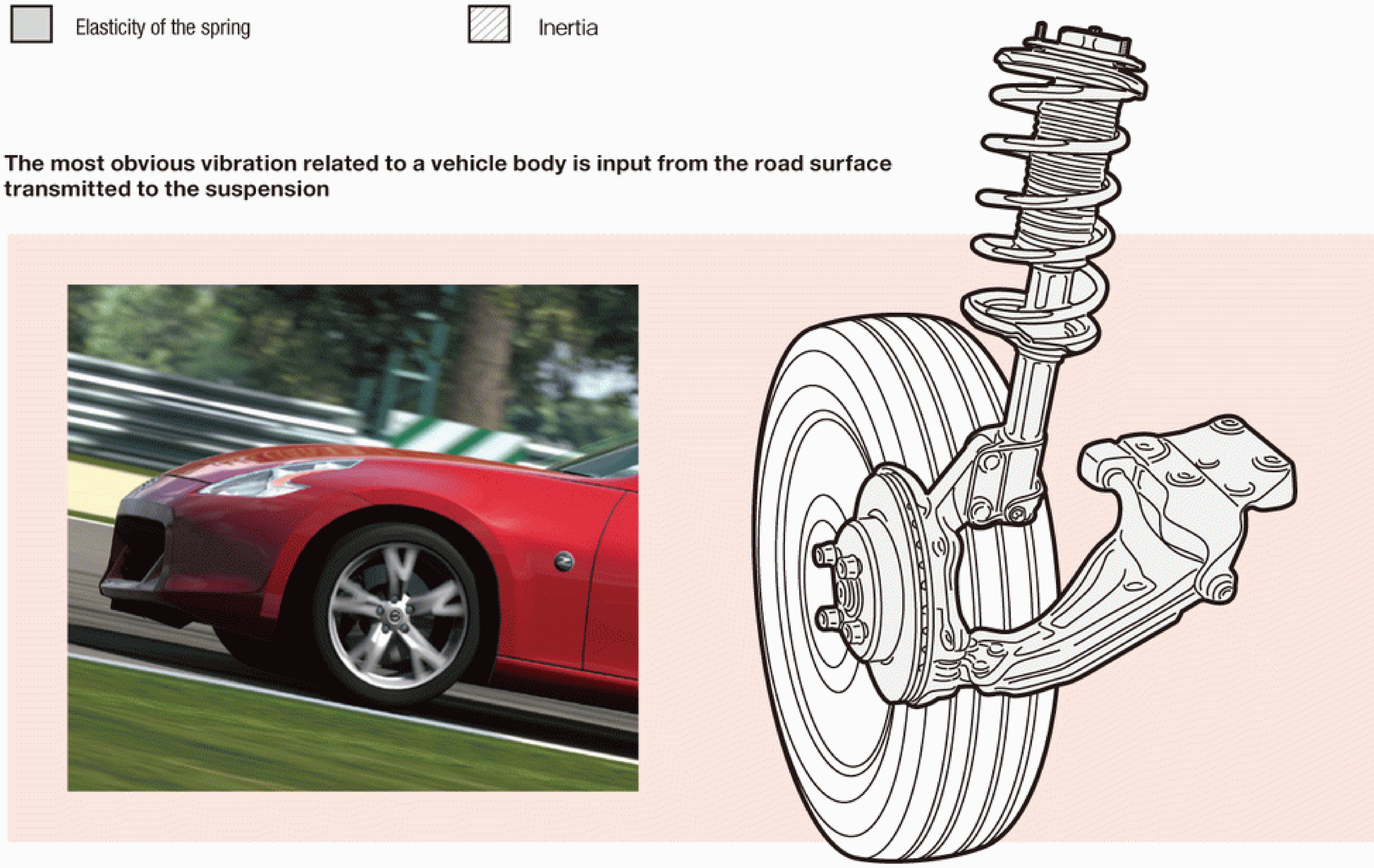


Diagram 1-3-3 The most obvious vibration related to a vehicle body is input from the road surface transmitted to the suspension



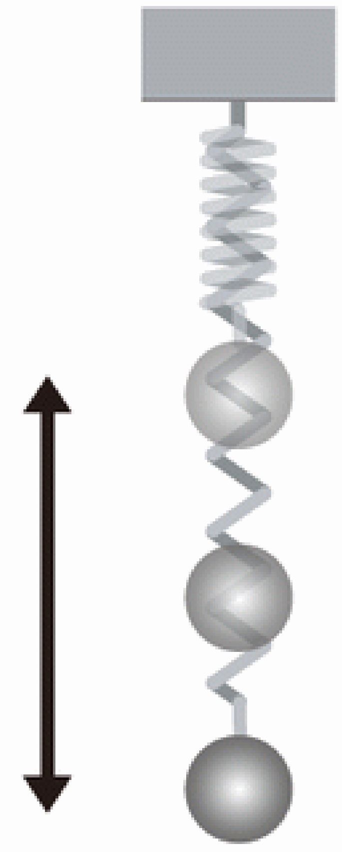
1 4 Resonance phenomenon

▶ Resonance is a state of becoming non-resistant against external excitation

The phenomenon known as resonance complicates the consideration of such subjects as suspension systems and engine vibration. Resonance must be avoided as much as possible, even when generated out of necessity. To that end, let's try to understand exactly what resonance is.

Diagram 1-4-1

When we let the system vibrate freely, it vibrates at its natural frequency and does not vibrate at any other frequencies



Free vibration and natural frequency

Let's consider a vibration system consisting of a spring and a weight. After having stretched this system once, let it vibrate freely. This is called free vibration. Soon, the weight and spring vibrate at a certain consistent frequency. The result will be the same no matter how strongly or softly the system is pulled. number of vibrations per second is natural to the elasticity of the spring and the mass of the weight, hence it's called natural frequency. This natural frequency is a frequency based upon the vibration from the system itself, and when it is vibrating at its natural frequency, the elasticity of the spring and the inertia of the weight will always be equal, thus leading to repeated natural exchanges of energy.

Forced Vibration and Resonance

Now let's forcibly stretch and contract the spring and the weight by hand. This is called forced vibration. Doing this in a way that does not allow natural frequency should cause you to feel resistance in your hand. When a vibration system vibrates at its natural frequency, any other frequency is considered unnatural to the vibration system. Regardless of whether vibration is applied externally or not, a vibration system will try to vibrate at its natural vibration, so all other vibrations will lead to a sense of resistance.

Diagram 1-4-2

Even when we force a system to vibrate at a different rate than its natural frequency, the system tries to vibrate at its natural frequency. This movement results in resistance

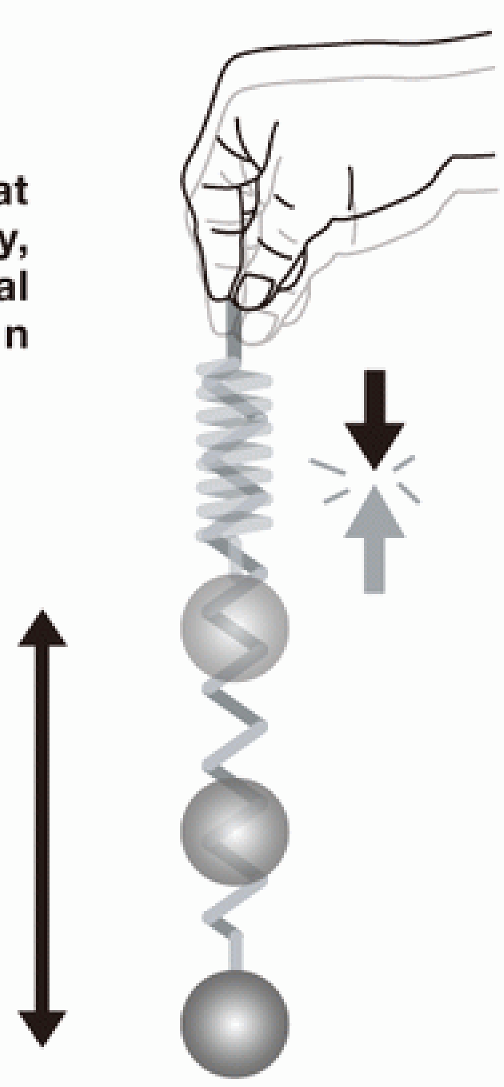
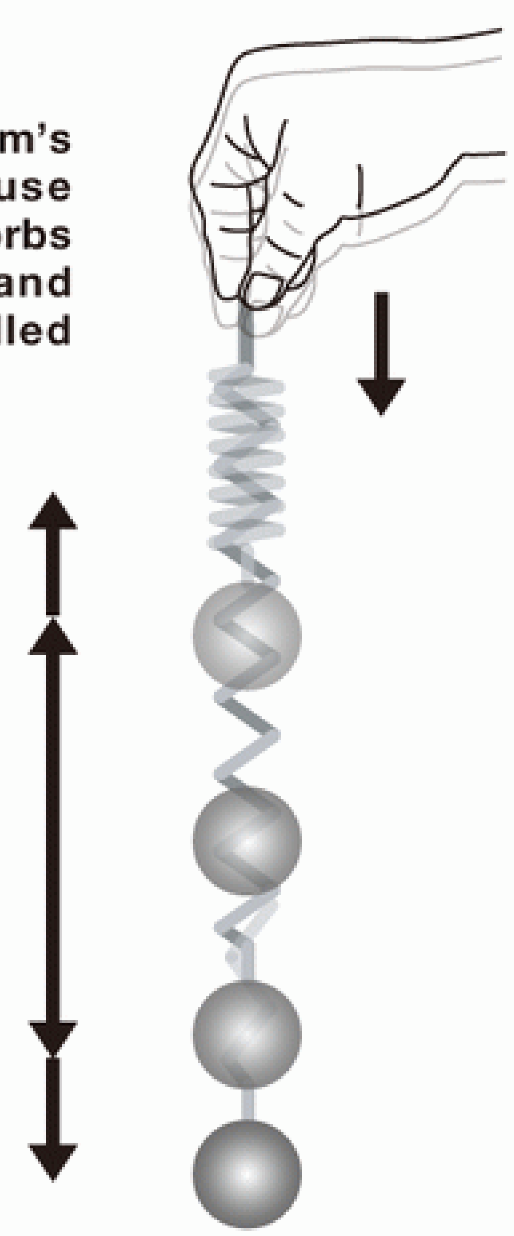


Diagram 1-4-3

When vibration is added at a system's natural frequency, it does not cause resistance. Instead, the system absorbs the kinetic energy from the hand and increases its amplitude. This is called resonance



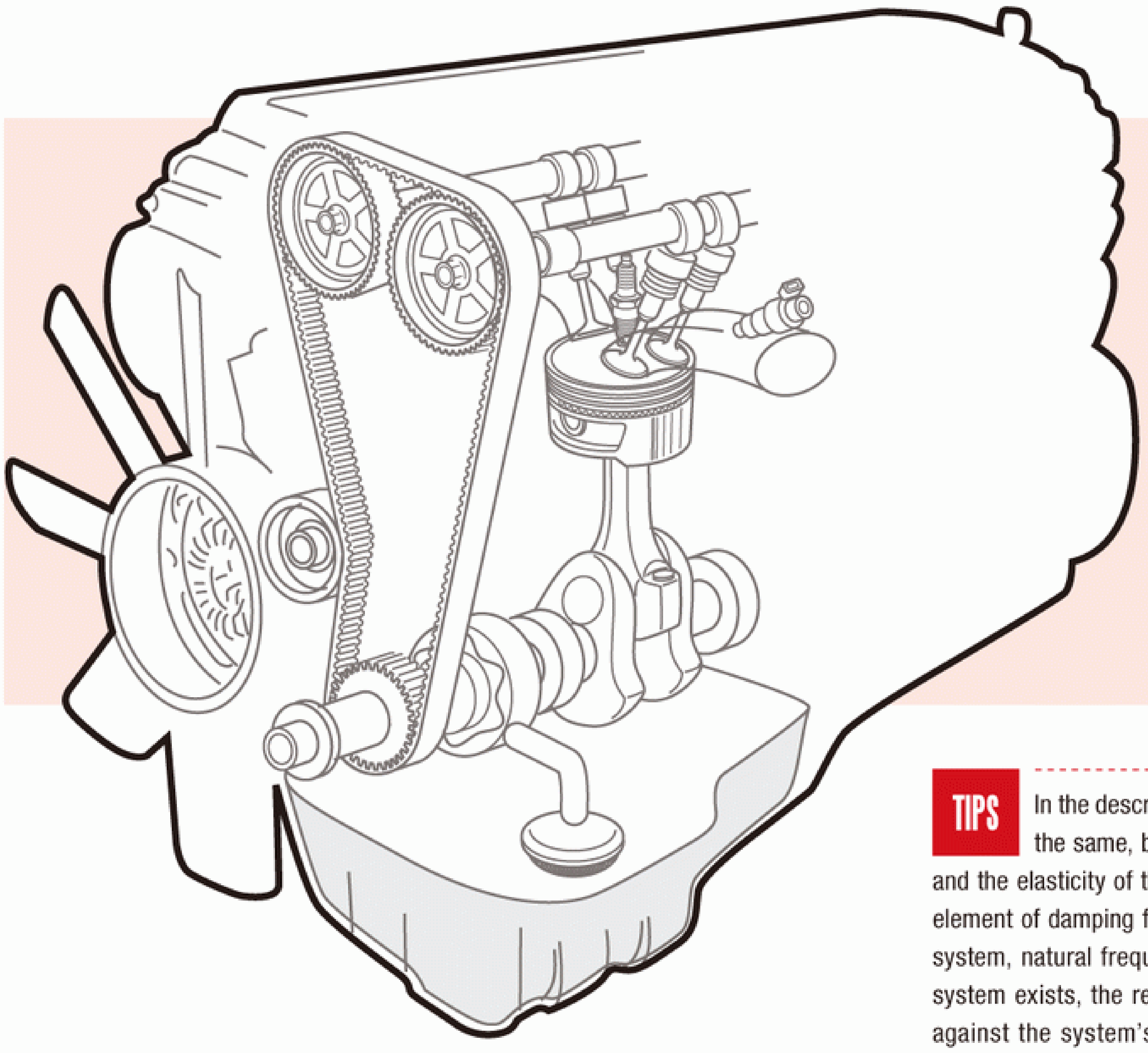
Forced vibration and resonance

What will happen if you stretch and contract the system at its natural frequency? Now, we will not feel resistance because the vibration is at its natural frequency. You should notice that the amplitude of vibration grows to match the added vibration. This is due to the system absorbing the energy from the external excitation instead of resisting it. The vibration of the system will continue to grow as long as the external excitation is added to the natural vibration.

As explained above, the phenomenon where the vibration increases due to the external vibration added at the system's natural vibration is called "resonance" and the frequency at that point is called the "resonance frequency".

For example, resonance in the suspension leads to a deterioration of ride comfort and ground resistance. In addition, if the engine causes resonance, the engine itself would be damaged. Hence, it is necessary to avoid resonance as much as possible. One way to prevent damage from resonance is using a damping system. The damper absorbs the energy of the vibration and converts it into thermal energy which is then dispersed externally. Thus, an effective damping system can prevent breakage of machineries.

Diagram 1-4-4 **The engine can be seen as a vibration system where the vibrations are caused by constant combustion. If an engine resonates, it can lead to serious damage to the engine block or head**



TIPS In the descriptions thus far, natural frequency and resonance frequency seem the same, but this is not the case. Natural frequency is determined by mass and the elasticity of the spring, but resonance frequency is determined by adding the element of damping force onto natural frequency. If there is no damping force on the system, natural frequency and resonance frequency would match, but if a damping system exists, the resonance frequency is reduced and will result in the mismatch against the system's natural frequency. Note that resonance frequency (natural frequency) not subject to a damping system is sometimes called "undamped natural frequency", and resonant frequency with damping is sometimes called "damped natural frequency".

1-5 Effect of damping force

▶ State of vibration varies with damping force

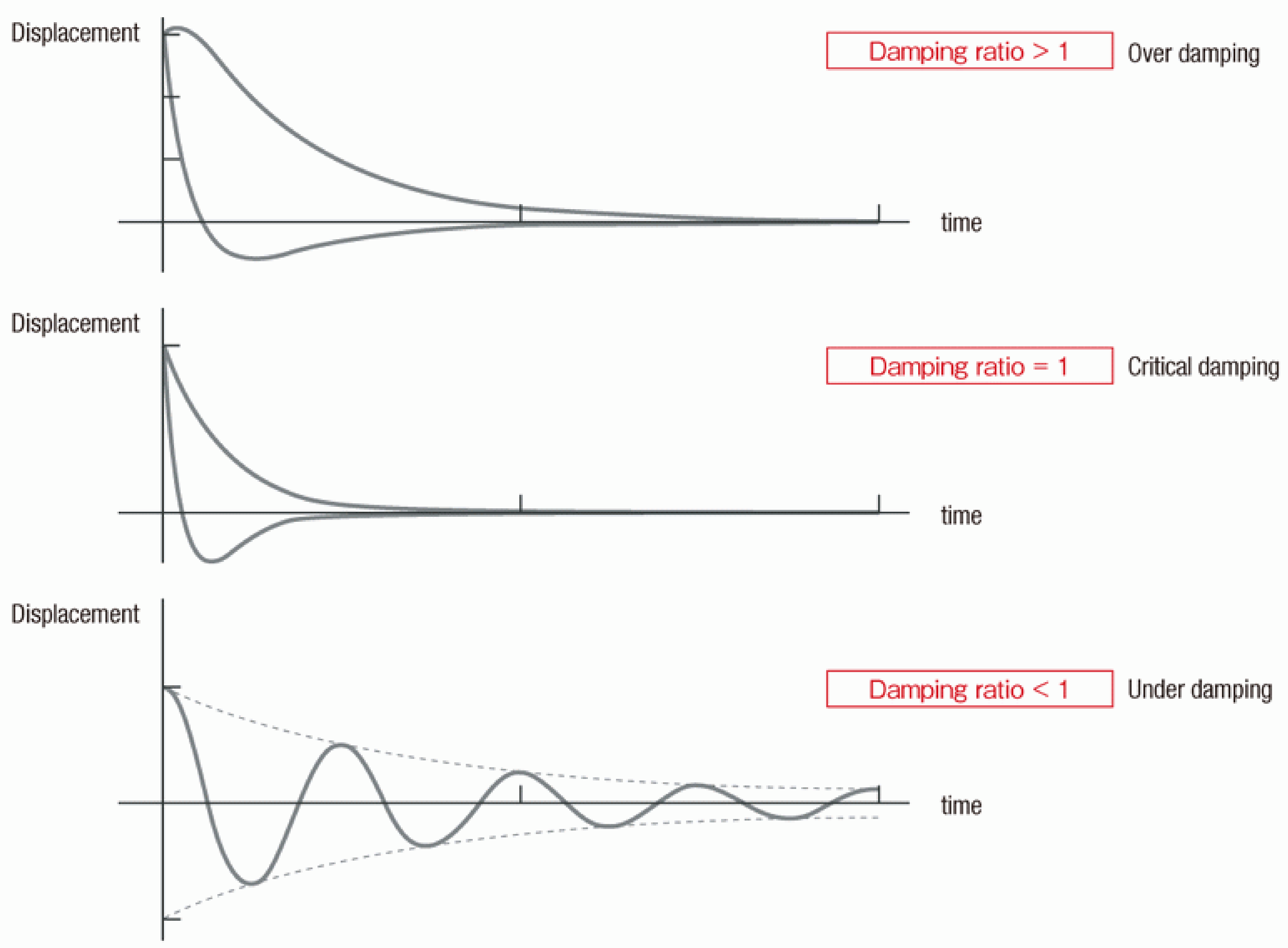
So far, we have considered the cases of vibration of a vibration system consisting of springs and weights as an example. And we've seen that resonance is a problem if the vibration system consisting of a spring and weight is vibrated by force at its natural frequency (resonance frequency). There are some methods to avoid problems caused by resonance, but the most common is to install a damper in the vibration system. A damper is a device that dissipates vibration by converting kinetic energy into thermal energy. However, the state of vibration is greatly changed by the damping force of the damper. Therefore, let's take a closer look at the effect of difference in damping force on the phenomenon of vibration.

Free vibration with a differing damping ratio

The vibration described so far is a result from the elastic force of the spring and the force of the mass, but if we insert a damper in the vibration system, the vibration is damped and the movement soon stops. During the process, the strength of the damping force will affect the damping of the vibration. Here the damping ratio is an indicator of the strength of the damper's damping force against the effect from the mass and elastic force of the spring.

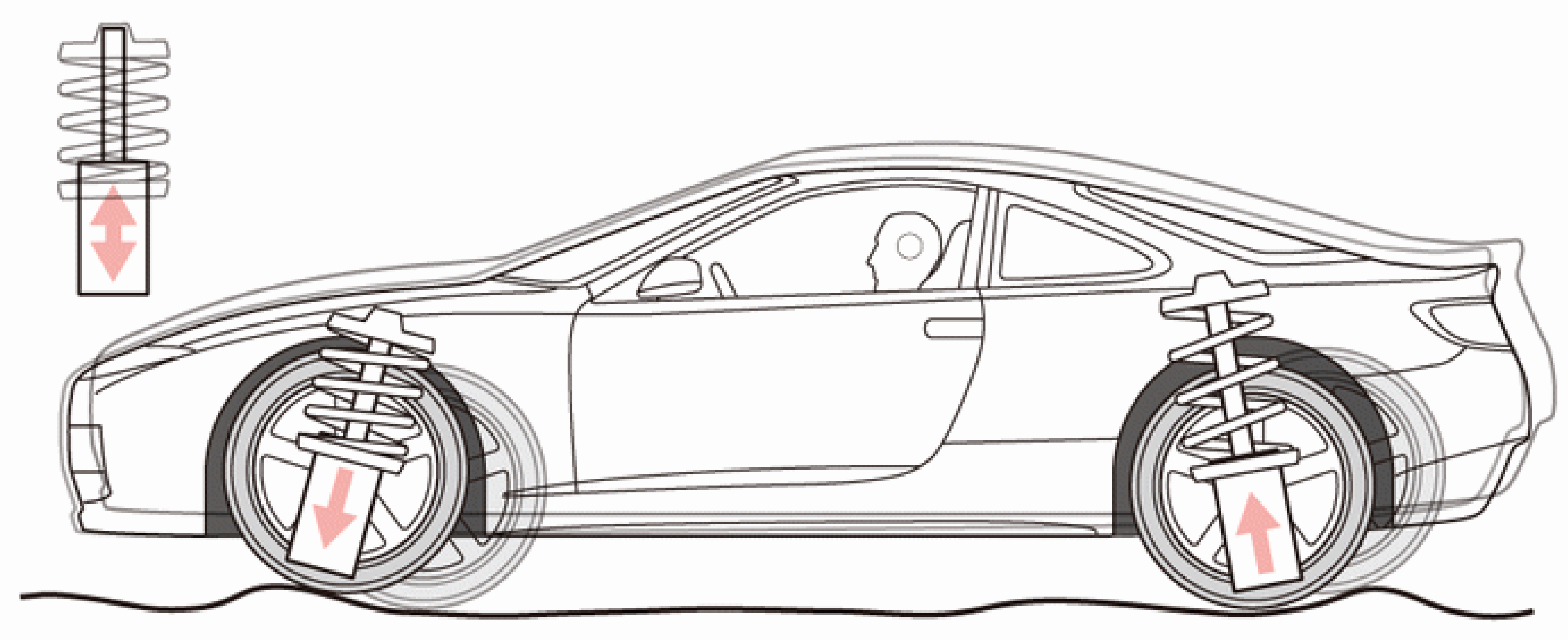
If the damping ratio is greater than 1, the movement of the vibration system converges into a non-vibration state because the damping force is stronger than the spring and mass. This state is called over-damping (over-attenuation). In the state of over-damping, the amplitude decreases with time and enters an aperiodic motion that is asymptotic to 0. If the

Diagram 1-5-1 Example of vibration of the damping system



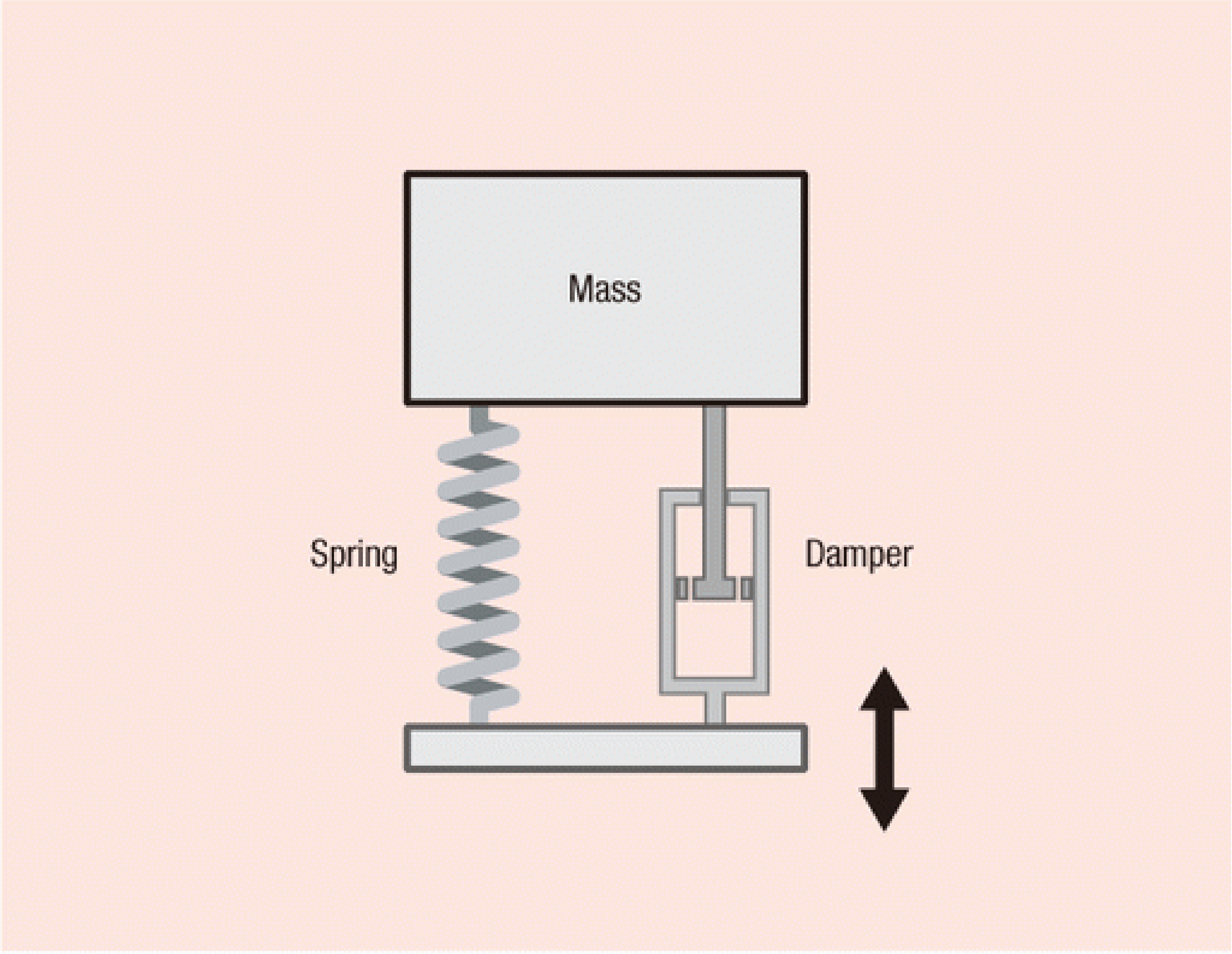
damping ratio is less than 1, because it is in a state where the force from the spring and mass is strong compared to the damping force, the amplitude of the vibration decreases with time and will continue to lengthen the period of vibration. This state is called under-damping (lack of attenuation). Incidentally, when the damping ratio is 0, damping force does not occur and is in a state similar to when the damper is not working, thus the vibration is not damped. Furthermore, if the damping ratio is 1, it is in a critical state of whether vibration should occur or not. This state is called critical damping.

Diagram 1-5-2 **Car suspension damper. The damping ratio is an important indicator when tuning the suspension. As for the aforementioned damping ratio , it is said to be around 0.1 to 0.3 for standard passenger cars, around 0.5 for sports cars, and around 0.7 for racecars (Note: there are exceptions to these figures)**



TIPS In order to prevent vibration from affecting the base that supports the vibrating machinery and other structures and vice versa, parts such as rubber, tires, springs, and dampers are often used for support. It is quite common to create a model of the vibration system, including such aforementioned supports, as shown in Diagram 1-5-3, to see how vibration affects the machinery and its base. For example, the suspension can be modeled and depicted along with the springs, dampers and mass all as one unit in order to evaluate the characteristic of the vibration. This will be touched upon further in Part 2.

Diagram 1-5-3 **Model of base vibration**



1-6 Phase difference

▶ Phase difference is the difference in the rhythm of the vibration

When a vehicle takes on the undulation of a road surface, that undulation is transmitted to the vehicle body through the suspension after being "reduced." In such a case, the amplitude of the body will be milder than the undulation of the road. In other words, the suspension reduces the amplitude relayed to the body of the vehicle. Assuming that the undulation of the road is an "input," it is very important to note how much of the amplitude, or "response", to the body is suppressed. However, that is not the end of the vibration theory. The "speed of response against an input" is also very important in order to discuss vibration.

Diagram 1-6-1 **Undulation of an actual road surface, and the amplitude of the body caused through the suspension. Let us focus upon this relationship. Reducing amplitude to the body is of top importance, but with respect to undulation of the road surface, how quickly the body responds is important as well**

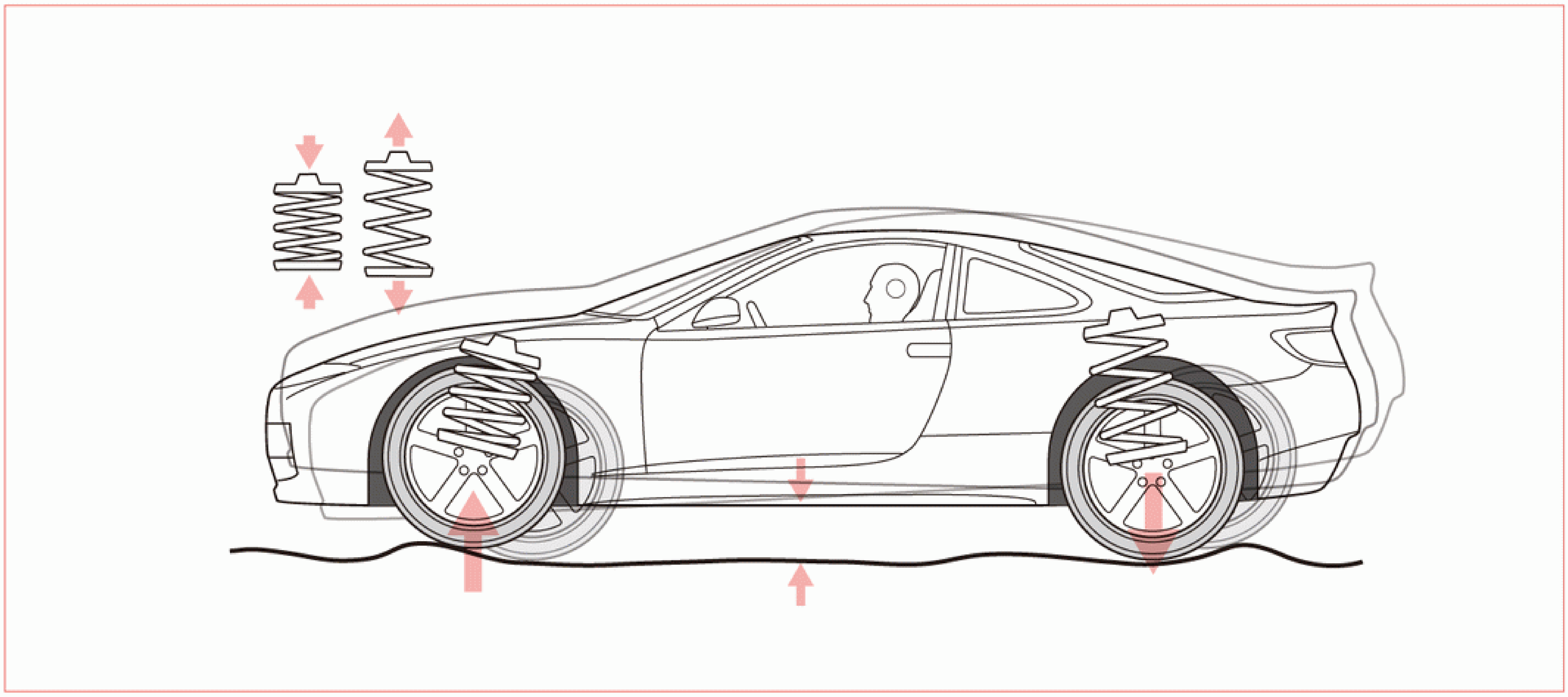
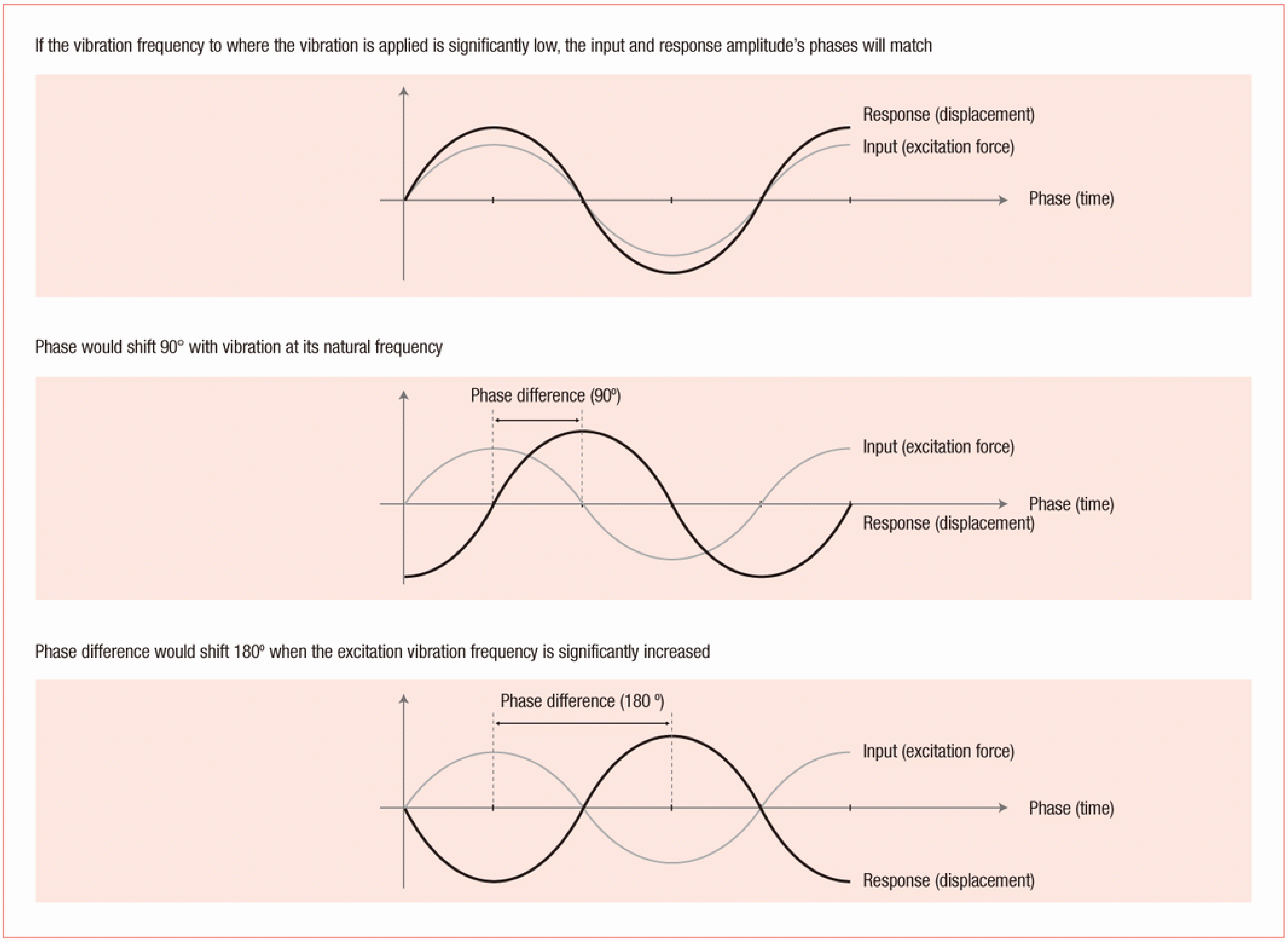


Diagram 1-6-2 **German suspension maker, KW's 7-post rig (underfloor)**

Diagram 1-6-3



Difference of the rhythm of vibration

"Phase difference" is used in evaluating how quickly certain vibration systems react to input. Let's discuss this again using a vibration system of weights and springs.

When your hand forces frequency excitation different to the natural frequency of the spring and weight's natural frequency (resonance frequency), why does your hand feel resistance? It was explained earlier that it is because "any vibration frequency aside from the natural frequency is considered unnatural, thus the vibration system causes resistance against it." Alternatively, it can be said that "the vibration rhythm from the hand is different from the natural vibration rhythm of the vibration system." To be more specific, the difference in rhythm is caused by "the difference between the direction the vibration is added and the direction of inertia of the weight." This difference in rhythm is referred to as the "phase difference."

Please look at Diagram 1-6-3. When we add vibration to the vibration frequency slowly, the direction of force from the hand and the expansion and contraction of the spring vibrates in the same direction and as the same rhythm. There is no mismatch in the input or response at this time, so the phase difference is 0 (Diagram 1-6-3, top). However, when the input frequency is raised significantly, the phase difference ultimately becomes 180 degrees, as the inertial force of the weight and the exciting force from your hand act in opposite directions (Diagram 1-6-3, bottom). Note that the phase difference would be 90 degrees if it is vibrated at its natural frequency (Diagram 1-6-3, middle).

1-7 Frequency Response

▶ For the analysis of vehicle motion and suspension

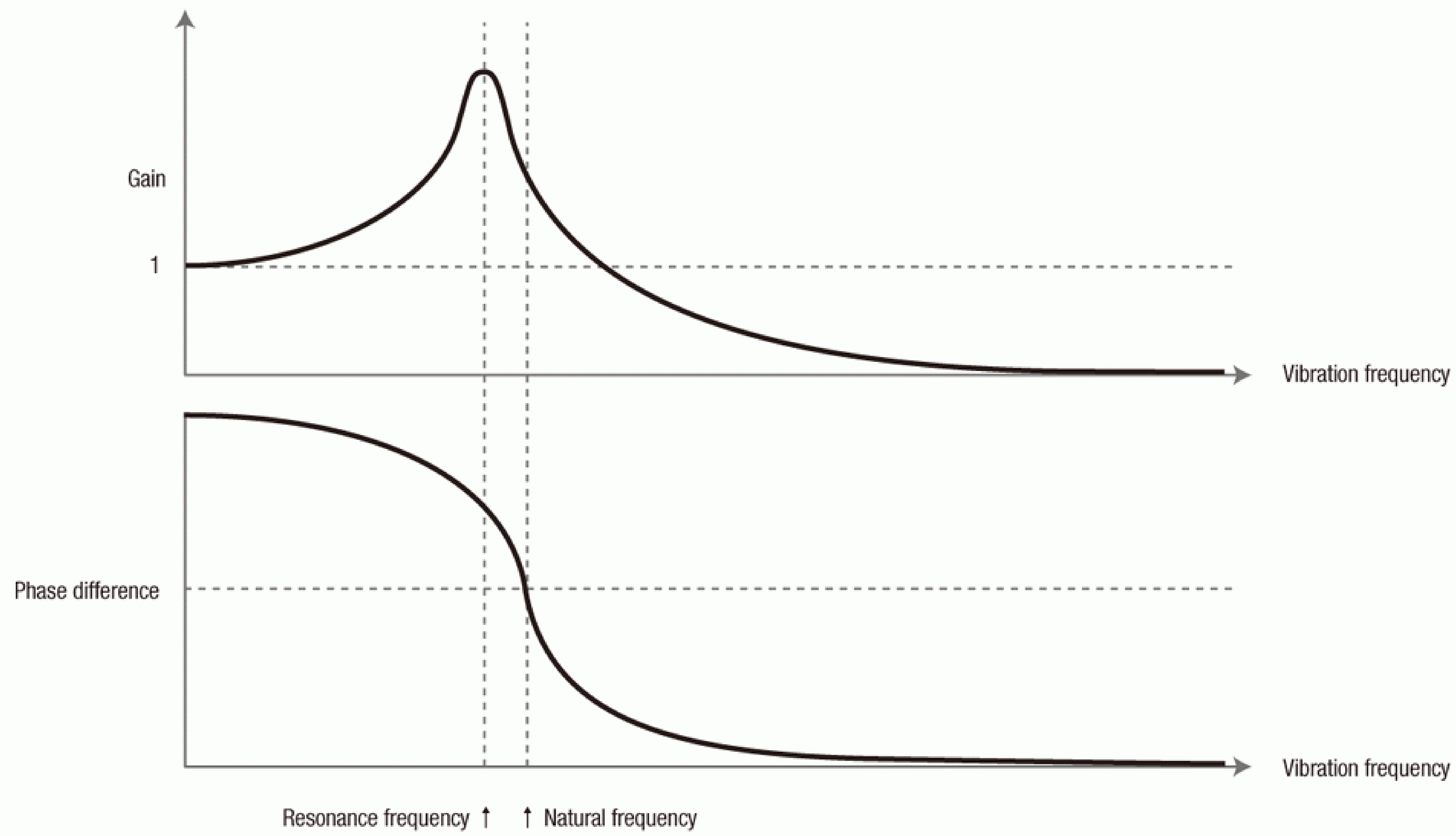
Grasping the difference in response to frequency excitation

Response such as the amplitude and phase difference against excitation frequency (excitation vibration frequency) is referred to as a frequency response. So far we've been discussing separately the phase difference and amplitude changes due to the vibration frequency of the excitation (frequency), but now we will take a look at how the phase and amplitude responses of the vibration system change due to the frequency of the excitation.

In the vibration analysis of a car, analyzing the frequency response is often done by a Bode Plot. Diagram 1-7-2 is a Bode Plot and the graph at the top is called the magnitude plot. It shows the magnitude (gain) of the response to the excitation frequency (input). The graph on the bottom of Diagram 1-7-2 is called a phase plot and it shows how off the response is (phase difference) against an input.

So far, we've been thinking of a vibration system consisting of a weight and spring. To make things a little more sophisticated, try to think about a vibration system with a damper added to it (Diagram 1-7-1). But, let us set the damping ratio to a number below 1, or in other words apply under damping.

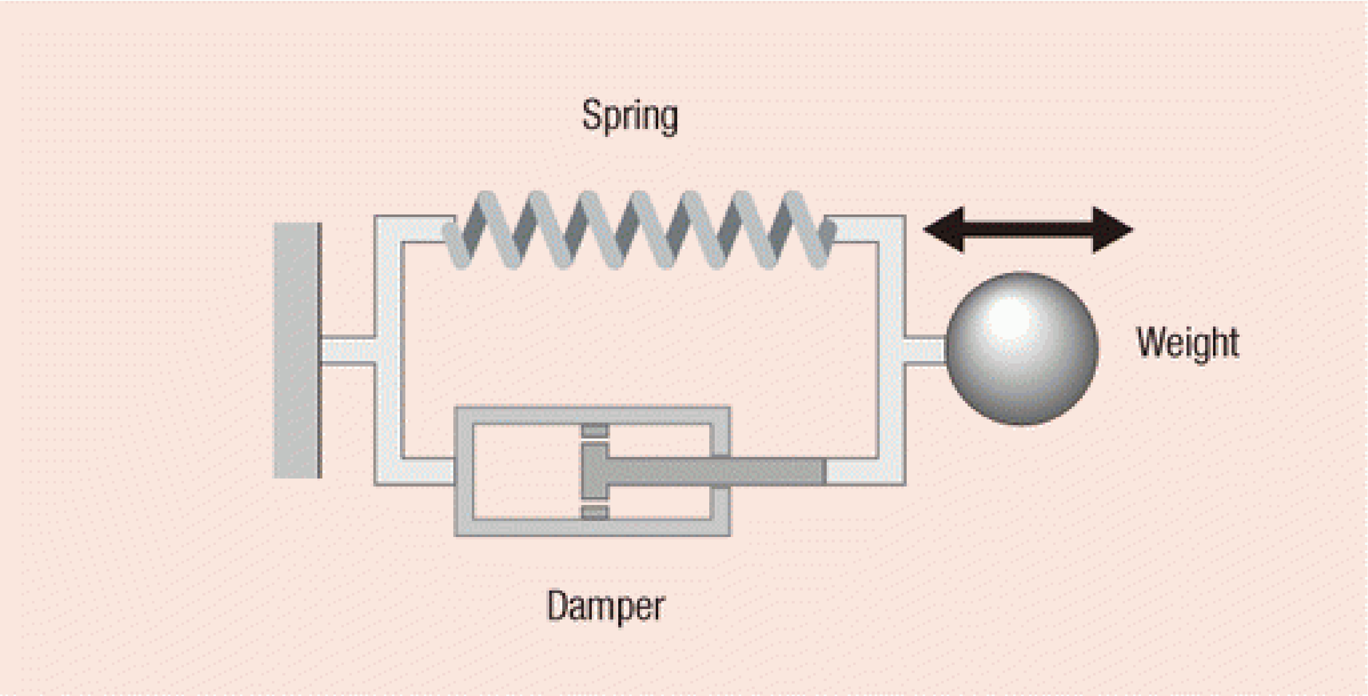
Diagram 1-7-1 This model consists of a spring, damper and weight. The damper is incorporated in parallel with the spring to prevent the amplitude from becoming infinitely large at resonance



Capturing the damping system's vibration through the Bode Plot

With this model, let's gradually increase the frequency of the vibration from its stationary state. When the frequency is significantly low, the amplitude ratio is 1, or in other words the amplitude of the excitation and the amplitude of the spring have no difference. From there, as the frequency is increased, the amplitude increases, and the phase difference becomes greater. Once the vibration frequency hits a certain figure, the amplitude is maximized, and this is referred to as resonance. From there, raising the frequency will reduce the amplitude, coming close to 0. On the other hand, in relation to phase difference, when the vibration frequency is significantly low, the excitation and spring is moving with the same rhythm and same direction, so the value is 0, but this leads to -90 degrees of the natural vibration frequency, and when at an extremely high vibration frequency the natural vibration frequency is at -180 degrees.

Diagram 1-7-2 Bode Plot showing the frequency response of a vibration system consisting of a spring, damper and weight



1-8 Vibration in suspension

▶ Vibration in a multi-degree freedom system

To make it easy, we've attempted to understand the basics of vibration by means of a simple vibration model that combines, one by one, each of the vibration elements of a spring, weight, and damper. However, an actual car is a vibration system combining multiple vibrations of these elements. Let's look at the basic characteristics of the multiple elements in the vibration-control system before performing vibration control, such as the tuning of the actual suspension.

Vibration characteristics of the suspension

Although there are various mechanisms in the suspension of an automobile, it is essentially a vibration system consisting of mass, a spring and a damper, and it can be modeled as shown in Diagram 1-7-1. The damper and spring, located between the wheel and the vehicle body, represent what we call the car's suspension system, and the damper and spring located between the road surface and the wheel are the tires.

Let's do a demonstration with the various vibration frequencies acting this model (Diagram 1-8-2). In a frequency very close to a resting state, the displacement of the body and the displacement of a road undulation will be the same, so the amplitude ratio would be 1. From there, if you slowly increase the frequency, the amplitude will increase as well. When we reach a certain vibration frequency, the amplitude reaches a peak and resonance of portions atop the spring occurs. If the frequency is further increased, the amplitude decreases, but is amplified again at a certain frequency and resonance to the portions below the spring occurs which in turn increases the amplitude of the body. If the frequency is increased even further, the amplitude will decrease again and ultimately will close in to 0.

Diagram 1-8-1 Model of only one wheel (1/4 of the vehicle vibration). The tire, spring, and damper all have distinct characteristics of a vibration system

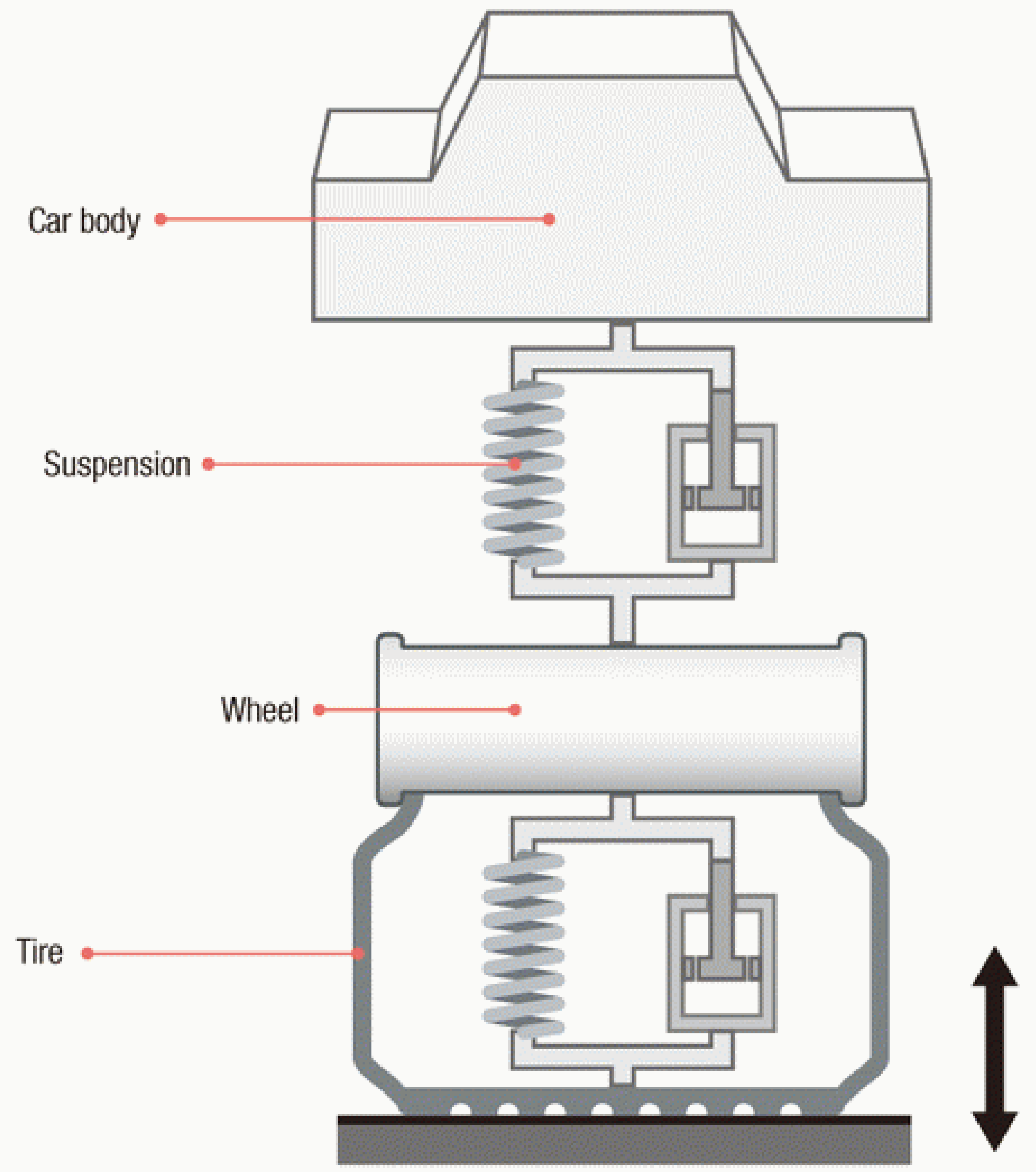
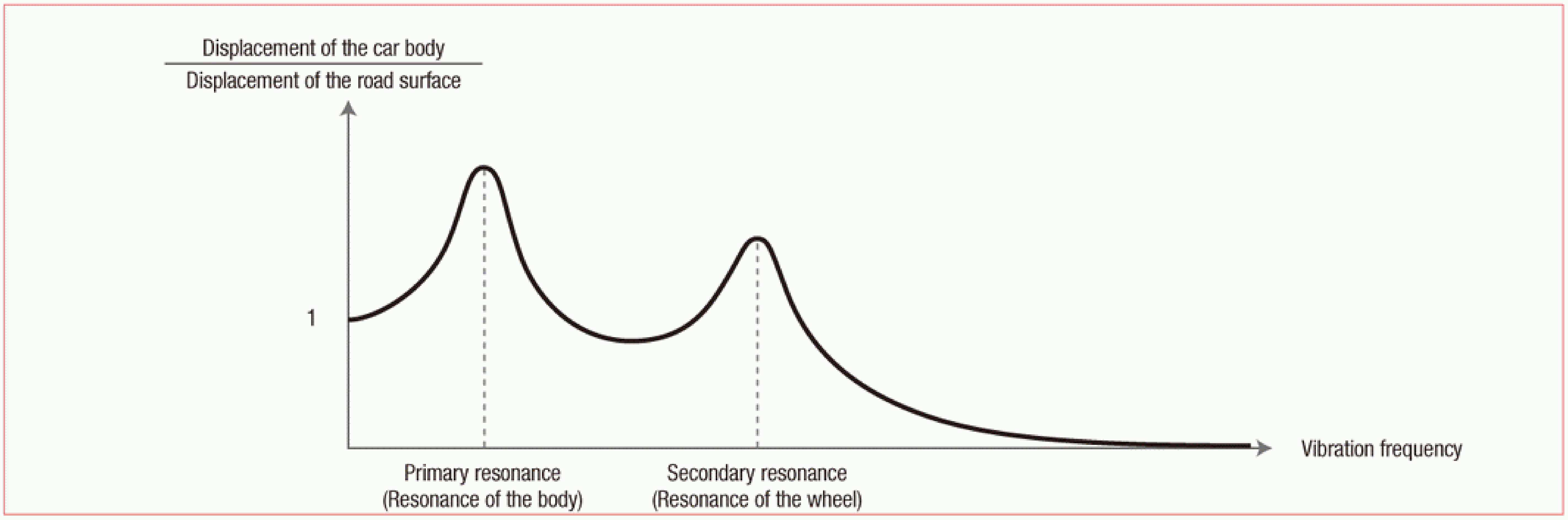


Diagram 1-8-2 **Change as vibration frequency is gradually increased. Resonance of the body takes place at a relatively low vibration frequency, and the resonance of the wheel occurs at higher vibration frequencies**



Vibration mode

Resonance occurred twice in the example above, but resonance may occur many times as the system moves in different directions. The amount of directions that the system can move to is referred to as the "degree of freedom." In this case, the tire and spring can each move up and down in one direction each, so a total of two natural frequencies are involved, and since two types of resonance can occur, this vibration system will have a degree of freedom of 2.

The initial resonance is called "primary resonance," and the second resonance is referred to as the "secondary resonance." Resonance in a machine generally occurs an unlimited number of times, but what is important in engineering is low order resonance, and high order resonance is generally ignored. In other words, in this example, the resonance of what is above the spring is more important than the resonance of what is below the spring. The reason is because even when the same level of vibration energy is involved, the low-frequency amplitude tends to be larger, and as these components dominate the phenomena of the entire system, they therefore determine the majority of vibration characteristics.

Diagram 1-8-3 **Performing the suspension evaluation of the GT-R that participated at the Nürburgring. Testing of the suspension at a variety of vibration frequencies, and analyzing the frequency response**

2-1 Tire Dynamics

▶ Understanding the forces created by the tire

Cornering force

The type of force that deforms an object in a shearing manner is called "shear force," and the object's property that counters against that force is called shear modulus. When a tire is exposed to a transversal direction of shearing forces, the tire will laterally deform as in Diagram 2-1-1; however, at the same time, shear modulus of the tire will counter against the shear force. This countering property of the tire that works against its deformation is what creates the forces necessary for the car to accelerate, decelerate and turn.

Let's take a closer look. Diagram 2-1-2 is a sectional illustration of a tire during cornering. As you can see, there is a difference between the rotational direction of the tire and the car's direction of travel. In other words, force is created from the tire's interaction with the road surface as the tire rotates and deforms laterally at the same time. The angle of the rotational plane and the direction of travel is called the slip angle. The force which works perpendicular to the direction of travel is called cornering force. A car is able to turn because of the cornering force from the tire.

In general, if the shear modulus is larger, a stronger cornering force can be created from the same slip angle. That said, if the shear modulus is too large, friction can be saturated by a small slip angle, which may result with unnatural feedback to the driver. If the shear modulus is too small, the deformation of the tire will be too extreme, and that can make the driver feel uncomfortable or unsafe.

Diagram 2-1-1 cross-section diagram illustrating tire deformation and force. In general, more shear modulus creates bigger cornering force

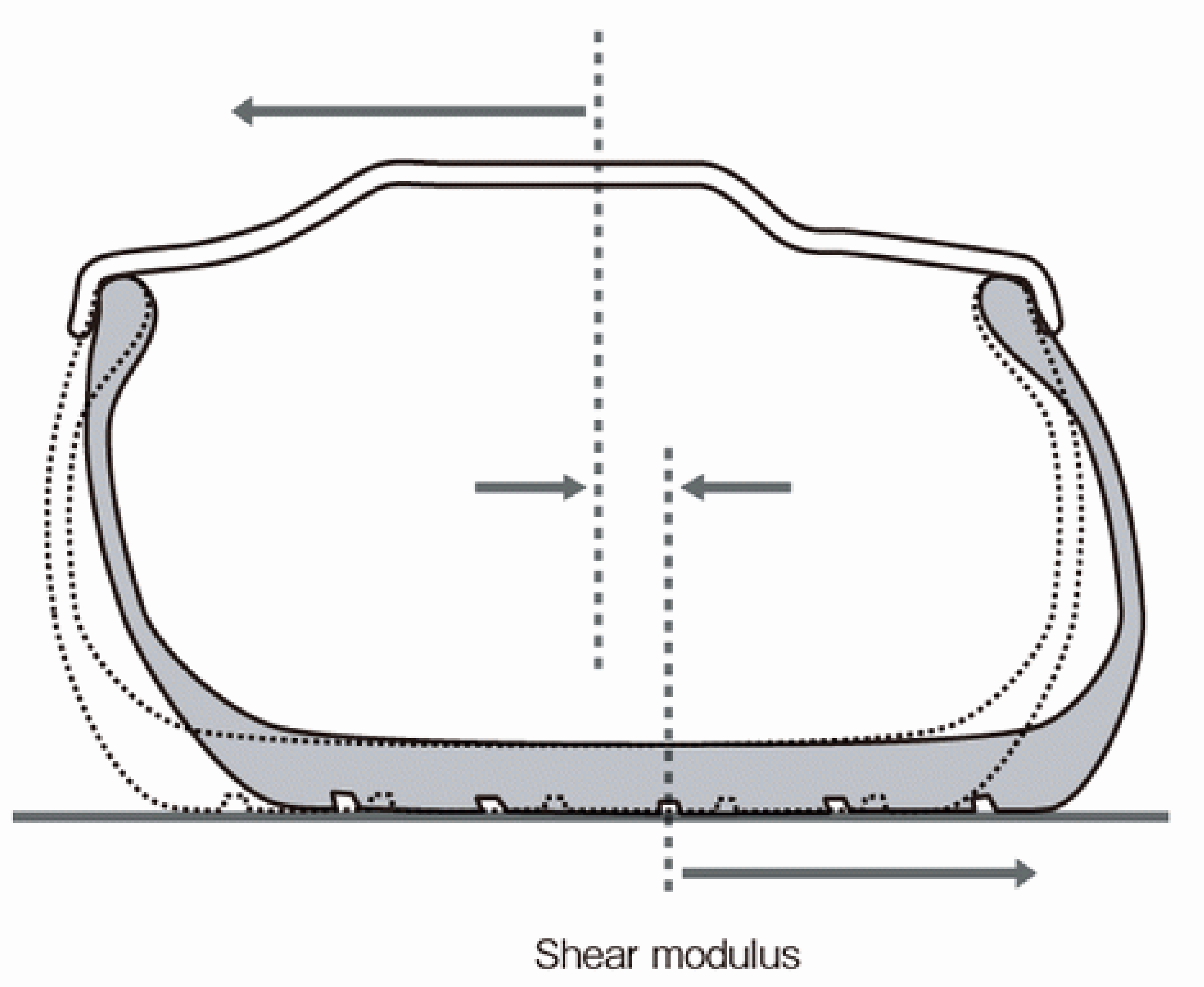
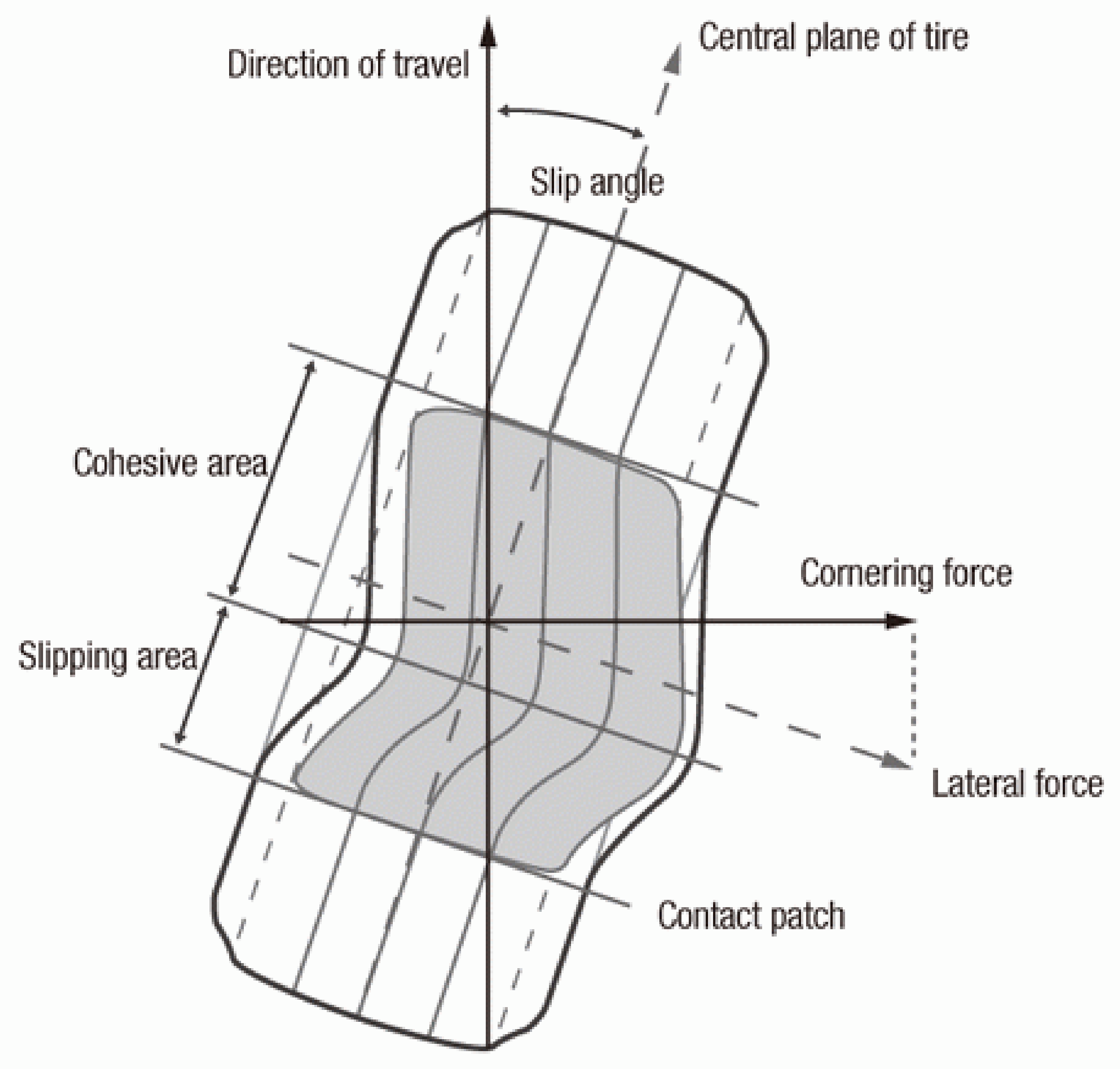


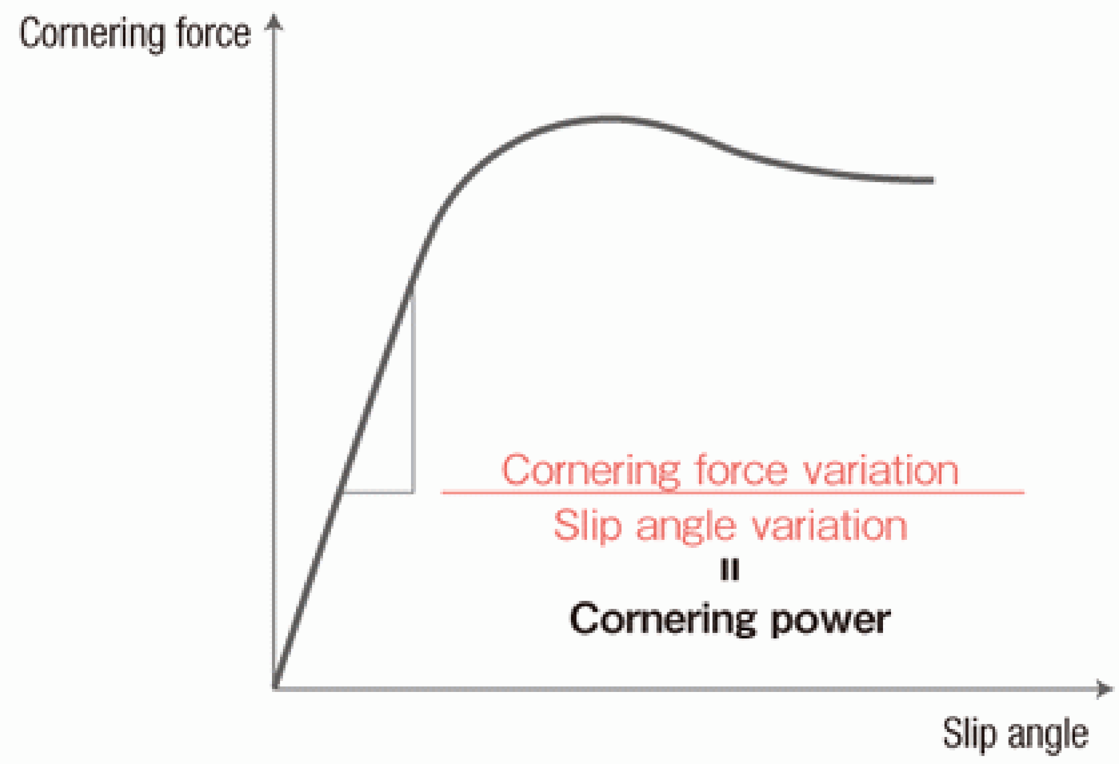
Diagram 2-1-2 Top view illustrating the relation between deformation and force. The lateral force occurs perpendicular to the central plane of the tire. Cornering force is an element of the lateral force that occurs perpendicular to the direction of travel



Relation between cornering force and slip angle

Diagram 2-1-3 shows the relationship between the slip angle and cornering force. When the slip angle is small, the cornering force maintains a linear increase. However, as the slip angle increases, the cornering force saturates. This rate of change in cornering force is called cornering power. A tire that creates a large cornering force with a small slip angle can be said to have a lot of cornering power.

Diagram 2-1-3 Correlation of slip angle and cornering force. Cornering power is big within the range where the slip angle is relatively small. After the slip angle reaches a certain value, cornering power stops increasing.



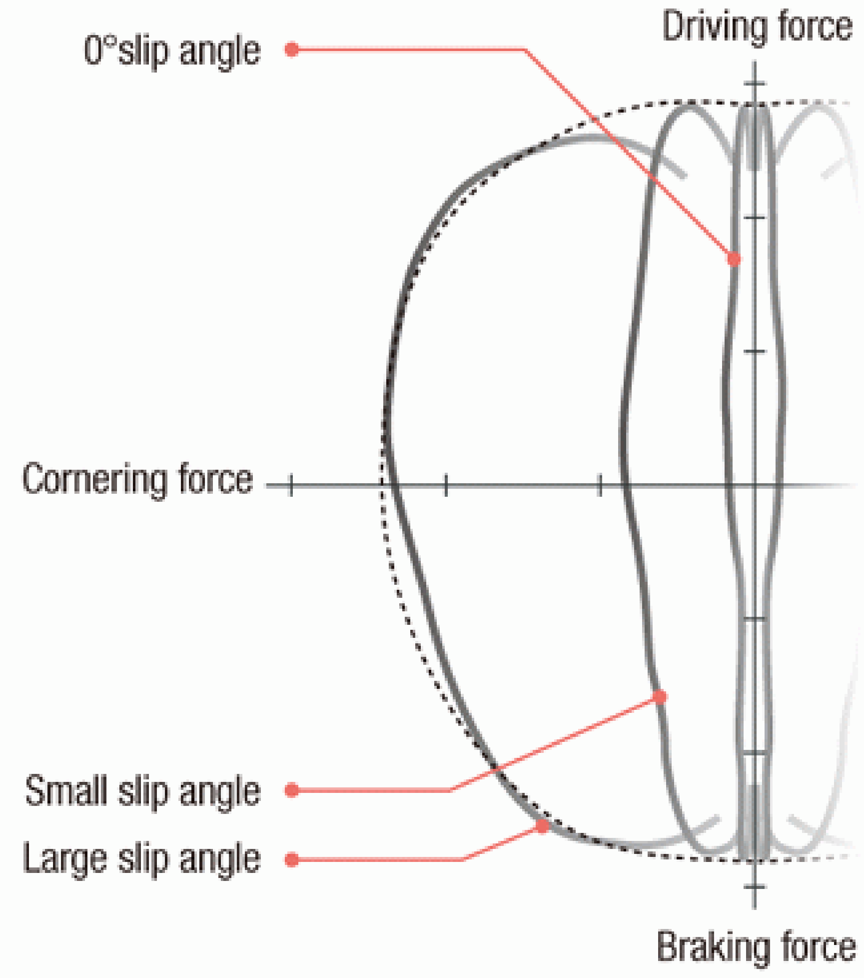
Air pressure and cornering power

In general, when the air pressure of the range is relatively low, shear modulus increases with the rise in air pressure, thus increasing cornering power. However, a rise in air pressure decreases the contact area of the tire. Shear modulus and the contact area of the tire contradict as the air pressure rises. At low vertical load, the decrease in contact area of the tire from the rise in air pressure is greater than the increase in shear modulus; therefore, cornering power decreases. On the other hand, when the vertical load is high, the resulting increase of shear modulus from the rise in air pressure becomes dominant, thereby increasing cornering power. To maximize cornering power, the characteristics of the tire and load must be carefully considered and balanced.

Lateral force of the tire associated with driving and braking

Looking at the tire from a bird's-eye view, the grip force that's created perpendicular to the tire's rotational direction is called lateral force. It is important to understand how this lateral force is associated with the driving and braking of the vehicle. When the gas or brake pedals are being pressed, the gripping power of the tire is used for driving and braking, as a result decreasing the amount of lateral force that can be created even at the same slip angles. This is illustrated in Diagram 2-1-4. Although it is called a friction circle, the diagram is actually oval shaped, and not perfectly round, since longitudinal and lateral friction affect the tire differently. Because acceleration and braking are continuously repeated on a race car, friction that occurs in the diagonal direction has a lot of effect on lap times.

Diagram 2-1-4 Friction circle. Cornering force of the tire is affected by the slip angle. The oval perimeter of the friction circle indicates the maximum cornering force.



2-2 Steady-state circular driving

▶ Cornering depends on the moment balance of the front and rear tires

Definition of steering balance

When a car is driven at a steady steering angle and speed, it will trace a circular course with a fixed radius. This is called steady-state circular driving and often referred to in automotive dynamics. Observation of a car in steady-state circular driving can reveal the fundamental properties of vehicular motion.

For example, imagine that a car is in steady-state circular driving, and the speed is gradually increased. If the moment of the front wheel should decrease as the car accelerates, the turning radius will increase with speed (the driving line will expand). As a result, the steering angle must be increased to keep the original steady-state circular driving course.

To the contrary, if the moment of the front wheel should increase, the turning radius will decrease as the car accelerates (the driving line will contract), so the steering angle must be decreased to maintain the original driving line. The state of lacking steering angle as the speed increases is called understeer (US), and the latter state of having a surplus steering angle is called oversteer (OS). When the turning radius can be maintained without any influence from speed variation, it is called neutral steer (NS). These different steering states of the car are called steering characteristics. It should be noted that a car with oversteer will reach the turning radius of "0" at a certain speed (Diagram 2-2-2).. Zero turning radius means that the car is in a spin. The speed where the car begins to spin is called the critical stability speed.

Diagram 2-2-1 Changes in vehicle sweep when speed is increased

OS: Moment of front wheel > Moment of rear wheel
US: Moment of front wheel < Moment of rear wheel
NS: Moment of front wheel = Moment of rear wheel

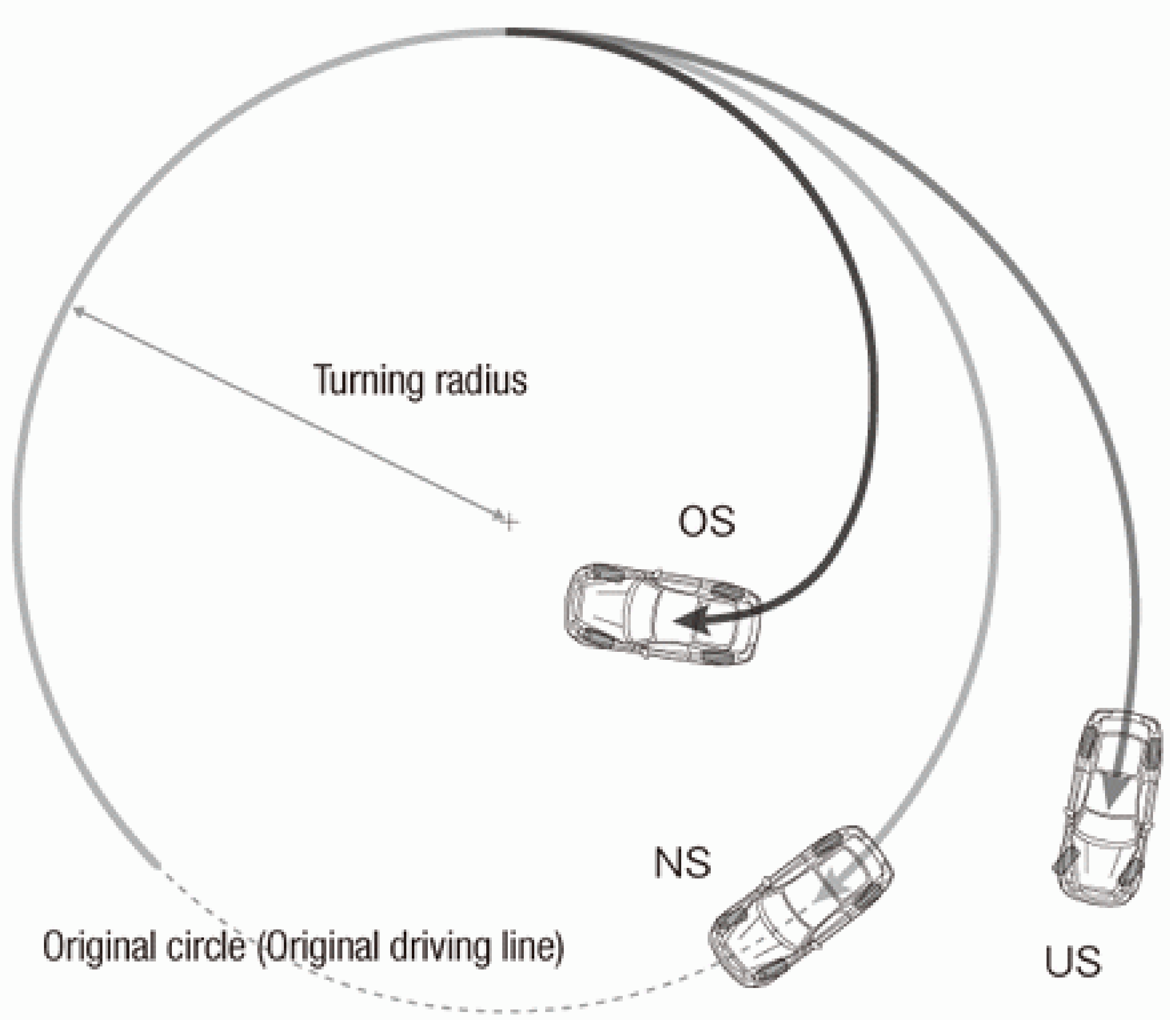
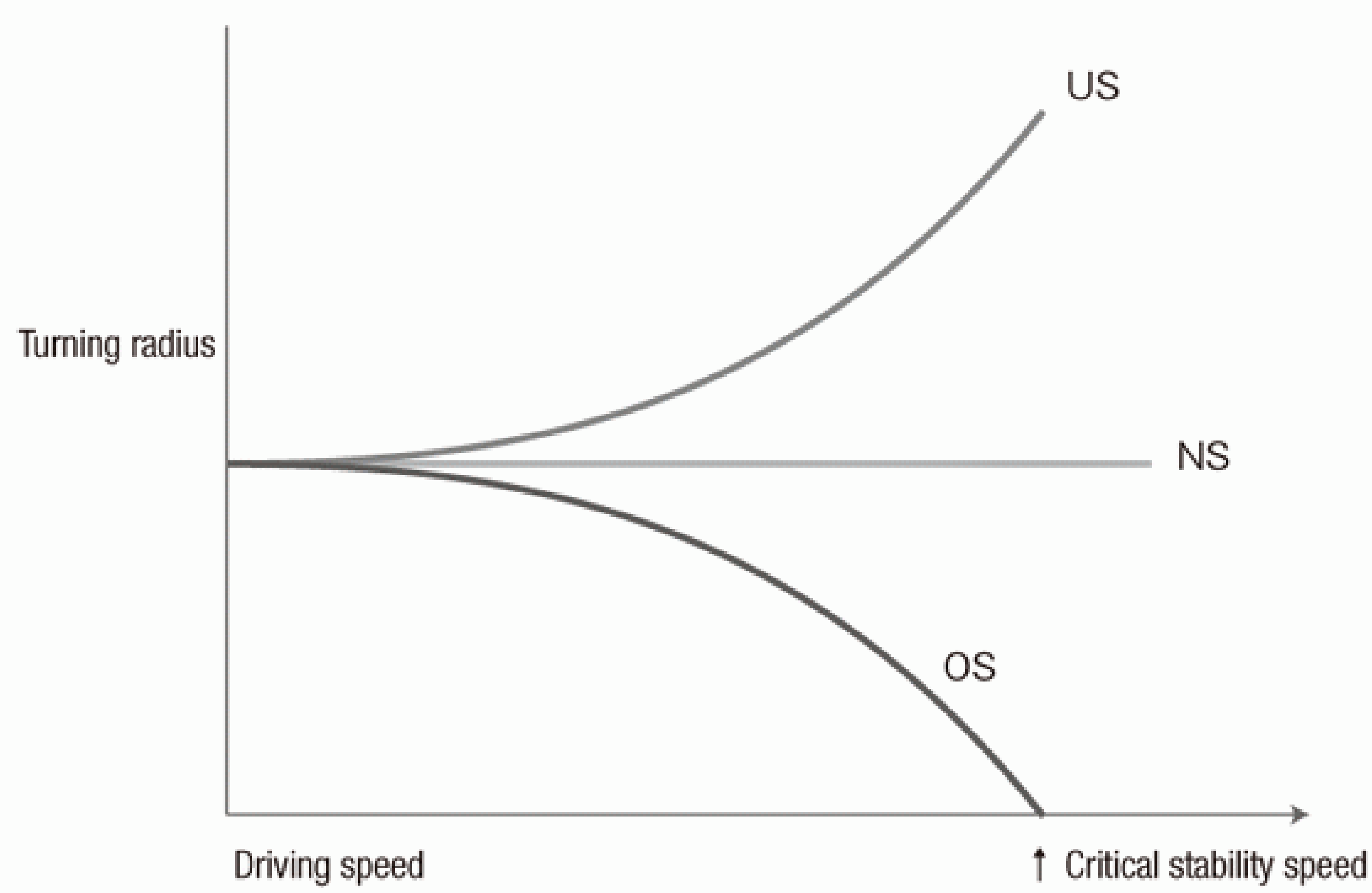


Diagram 2-2-2 Correlation of speed and turning radius under stable steering angle



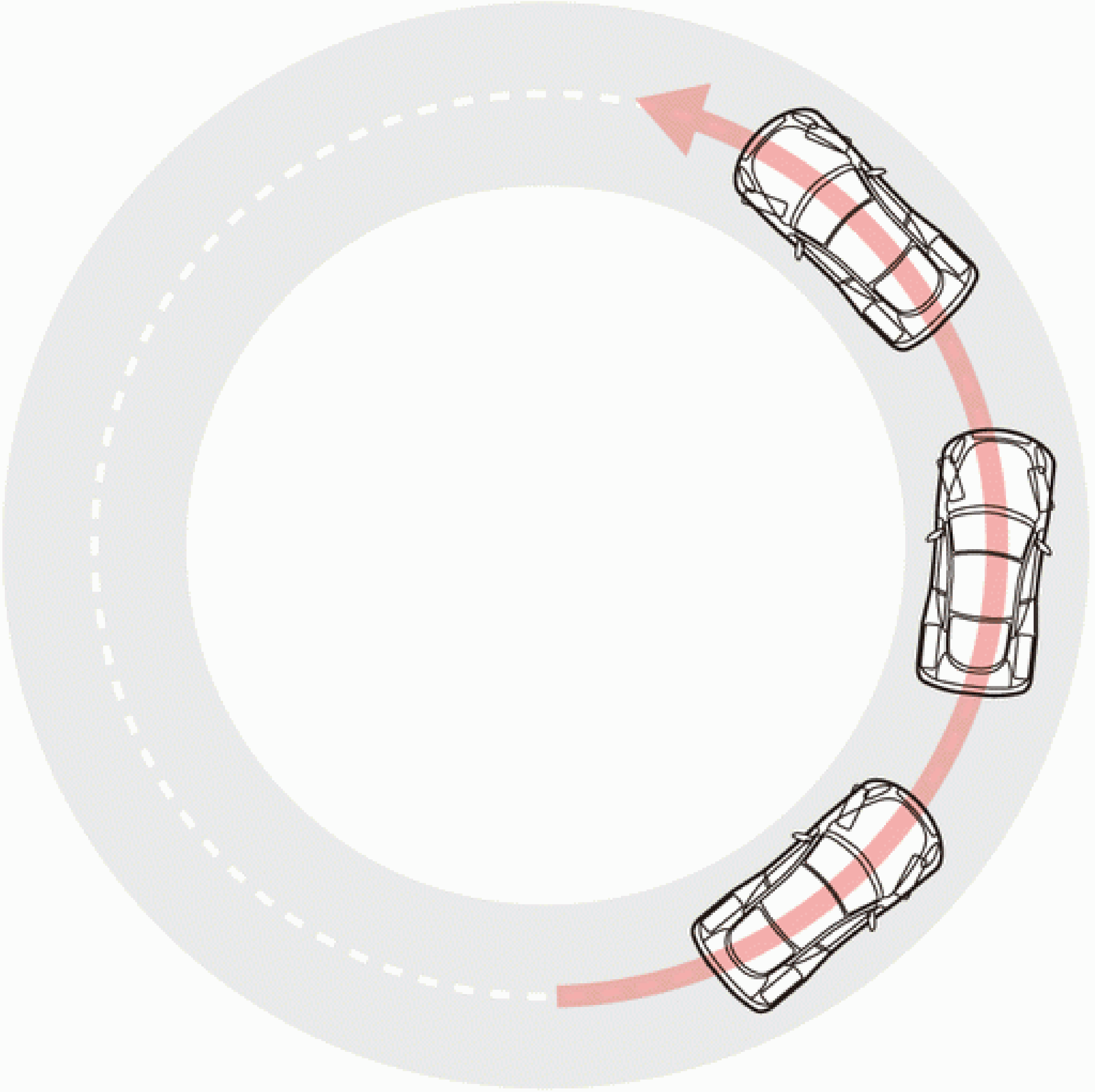
Graph 2-2-1 Steer Characteristic

	US	NS	OS
M ; Moment to turn the car	M front wheel < M rear wheel	M front wheel = M rear wheel	M front wheel > M rear wheel
β : Slip Angle	β front wheel > β rear wheel	β front wheel = β rear wheel	β front wheel < β rear wheel

Relation of steering characteristic and slip angle

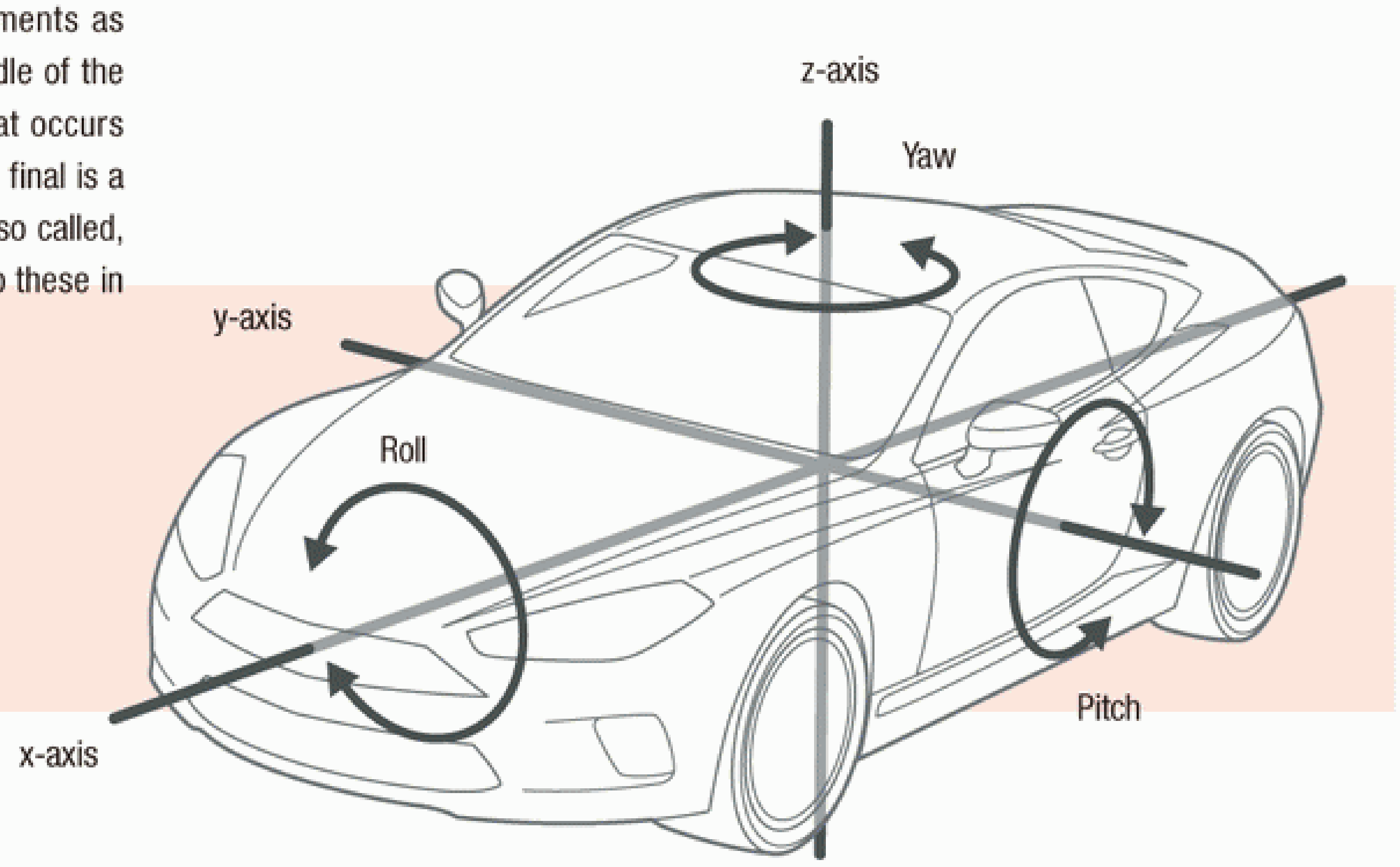
There is an interesting connection between the front/rear wheel slip angle (β front wheel, β rear wheel) and steering characteristic. Please refer to Diagram 2-2-3. Under steady-state circular driving, if the front and rear slip angle is β front wheel > β rear wheel it is understeer, when β front wheel = β rear wheel it is neutral, and when β front wheel < β rear wheel it is oversteer. This connection is true even when there is lateral force other than cornering force and whether or not the cornering force is proportional to the slip angle. The connection is geometrically fixed when a car is in steady-state circular driving.

Diagram 2-2-3 **Steering characteristic changes according to the difference in slip angle of the front and rear tires**



TIPS When speaking of cornering and suspension movements, the force derived from the vehicle is often categorized into three rotational movements as shown in Diagram 2-2-4. The first is a rotation that occurs towards the middle of the length of the vehicle (x-axis) also called, "roll." The second is a rotation that occurs towards the middle of the width of the vehicle (y-axis) also called, "pitch." The final is a rotation that occurs towards the middle of the height of the vehicle (z-axis) also called, "yaw." These terminologies will appear frequently, so it would be good to keep these in mind.

Diagram 2-2-4 **The three rotational movements that occur on a vehicle**



2-3 A car's response to changes in steering angle

▶ Automotive motion is an oscillation phenomenon

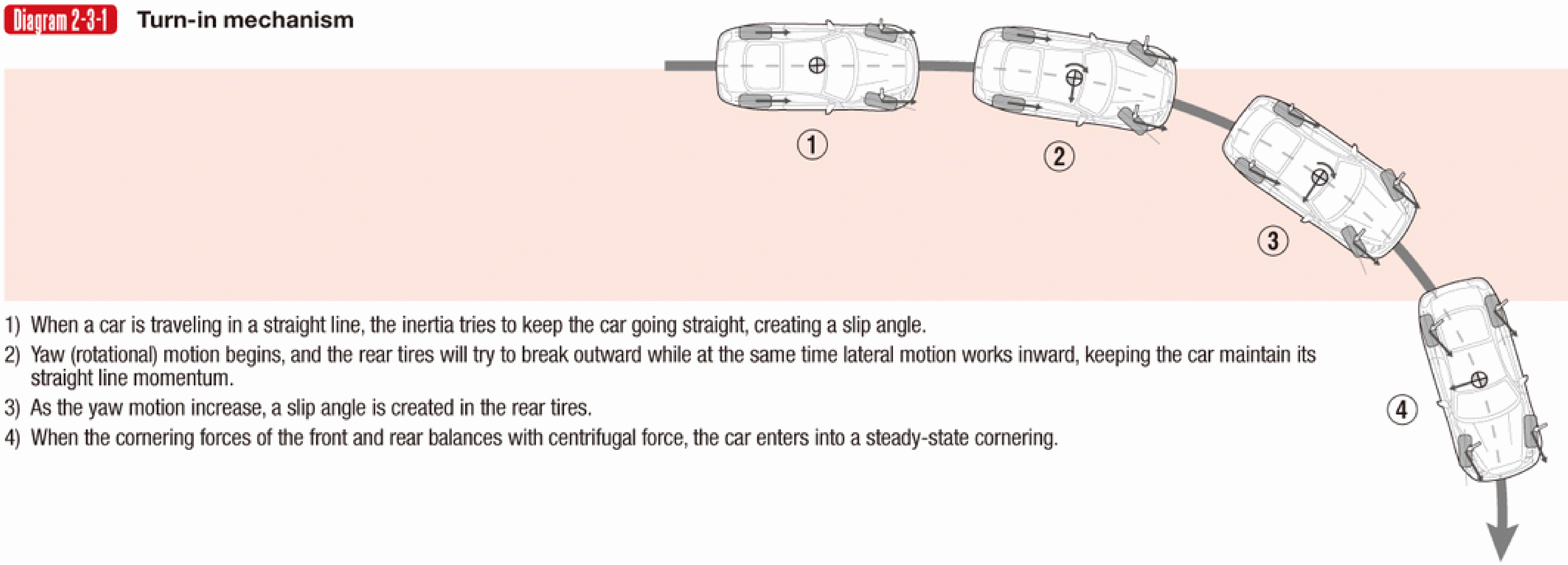
Turn-in mechanism

Observation of a car in steady-state circular driving reveals the fundamentals of vehicular motion. It also reveals how the car responds to changes in steer angle, which is another important topic in the analysis of vehicular motion.

Using Diagram 2-3-1, let's take a step-by-step look at the turn-in mechanism. (1) When the steering of a car traveling straight is turned, the initial momentum of the car will try to keep the vehicle going straight. At that instant, a slip angle is created between the direction where the front tires are pointing and the momentum of the car going straight, resulting in the occurrence of cornering force. Since cornering force occurs with the deformation of the tire, there exists a slight time lag. (2) The occurrence of cornering force initiates yaw (rotational) motion; however, at that time, the rear tires will continue to move straight due to the original inertia momentum. (3) After some time lapse, a slip angle is created on the rear tires as well, resulting in the creation of cornering force. (4) When boththe front and rear cornering force stabilizes, the yaw rate (yaw velocity) becomes defined and The car is now in a stable turn, it began to turn earlier (see diagram 2-3-1).

It is important to understand that yaw motion does not occur simultaneously without any time lapse with steering motion, but there is a slight phase difference due to the relationship between the car's moment of inertia and the occurrence of cornering force from the tires.

Diagram 2-3-1 Turn-in mechanism



1) When a car is traveling in a straight line, the inertia tries to keep the car going straight, creating a slip angle.
2) Yaw (rotational) motion begins, and the rear tires will try to break outward while at the same time lateral motion works inward, keeping the car maintain its straight line momentum.
3) As the yaw motion increase, a slip angle is created in the rear tires.
4) When the cornering forces of the front and rear balances with centrifugal force, the car enters into a steady-state cornering.

Steering characteristic and car response

Response of the car to the driver's steering motion depends on the steering characteristic and the car's velocity. Diagram 2-3-2 illustrates how the car responds to a pulsed (sharp steer then back) steering action. A car with understeer, when driven above a certain speed, will initially become unstable and then gradually come to a steady state. A car with neutral steer will not become unstable but settle into a steady state immediately. Meanwhile, a car with oversteer, if driven above the critical stability speed, will immediately go into a spin. These different reactions have been summarized in chart 2-3-1.

Cars with understeer or neutral steer will eventually become stable; however, a car with oversteer will lose stability if and when it reaches speeds exceeding the critical stability speed.

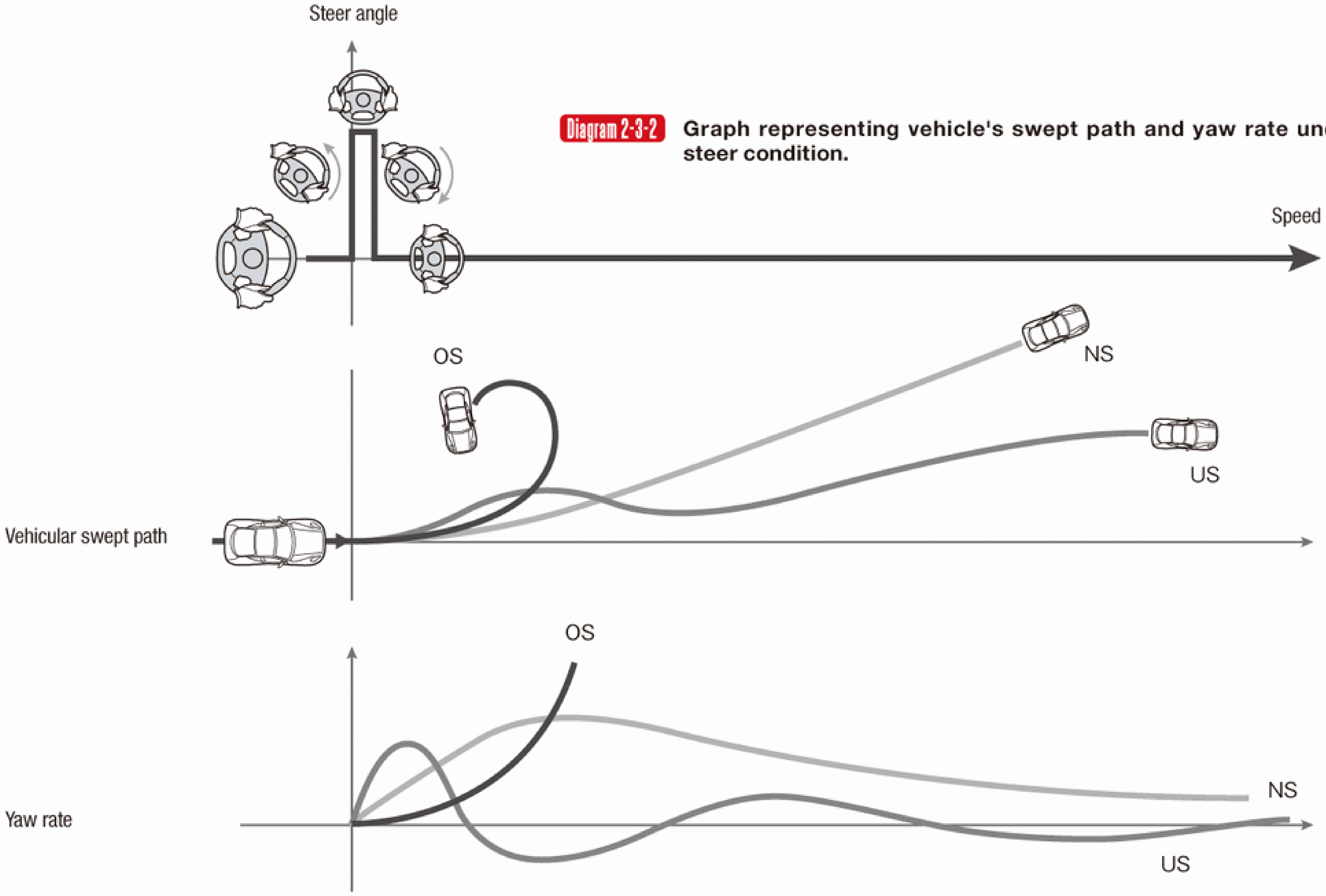
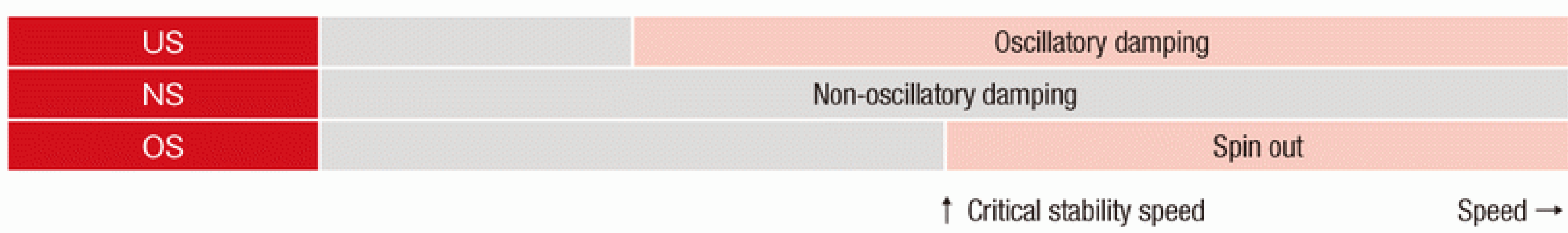


Diagram 2-3-2 Graph representing vehicle's swept path and yaw rate under pulse steer condition.

Graph 2-3-1



Response summary of cars with different steering characteristics: understeer (US), neutral Steer (NS), and oversteer (OS). A car with oversteer will spin after exceeding the critical stability speed

Applying oscillation theory to vehicle motion

Please recall the oscillation difference associated with the damping ratio as explained in section 1-5. In that section, we confirmed that under-damping occurs when the damping ratio is less than 1, which means that vibration response becomes oscillatory. If the damping ratio is greater than 1, in the state of over-damping, vibration response is damped without oscillation. When the damping ratio equals 1, we confirmed that it was in a state of critical damping. Here we realize that the behavior of the oscillatory components consisting of mass, spring and damper resembles that of the entire car.

The oscillatory components of mass, spring and damper as explained in Chapter 1, and car dynamics, can both be considered from certain abstract concepts like damping ratio and resonance frequency (or natural frequency). One can observe that there are no differences and both can be considered as oscillatory systems. In other words, vehicle motion is a type of an oscillatory phenomenon.

As an example, please take a look at diagram 2-3-2. The yaw damping of a car with understeer has a damping ratio of less than 1; therefore, response is oscillatory. The yaw damping of a car with oversteer has a damping ratio of more than 1 hence response is non-oscillatory. The yaw damping of a car with neutral steer is at a critical damping state with the damping ratio of 1, and the response becomes non-oscillatory. (Yaw damping refers to the effect of damping yaw motion).

2-4 Vehicle response to periodic steer motion

▶ Understanding vehicle characteristic from the Bode Plot

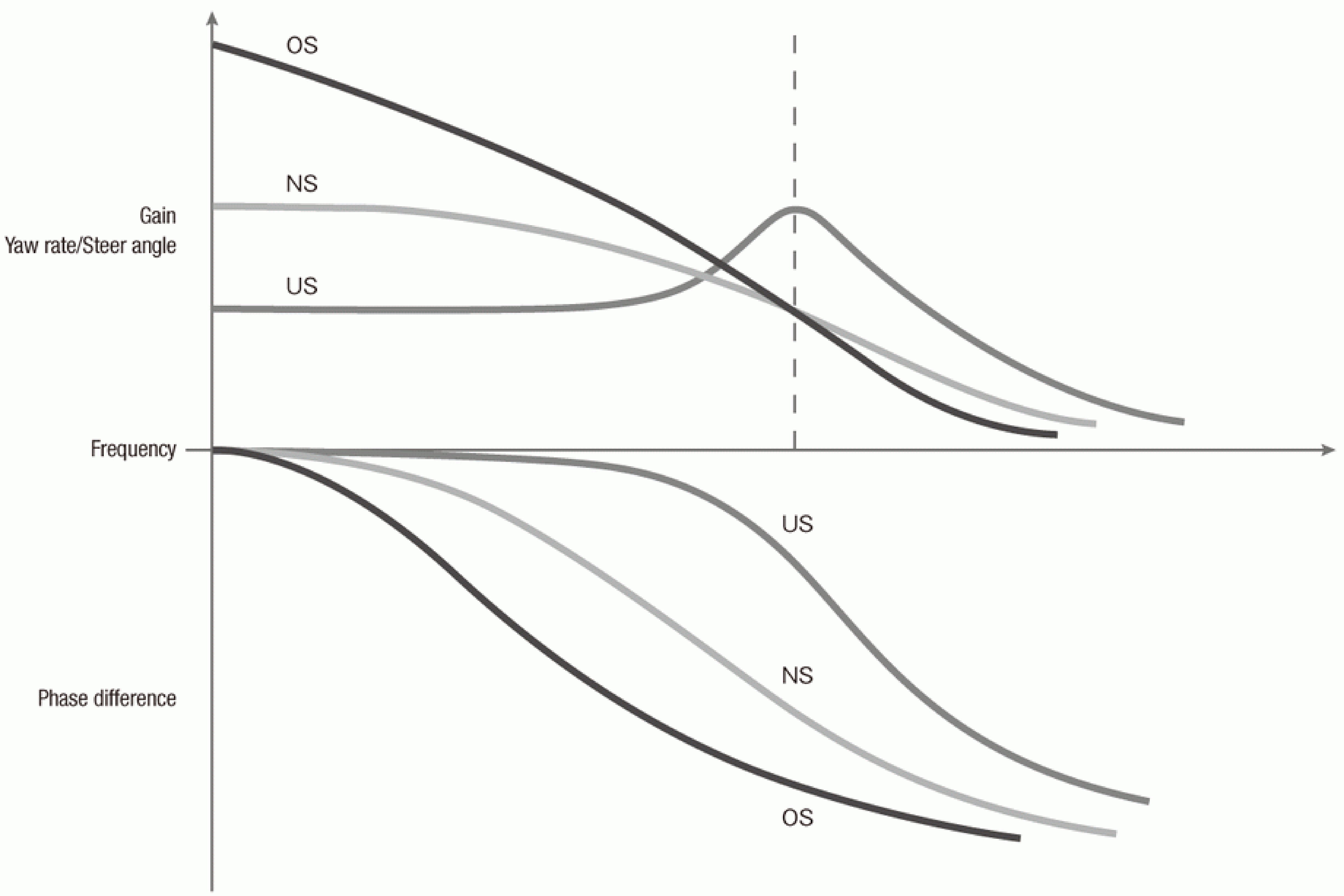
Steering characteristic and response to periodic steering

In the last section, we have explained that vehicle motion is considered an oscillatory phenomenon. Here we explore how steering characteristic affects the overall vehicle characteristic by studying vehicle response with reference to the oscillation theory. We will observe how a car, traveling at a stable speed, responds to a periodic steering motion of turning the steering wheel than returning it to neutral (straight) position. We shall also change the speed of steering (steering frequency) for this observation.

Please recall the Bode Plot explained back in section 1-6. Diagram 2-4-1 is a Bode Plot illustrating yaw rate response frequency against periodic steering. When the steering frequency is extremely slow (when the steering wheel is turned very slowly), the gain (amplitude ratio) basically resembles the yaw rate of oversteer, neutral steer and understeer in steady-state circular driving. When the steering frequency increases, the amplitude ratio for understeering cars will increase with a peak at a certain frequency and the gain increases. For neutral and oversteering cars, a peak does not exist, and the gain (amplitude ratio) continues to decline as the steering frequency increases.

Taking a look at the phase line graph, lag in phase gets larger as the steering frequency increases for all types of steering characteristics. However, the lag in phase is minimal with understeering cars. This means that a car with understeering characteristics has the fastest response to steering movement.

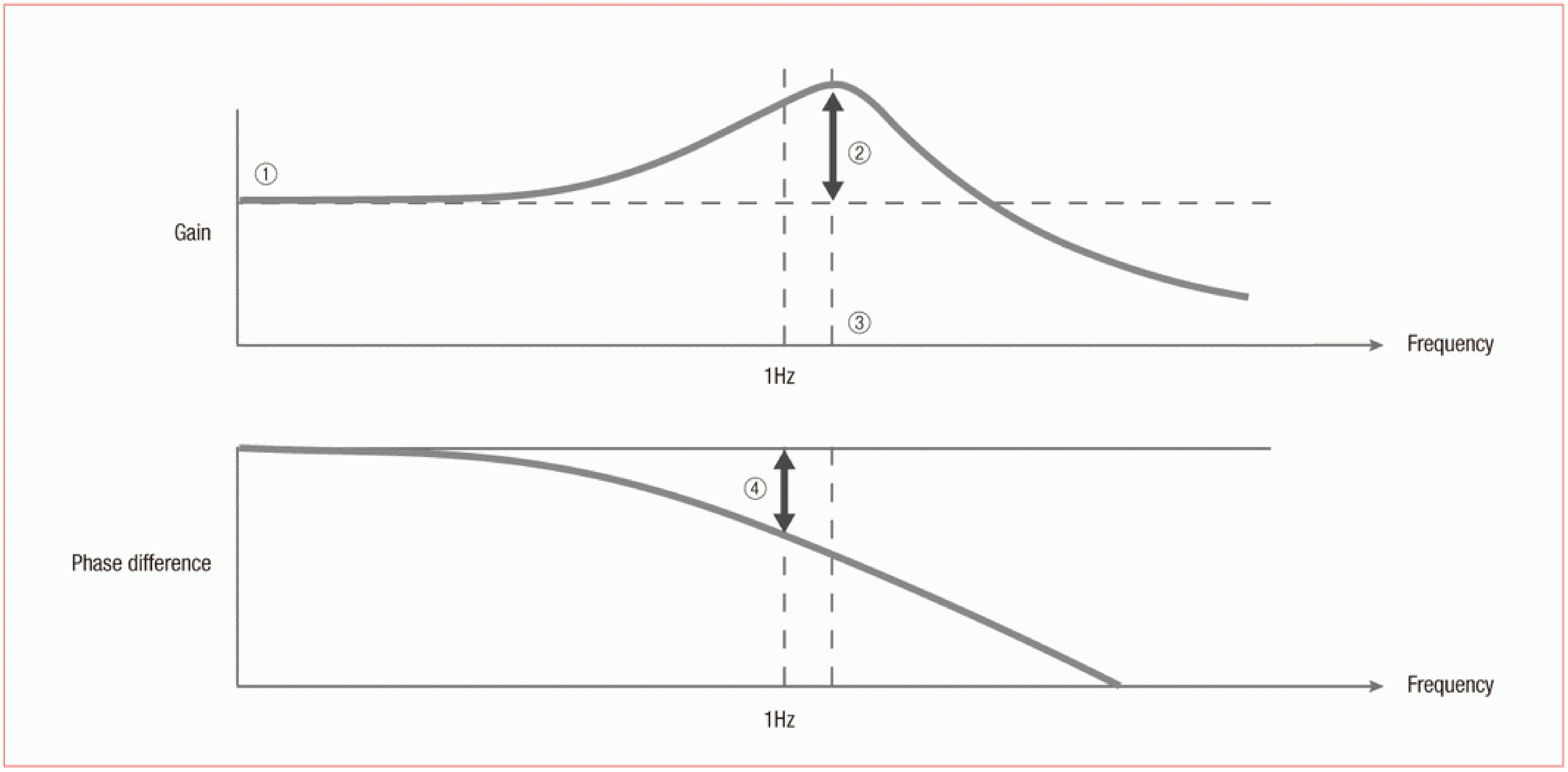
Diagram 2-4-1 **Conceptual diagram showing the yaw rate response against periodic steering maneuver for cars with different steer characteristics**



Four points to be noted from the Bode Plot

Let us explain how the Bode Plot can be implemented for practical use. There are several points to be noted on a Bode Plot. Take a look at the frequency response of the yaw rate. First to be noted is the gain at very low frequency (see ① in diagram 2-4-2). This value basically equals to the value in steady state circular driving. Point 2 is the height of the gain peak (see ② in diagram 2-4-2). Cars with strong understeer have bigger resonance due to the decline in yaw damping thus the peak of the gain becomes higher. However, there are no peaks to the gains of neutral and oversteering cars. To obtain the optimum steer characteristic, a moderate resonance peak should be secured. The third point is the resonance frequency (see ③ in diagram 2-4-2). The higher the resonance frequency, the faster the response, meaning the driver can obtain sharper feedback from the steering wheel. Point 4 is the lag in phase (see ④ in diagram 2-4-2). If the lag in phase is large, the yaw rate generation becomes slower. Therefore, for faster steering response, minimizing the lag in phase is the way to go.

Diagram 2-4-2 4 Points to note on the Bode Plot

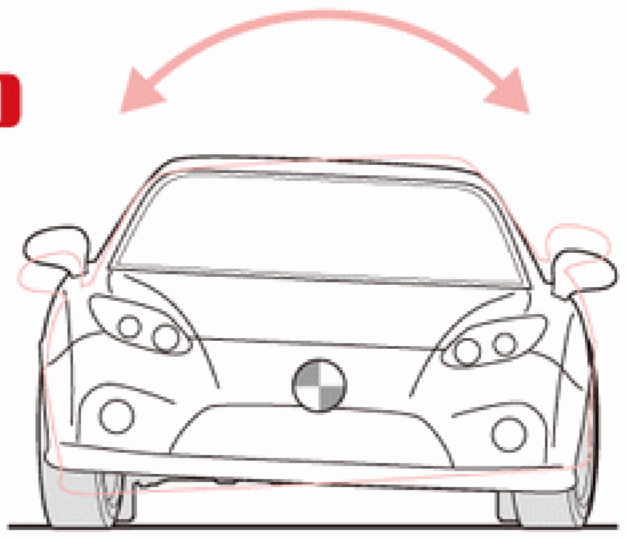


2-5 Body roll and vehicle motion

▶ Utilizing body roll to adjust steering characteristic

The body of the car rolls outward during cornering. Up to this point, we have intentionally omitted the effects of body roll to simplify our discussions. However, vehicle motion greatly changes by considering or not considering body roll. Let us explain the effects of body roll in relation to overall vehicle performance.

Diagram 2-5-1



Effects of body roll to steering characteristic

From Diagram 2-6-1, we can observe that even if the load should double, the cornering force does not multiply by the same amount. This is because there is a diminishing return of cornering force as it increases, tracing a saturation curve on a graph. When a car is cornering, weight transfer occurs from the inner wheel to the outer wheel. The sum of the cornering force of the inner and outer wheels becomes smaller when weight transfer is considered compared to the sum without weight transfer. In other words, the bigger the amounts of weight transfer, the smaller the amounts of cornering force.

Diagram 2-5-2 Relationship between tire load and cornering power. Load and cornering power are not proportionally related; therefore, even if the load should double, the cornering power does not double.

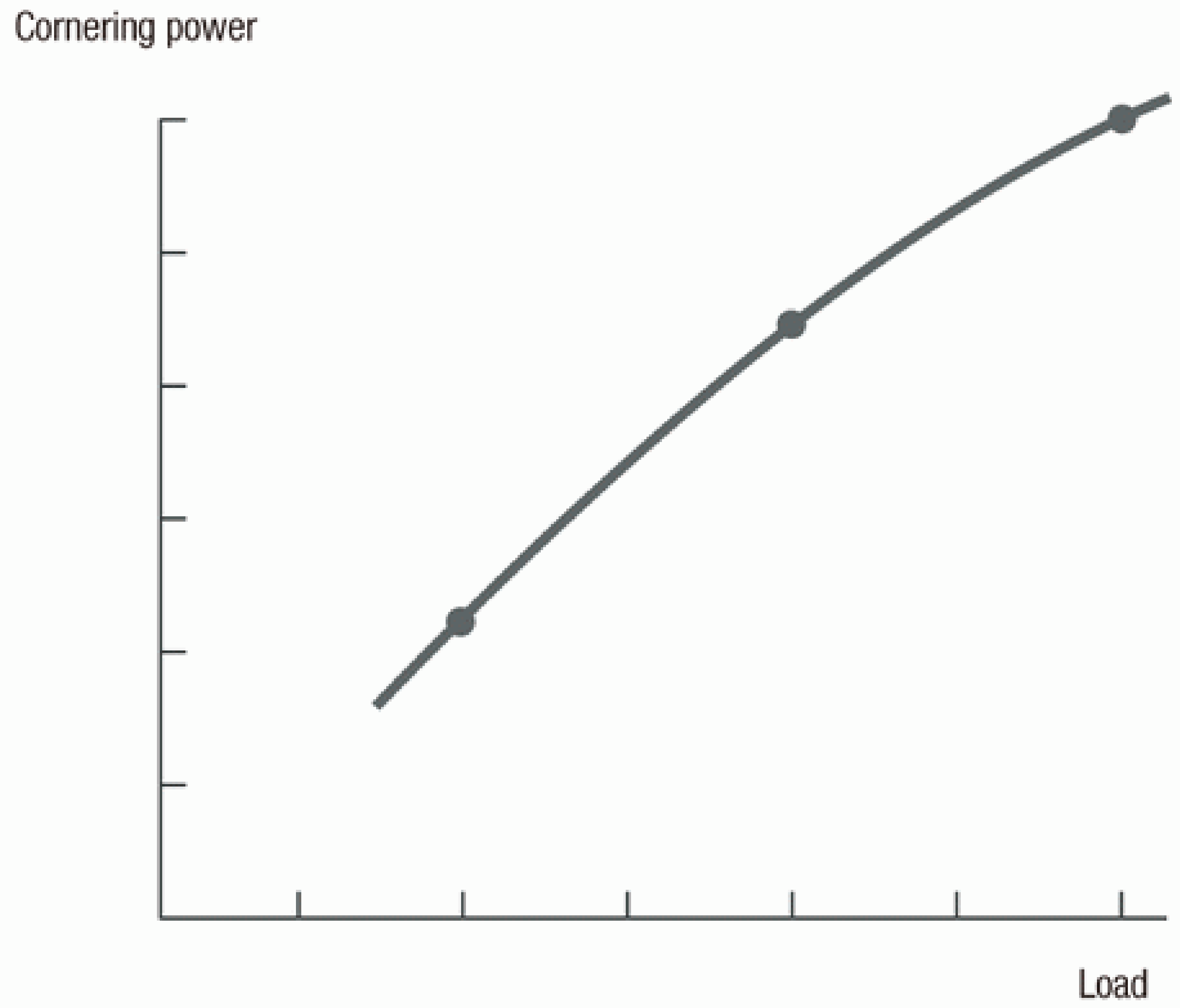
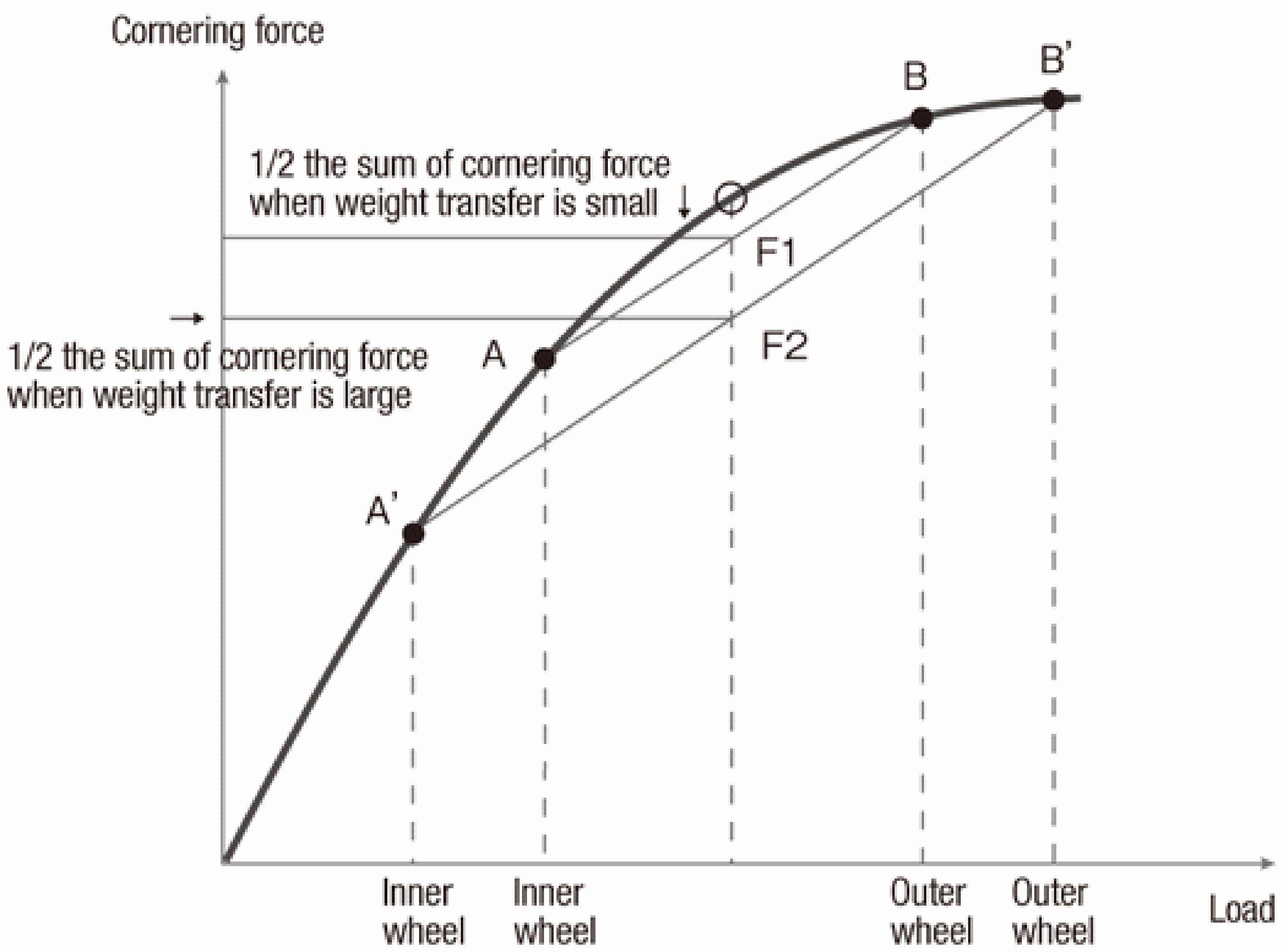


Diagram 2-5-3 Comparison between a car with a large amount of weight transfer and a car with a smaller amount. On a car with a smaller amount of weight transfer, cornering force F1 is 1/2 the sum of Inner Wheel A and Outer Wheel B. For a car with a larger amount of weight transfer, cornering force F2 is 1/2 the sum of A' and B.' A car with less weight transfer has a larger total cornering force.



Steering characteristic when the load transfer differs between front and rear

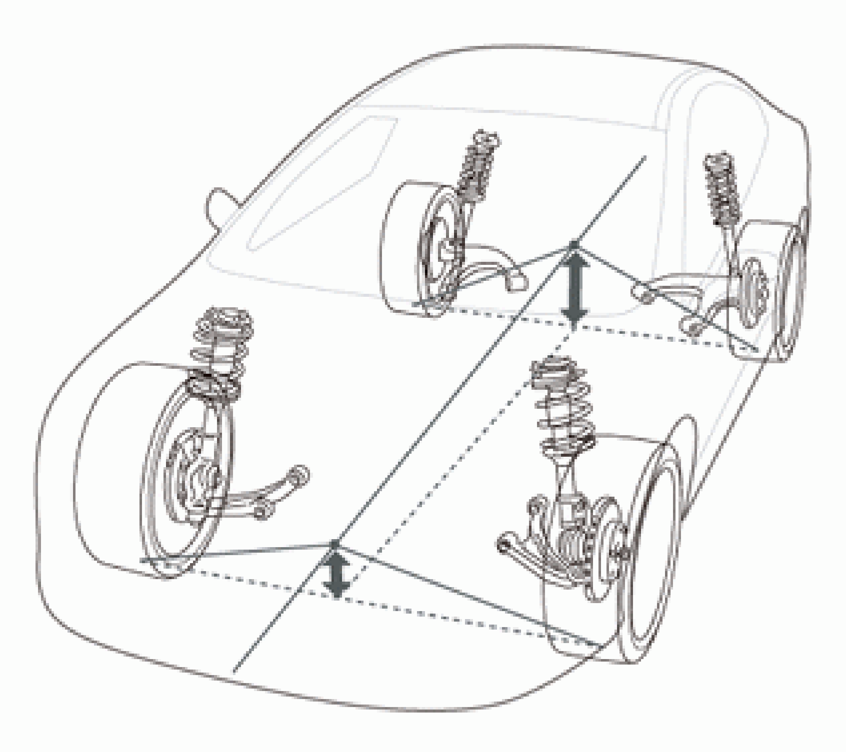
The occurrence of cornering force of the tires against vertical load, hence if the weight transfer by body roll is different between the front and rear tires, the steer characteristic will be different. Should the "weight transfer in the front wheels > weight transfer in the rear wheels," the car will have understeer . If the "weight transfer in the front wheels < weight transfer in the rear wheels," such car will have oversteer.

The amount of weight transfer between right and left is defined by the balance of "the effect of external force related to body roll" and "the effect of the reacting roll stiffness of the car." This relationship is mainly determined by the front and rear roll center height, roll stiffness ratio and track width. Without getting into too much detail, the roll center height is related to the moment created from the lateral force of the tire, roll stiffness ratio is related to the front and rear distribution of the moment from external force, and track is related to the moment created from the weight transfer. The amount of weight transfer is determined from these relationships, helping to clarify the effects of body roll on the steering characteristic as summarized in chart 2-6-1.

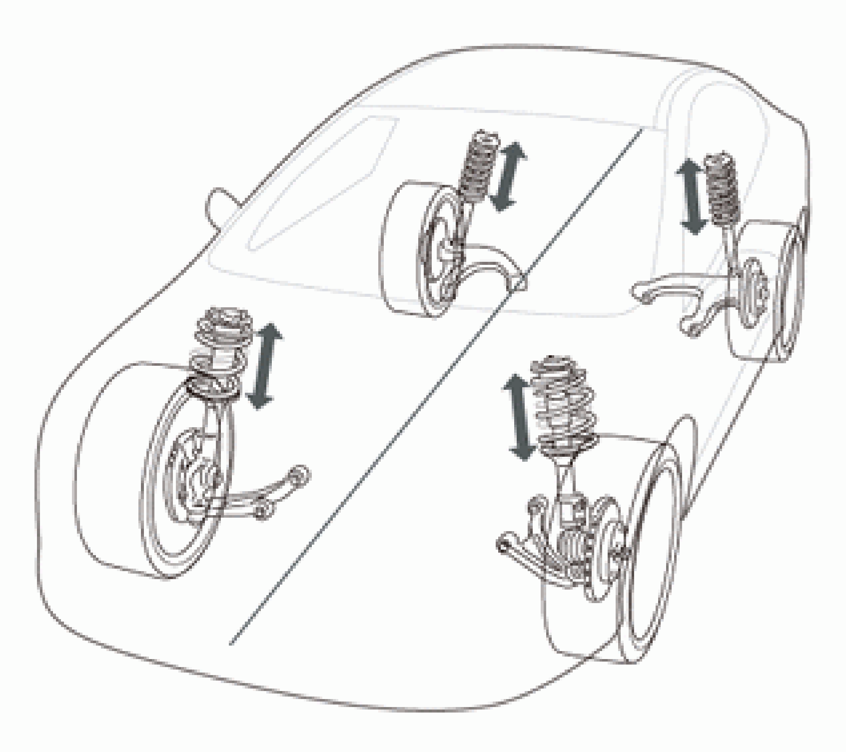
Graph 2-5-1 **Change in steer characteristic and suspension tuning**

	US	OS
Roll center Front wheel	High	Low
Roll center Rear wheel	Low	High
Roll stiffness ratio	Large	Small
Tread Front	Small	Large
Tread Rear	Large	Small

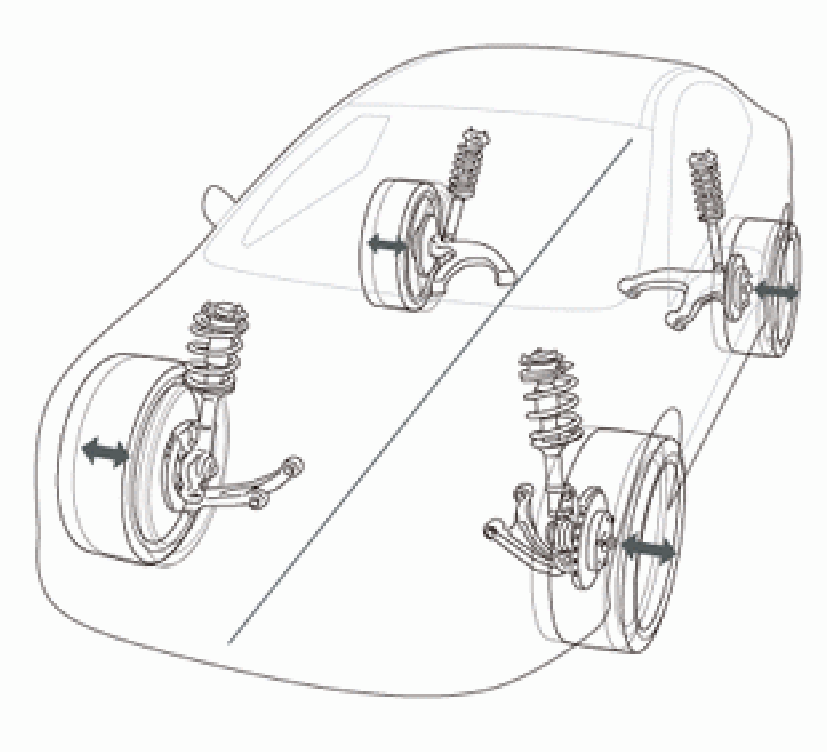
Diagram 2-5-4



Understeer will become stronger by raising the roll center height of the front wheels or by lowering the roll center of the rear wheels.



Understeer will become stronger by increasing the roll stiffness ratio of the front tires



Understeer becomes stronger by reducing the front wheel track or by increasing the rear wheel track.

2-6 Vibration of sprung mass and unsprung mass

▶ A theory not to be ignored in suspension tuning

Vertical vibration has a direct impact on a car's ride comfort and the tire's road holding ability. Strong vibration can make the ride intolerable and may even disturb the road holding ability of the tire to the point of losing traction. To avoid this, the spring and dampers of the suspension must be carefully tuned. This section will be an introduction to the basics of vertical vibration that should be understood for suspension tuning.

Mode of vibration

Sprung mass refers to the total mass supported by the suspension, while unsprung mass is the total mass between the suspension and tires. Here, we focus on the bouncing and pitching vibration of sprung mass, as well as the vertical vibration of unsprung mass.

Diagram 2-7-1 is a simplified illustration of vibration with the front and rear wheels supporting the entire car. In this model, direction of displacement for sprung mass is either up or down (total two directions). The direction of displacement for unsprung mass is also up and down (total two directions). Therefore, there are four directions of displacement, four degrees of freedom, which means there are four natural frequencies. Primary resonance is the bounce resonance, which is the vibration that occurs to the front and rear sprung mass (the front and rear extends and contracts simultaneously). Secondary resonance is the pitching resonance where the front and rear sprung mass vibrates in opposing directions (when the front extends the rear contracts, when the front contracts the rear extends). Tertiary and quaternary resonances occur to the unsprung mass.

Diagram 2-6-1 **Simplified vibration model with the body supported by front and rear wheels. There are four directions for displacement.**

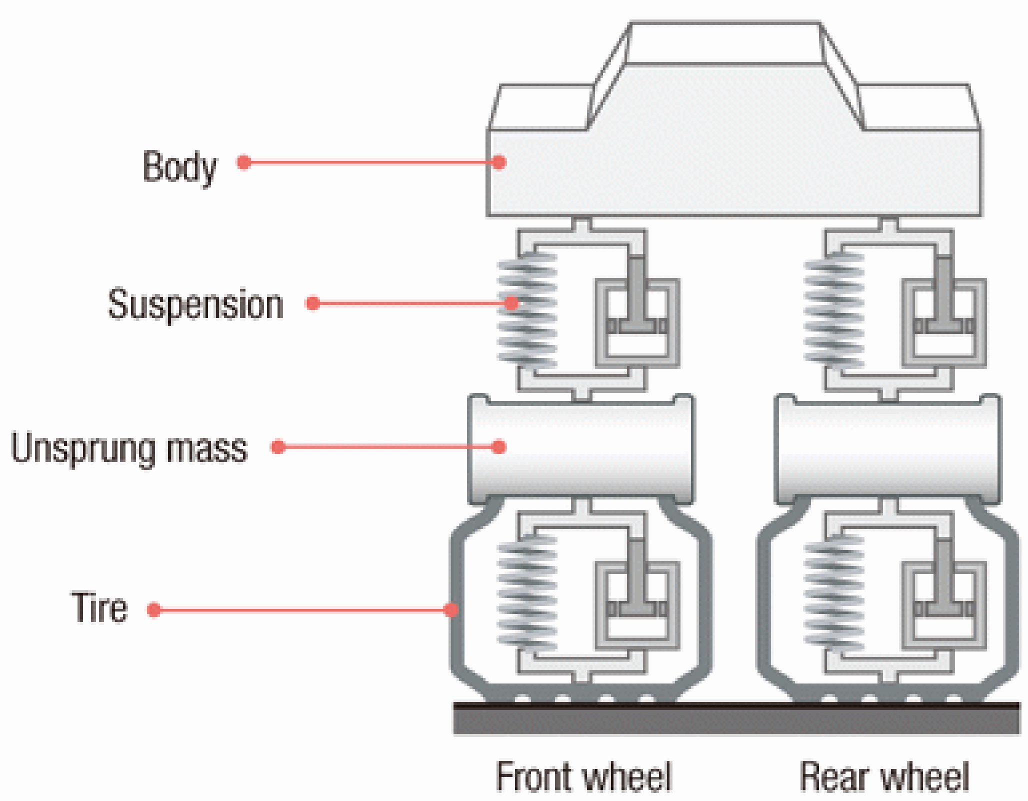
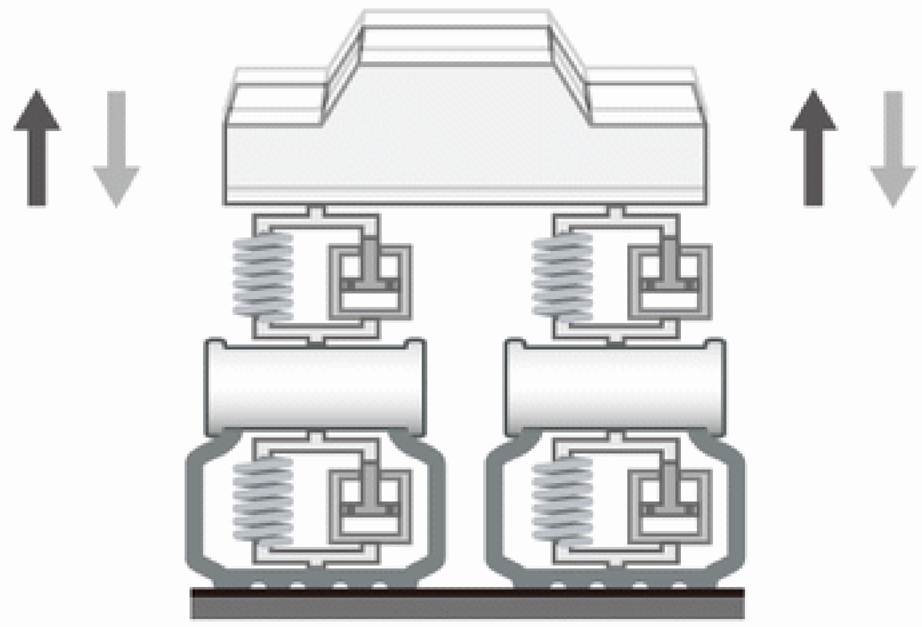
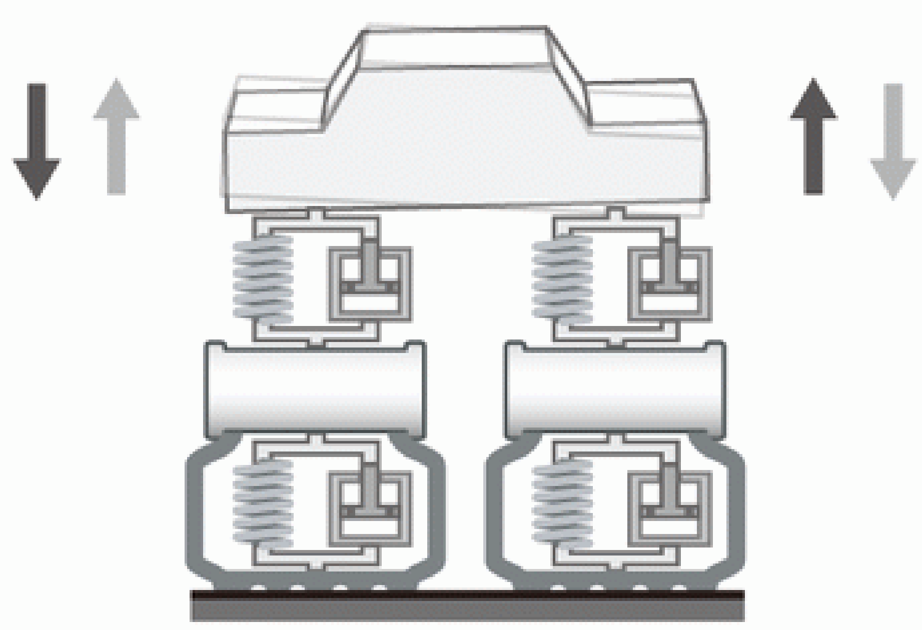


Diagram 2-6-2 **Mode of vibration**

Primary resonance: Bounce mode. Front and rear suspension extends and contracts in the same direction simultaneously to make the body bounce.



Secondary resonance: Pitching mode. Front and rear suspension extends and contracts in opposite directions inducing pitching motion to the body.



Tertiary resonance and quaternary resonance: Resonance modes of unsprung mass

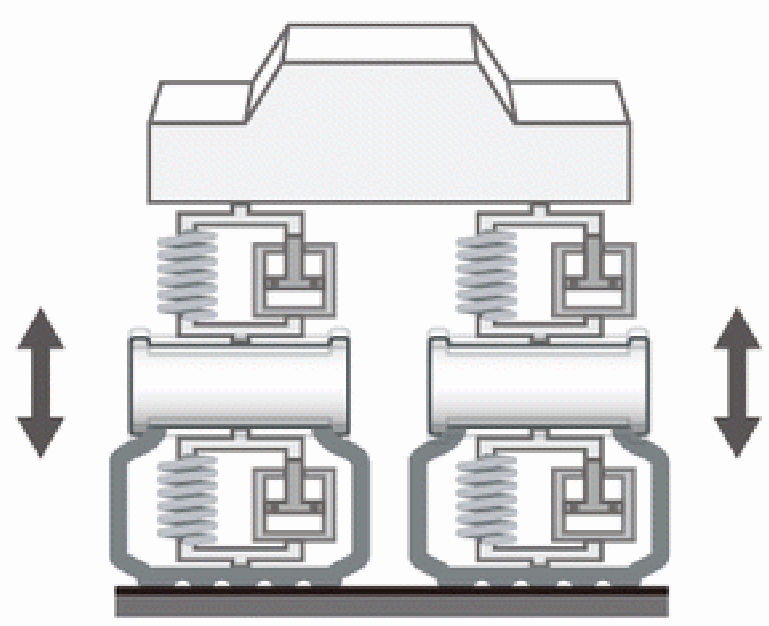
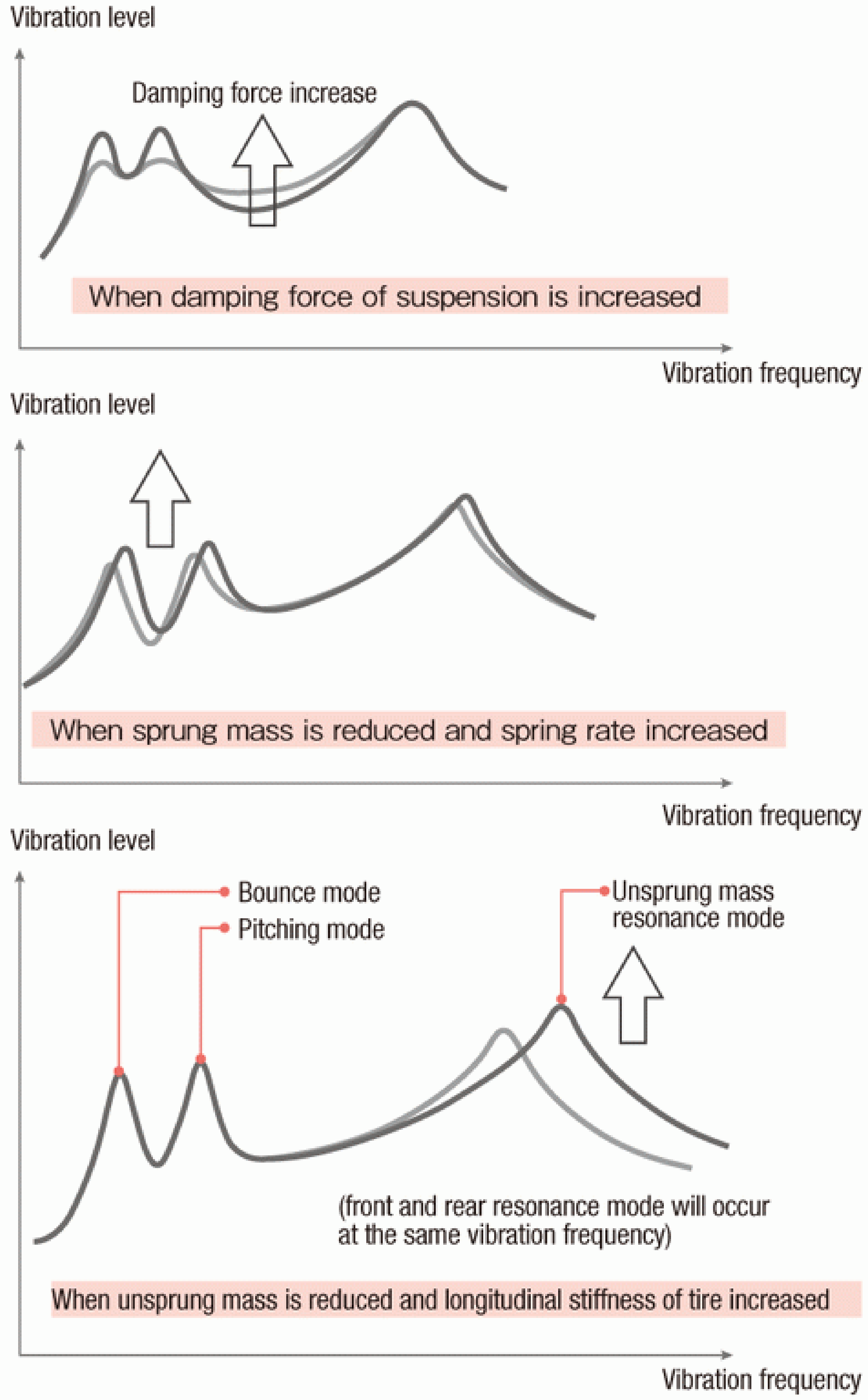


Diagram 2-6-3

Influence of suspension algorithm to vertical vibration



Effects to the mode of vibration from suspension tuning

Body vibration has a negative impact on the tire's road holding and overall ride comfort hence should be minimized as much as possible. Vibration of sprung mass also affects aerodynamic performance, especially to competition vehicles.

It should be noted that vibration of sprung mass and unsprung mass has the following characteristics. The knowledge should become useful in suspension tuning.

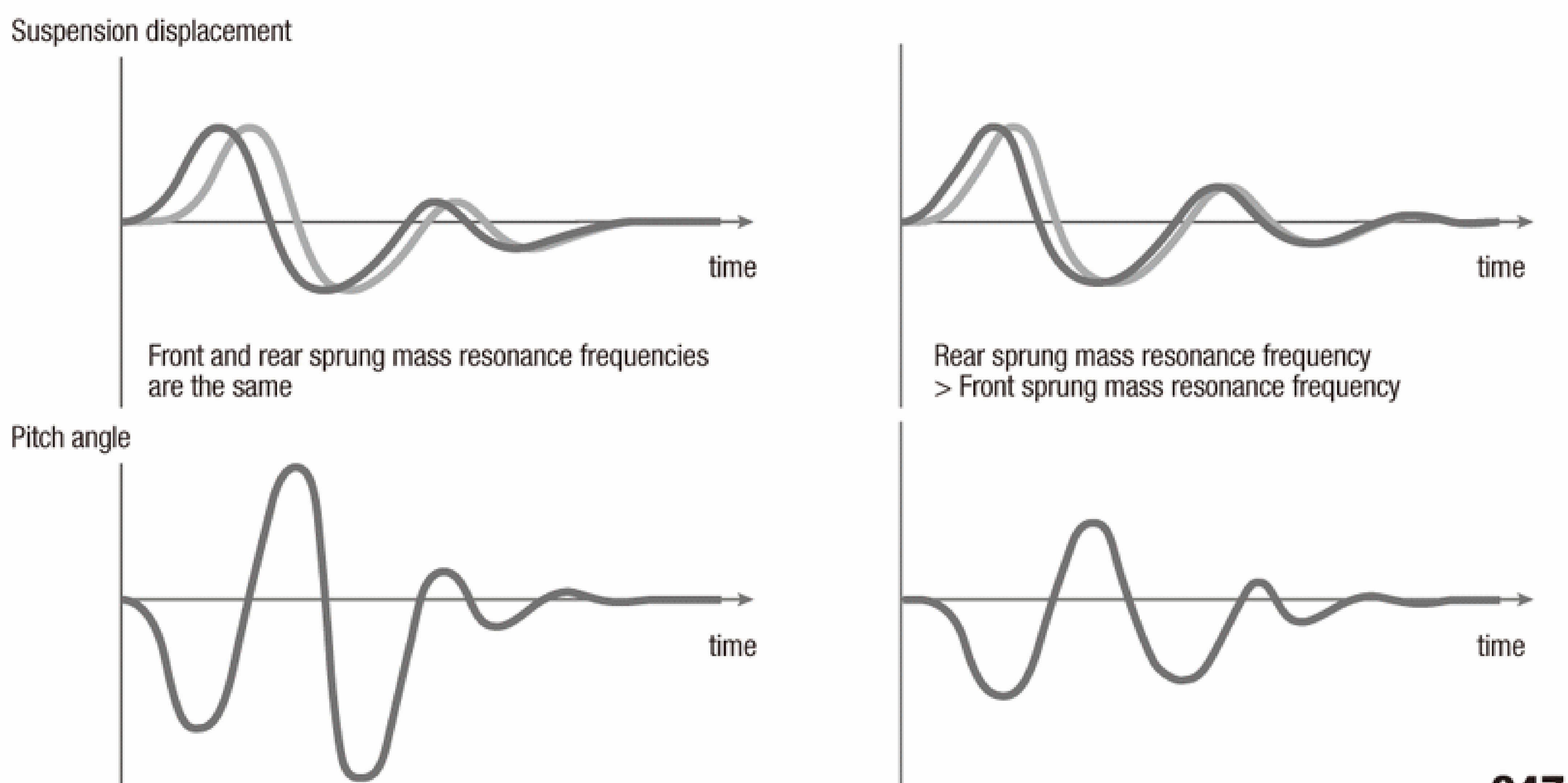
1) **Increasing damping force will help to reduce the vibration of sprung mass around the resonance frequency; however it will increase vibration in other areas. (See Diagram 2-7-3 top graph.)**
2) **Increasing damping force will also increase the resonance frequency of sprung mass. (See diagram 2-7-3 top graph.)**
3) **Changing sprung mass or spring rate will affect the resonance of sprung mass, but it will have little influence to the resonance of unsprung mass. (See diagram 2-7-3 middle graph.**
4) **Changing unsprung mass or longitudinal stiffness of the tire will affect the resonance of unsprung mass, but it will have little influence to the sprung vibration. (See diagram 2-7-3 bottom graph.)**

Pitching control

When a car is being driven on a straight line, the input from the road surface to the rear wheel will be delayed by the time lapse derived from "wheelbase / vehicle speed." By setting up the resonance frequency of sprung mass on the rear wheels slightly higher than that of the front wheels, the vibration of the rear wheels catches up to and converges with the vibration of the front wheels, helping to minimize pitching.

Diagram 2-6-4

Control of pitching motion. Pitching can be minimized by increasing the rear sprung mass resonance frequency.



2-7 What constitutes a high performance car?

▶ Vehicle performance is in the rear wheel

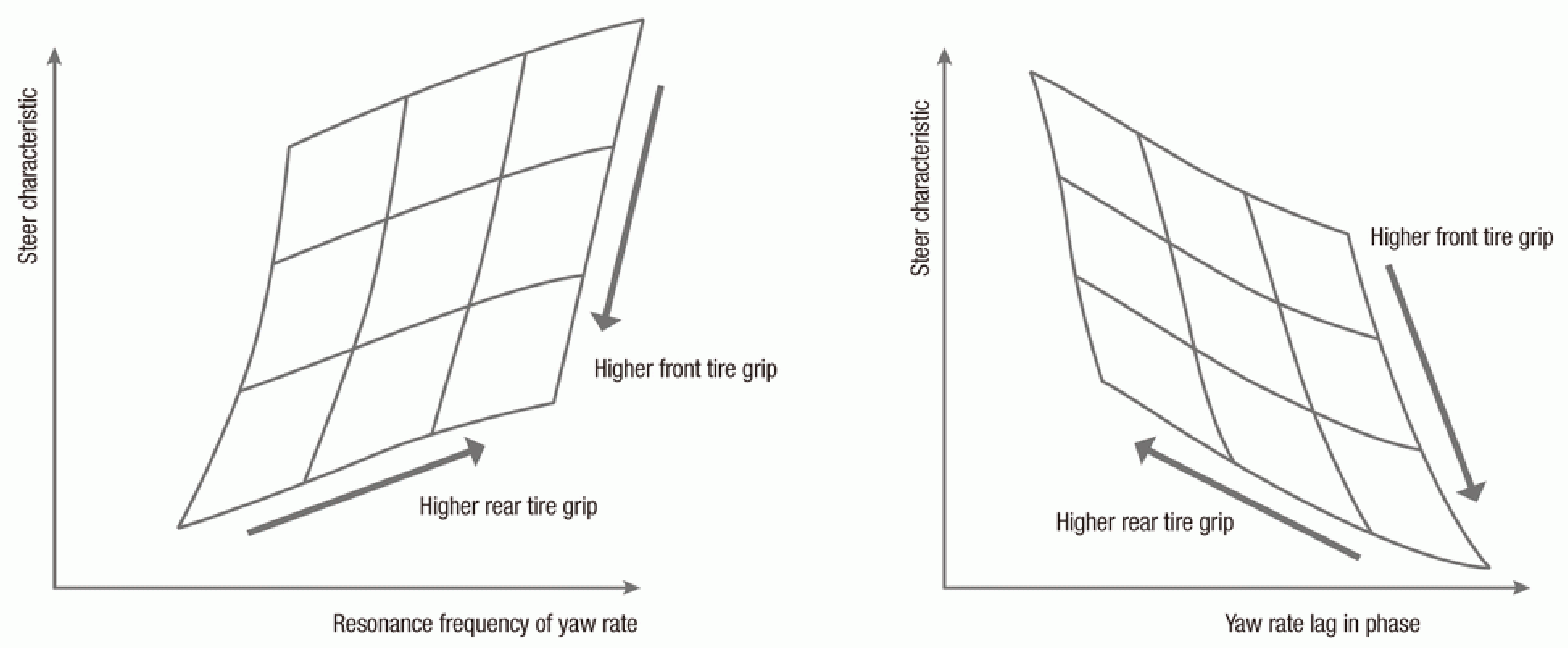
Resonance frequency of yaw rate and steer characteristic

In general, if the resonance frequency of yaw rate is high, the car should respond quickly and be considered a high-performance vehicle. Improving the cornering power of the rear tires or making the car lighter are examples of how the resonance frequency of the yaw rate can be increased.

Diagram 2-5-1 illustrates how front and rear tire grip can affect overall vehicle performance. From this diagram, you can see that increasing grip of the rear tires will enhance understeer and increase the resonance frequency of the yaw rate. Vice versa, increasing grip of the front tires will decrease the resonance frequency of the yaw rate resulting in stronger oversteer. To the contrary, increase in rear tire grip will diminish the lag in phase while increasing front tire grip will enhance the lag in phase.

As illustrated before, the grip level of the rear tires have a significant effect on overall vehicle performance. When modifying the suspension system, sufficient level of rear tire grip should first be secured. Then, the grip level of the front and rear tires should be well balanced. Such steps should be understood because they serve as the fundamentals of increasing vehicle performance.

Diagram 2-7-1 Correlation of tire grip, steering response and steer characteristic



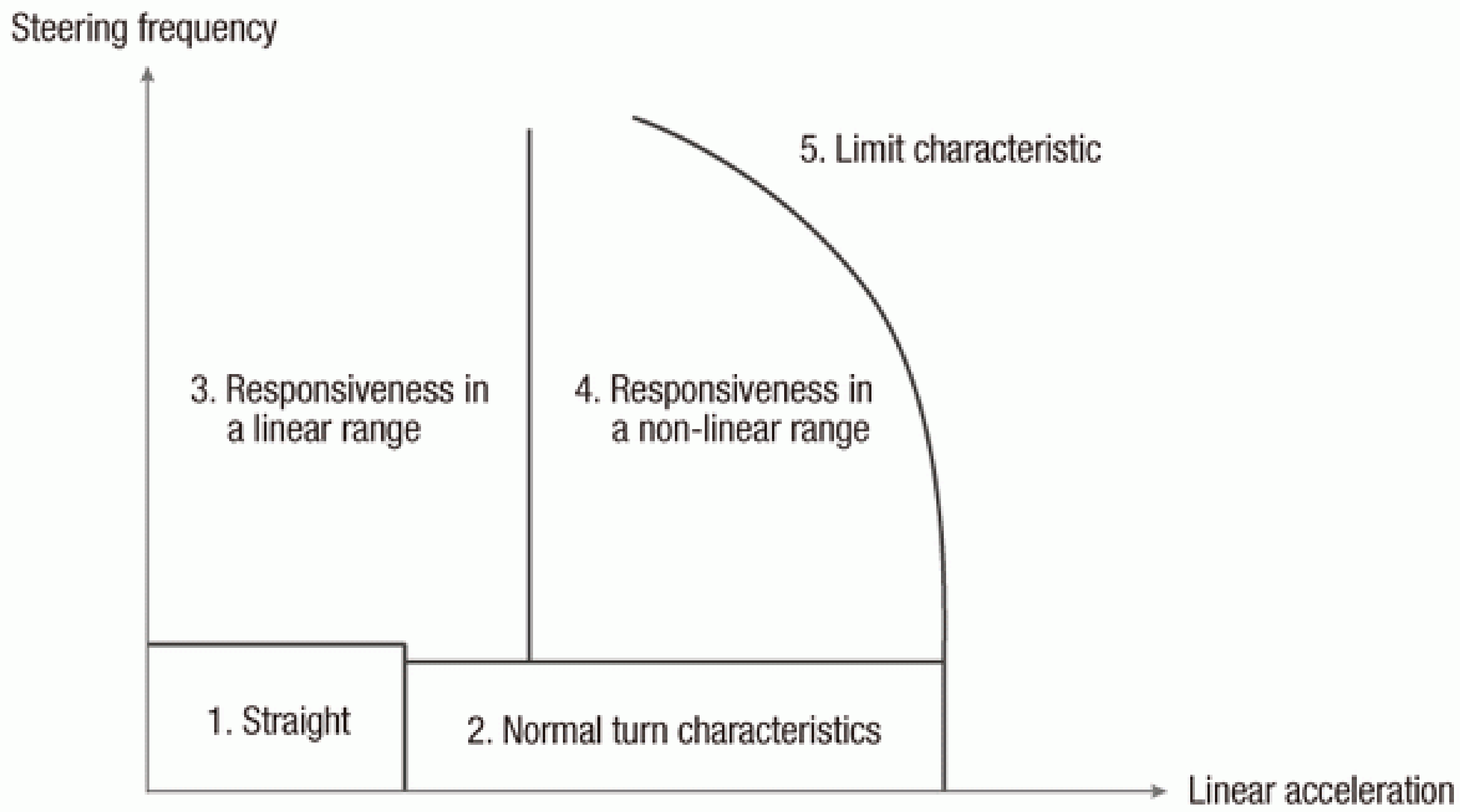
TIPS If the vehicle's yaw inertia moment can be formatted to $I=mK^2$, the yaw inertia radius can be shown as, $K=\sqrt{I/M}$. The "I" here represents the yaw inertia moment, while the "m" represents vehicle mass.

Categorizing vehicle responsiveness

Much can be argued over the concept of responsiveness of vehicles, but, since vehicle movement can be placed into an equation of motion (as explained in 1-1 relating to F=ma), there is a side to it that makes logical handling of this subject much easier to organize. That said, if we use lateral acceleration and steering frequency to categorize a vehicle's motion characteristics, a figure similar to Diagram 2-7-2 appears.

Up until now, we have centered our examination of responsiveness based on (2) normal turn characteristics, and in a (3) linear range. The linear range we speak of here refers to a hypothetical understanding of a situation where the cornering power is stable, regardless of the travel situation. On the other hand, the responsiveness of (4) non-linear range is travelling based on a range where the cornering power saturates. For racing cars, this range is of particular importance in relation to its capabilities. But, even when we look at a non-linear range, the basic characteristics of a linear range applies, so if we properly understand the balance between the cornering force and moments of the front and rear wheels, it can be applied similar to that of a linear range. Also, it is best to have the (5) limit characteristic range positioned as far away from the starting point as possible.

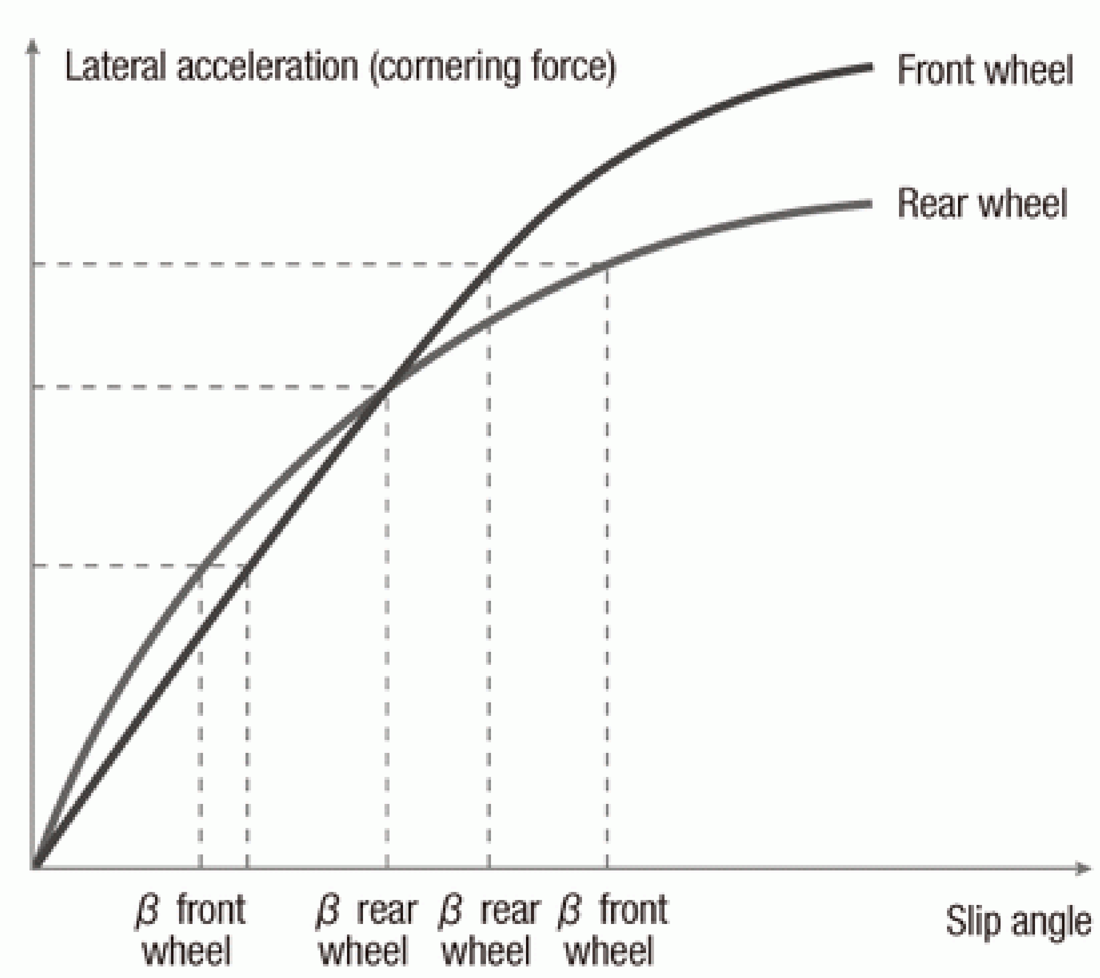
Diagram 2-7-2 **Category of vehicle motion characteristics**



TIPS A very standard sample of a non-linear range vehicle movement is called reverse steering. We explained earlier in 1-2 that you could determine the steering characteristic based on the degree of slip angle from the vehicle's normal turns. This time, let us examine what reverse steering is using a vehicle with the characteristics as shown in diagram 2-7-3.

When vehicles with similar characteristics conduct normal turns and the lateral acceleration is low, the front wheel slip angle becomes larger and the understeering characteristic of the vehicles show. But, as the lateral acceleration increases, the tires need to produce force strong enough to balance against it, so the slip angle increases and the cornering force enters the saturation range. This leads to an increased slip angle of the rear wheel as the lateral acceleration increases to a certain point, making the vehicle exhibit oversteer characteristics, thereby making the movement unstable. This situation where the steering characteristic changes, depending on lateral acceleration, is called reverse steering.

Diagram 2-7-3



3-1 Temperature and pressure

▶ Molecular motion causes temperature and pressure

Today we know that heat, temperature and pressure are all caused by molecular motion. Such understanding only came to light in the 19th century, and was only accepted as proven theory in the 20th century. In order to correctly understand efficiency and energy loss of engines and aeromechanics (hydromechanics) which we will touch on later, we should first learn about molecular motion in relation to temperature and pressure.

Erratic molecular activity in an enclosed space

Let us visualize a gaseous matter enclosed in a sealed container. A macroscopic observation of the gaseous matter inside the container would be that the temperature and pressure are both stable. This is called the equilibrium state. However, from a microscopic perspective, there exists a myriad of gas molecules moving around inside the container in an erratic manner. One molecule may be moving at a very slow speed, while another may be moving at an extremely high speed. Such molecules collide into each other and the walls of the container, changing speeds as they move.

Diagram 3-1-1 Gas inside a sealed container in an equilibrium state

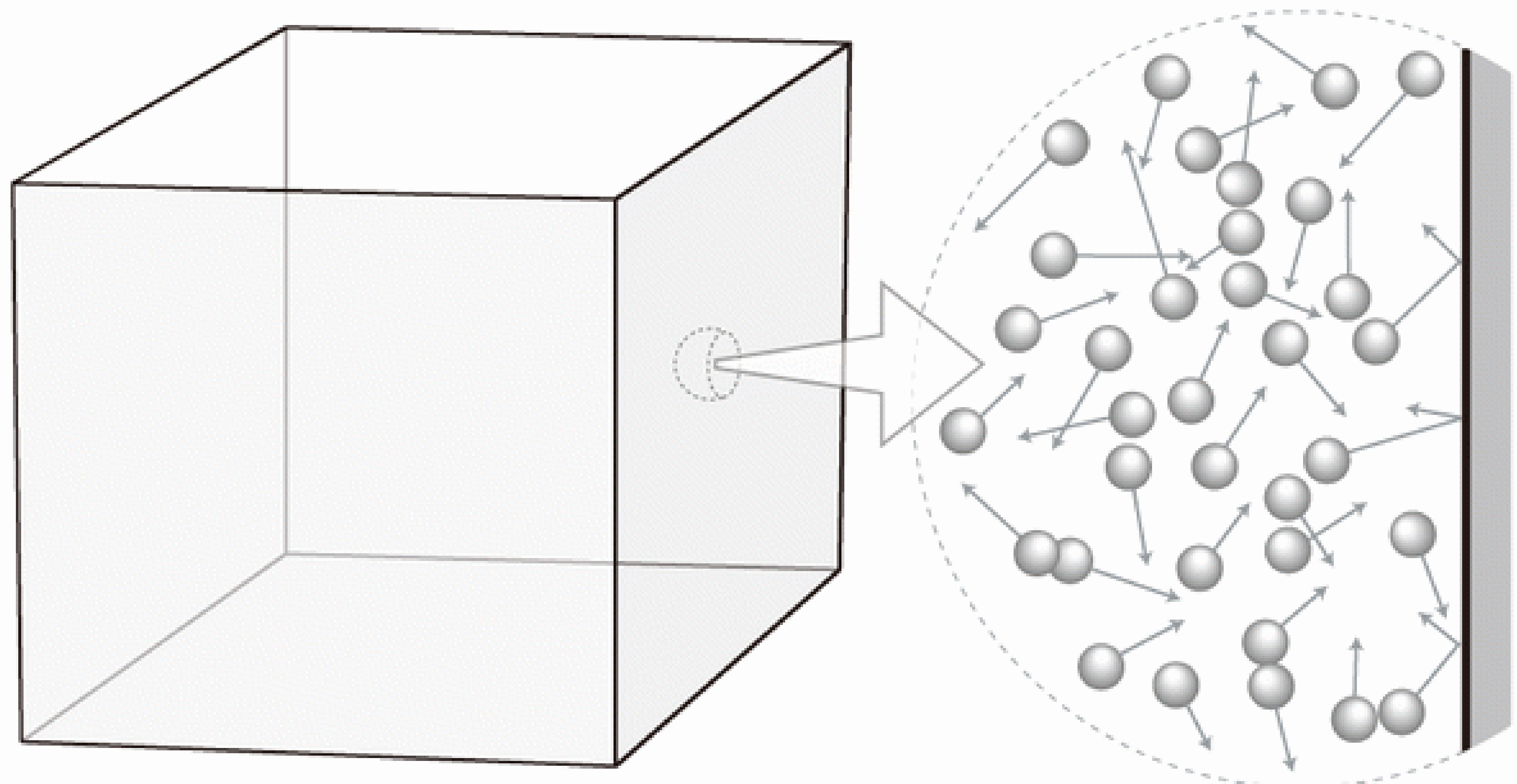
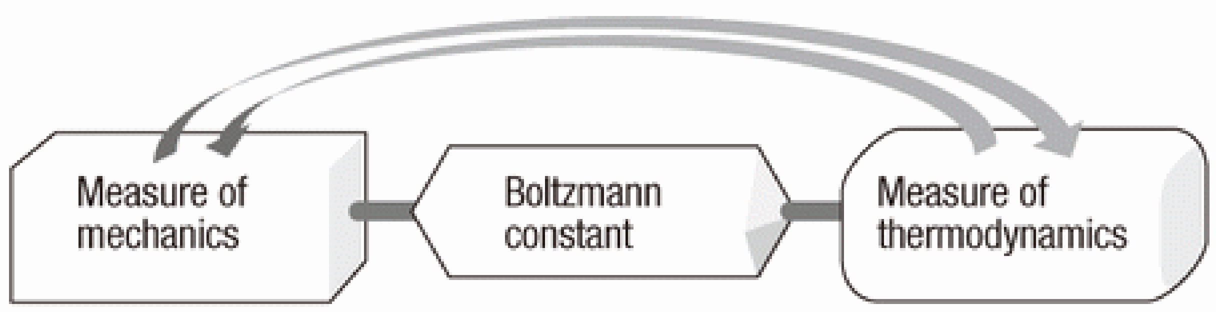


Diagram 3-1-2 **Boltzmann constant links the measure of mechanics and thermodynamics**



Temperature is a numeric measure of average kinetic energy of each molecule

Inside the container, there are countless numbers of gas molecules moving at various speeds. From an energy perspective, the gas molecules have various levels of kinetic energy. Temperature is actually the numerical measure of the average kinetic energy of each molecule moving about in an erratic fashion at various speeds. It can be expressed mathematically as below.

Average kinetic energy per molecule = 3/2 kT

"T" is the absolute temperature and "k" is the Boltzmann constant. It is a proportional constant not affected by the gas temperature, density, pressure, quantity, or type. This equation links to the mechanical measure of kinetic energy with the thermal measure of temperature, but the Boltzmann constant is what acts as an important bridge between mechanical measures and thermal measures.

Pressure is the average value of force from moving molecules

Please go back to Diagram 3-1-1. The gas molecules continuously collide with the walls of the container. Some molecules are moving at high speeds while others might be moving very slowly. Some molecules may impact perpendicular to the wall and some may impact at an angle. Therefore, each molecule has a different force of impact.

But, when we measure pressure, what we are actually doing is only deriving the average force of impact from the pool of molecules moving about erratically. It is important to acknowledge that in an equilibrium state, the average force of impact and pressure will be the same regardless of the direction or point of measurement. In other words, although the molecules are moving with various speeds erratically, from a macroscopic perspective, the force of impact is equally dispersed in all directions.

Diagram 3-1-3 **Pressure is the average value of force from moving molecules**

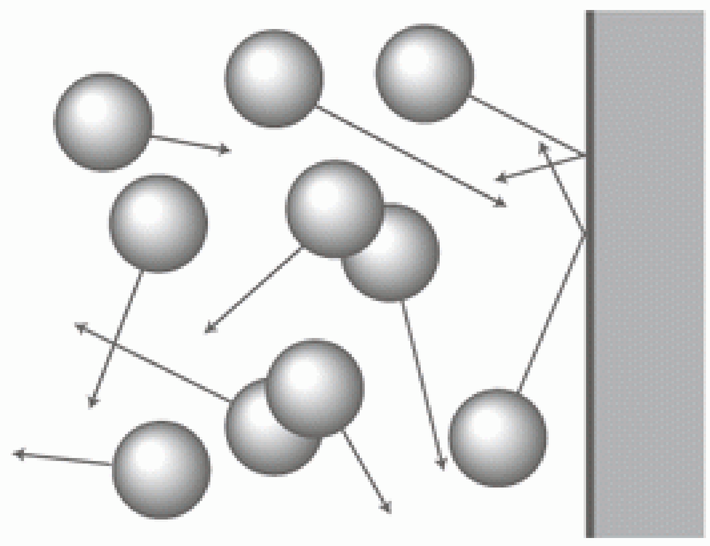
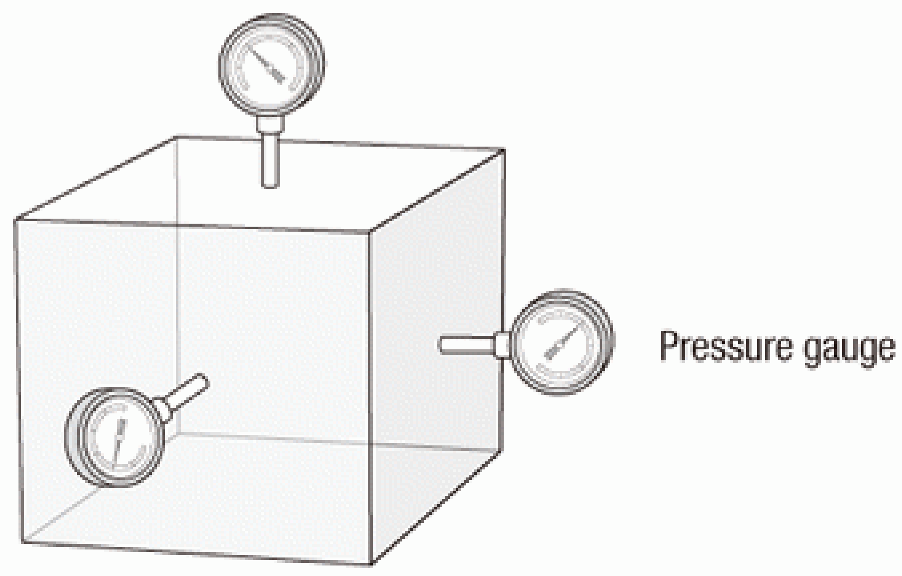


Diagram 3-1-4 **In an equilibrium state, pressure value is constant in all directions**



3-2 The ideal heat engine

▶ Eliminating wasteful thermal transfer: The Carnot Cycle

The engine is a machine that converts thermal energy to a desired type of mechanical energy. What determines the conversion efficiency when thermal energy is converted to mechanical energy? The first person to shed light on this was the French engineer and physicist, Sadi Carnot. In the 19th century, Carnot was able to form an understanding of what the ideal efficiency of a heat engine should be and how that efficiency would be determined through logic. Carnot's conclusion became an important beacon to development of the heat engine thereafter.

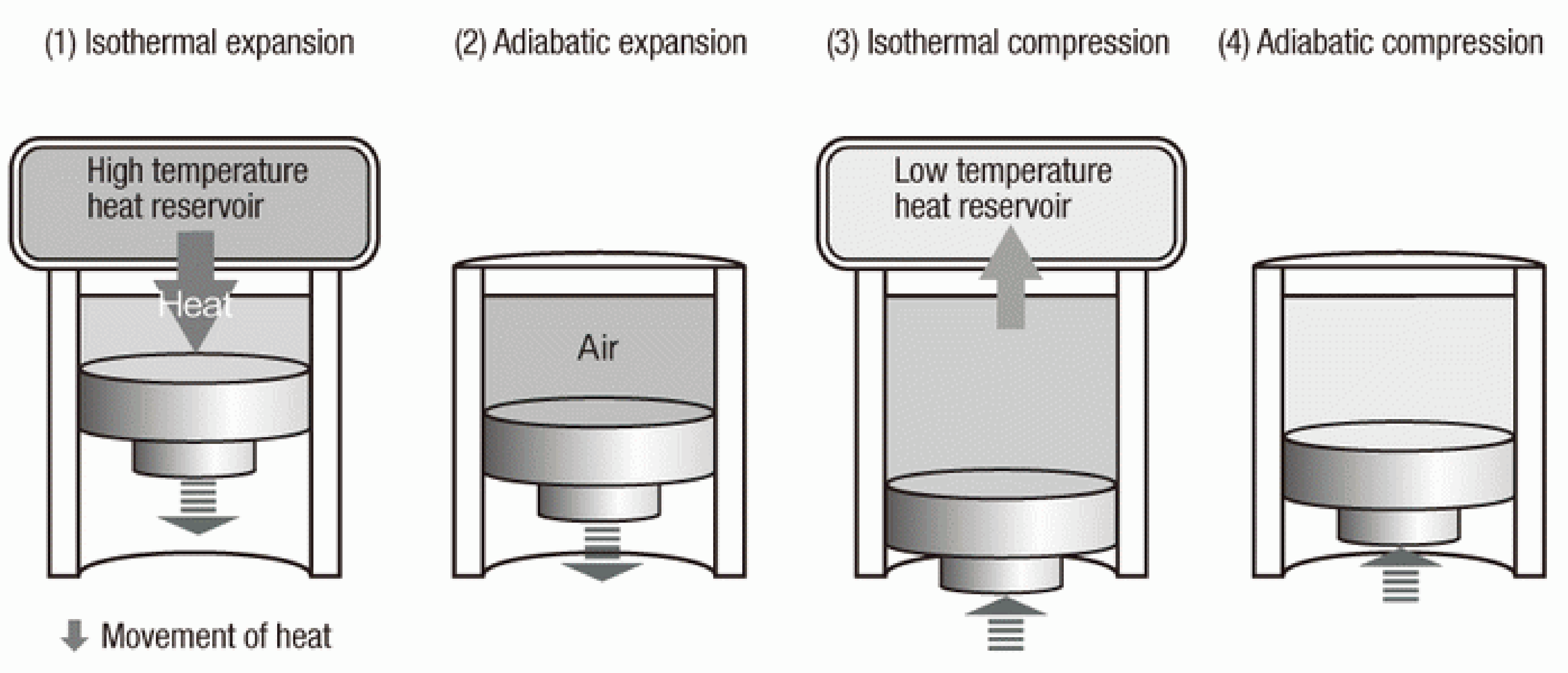
Nicolas Léonard Sadi Carnot (1796-1832)

Carnot's two properties

When Carnot set out to understand the ideal heat engine, he focused his attention on two properties. First, for the heat engine to work, differences in temperature needed to exist. Without such differences in temperature, thermal transfer would not occur, and in turn, the heat engine would not work. However, if there was an unnecessary difference in temperature within the heat engine after work output, it would cause wasteful thermal transfer. Hence, Carnot understood that, in relation to work output (energy), a heat engine that is not reliant of thermal transfer would be ideal.

The second property he focused on was the fact that if the volume of a material is allowed to change, thermal transfer could occur without changing the temperature of the material. This is called an isothermal change. Carnot thought that if isothermal change was utilized, energy could be created without causing unnecessary thermal transfer. Based on such preparatory considerations, Carnot went through a thinking process to invent an innovative concept of a thermodynamic cycle that does not involve a wasteful thermal transfer due to unnecessary differences in temperature.

Diagram 3-2-1 Carnot Cycle process (attach (1) - (4) to each diagram)



Carnot Cycle

To clearly observe the true nature of heat, Carnot imagined an air engine made of a high and low temperature heat reservoir, a cylinder enclosed with air, and a piston. By letting the cylinder come in contact with the heat reservoir, he examined the thermal transfer properties to come up with an ideal thermodynamic cycle. The thermodynamic cycle he invented is shown in Diagram 3-2-1 and in Diagram 3-2-2.

1) By letting the cylinder come in contact with the high temperature heat reservoir, heat is transferred from the reservoir to the cylinder, expanding the air inside the cylinder. But, temperature differences need to be prevented, so at this point, the temperature of the heat reservoir and the air inside the cylinder needed to be maintained at the same level. Also, the air temperature must be stable as well. In order to achieve that, the air must be slowly and gradually expanded. Expanding or compressing gas matter by a controlled constant temperature is called isothermal change.

2) Next, the expanded cylinder must make contact to the low temperature heat reservoir. However, doing so would create a difference in temperature. To prevent that, Carnot first applied adiabatic change where the compression increases temperature, and expansion decreases temperature. Carnot realized that the air expanded by the high temperature heat reservoir can further be expanded by applying adiabatic change, thereby decreasing air temperature without any thermal transfer. Note that this process still requires that the piston to be moved very slowly.

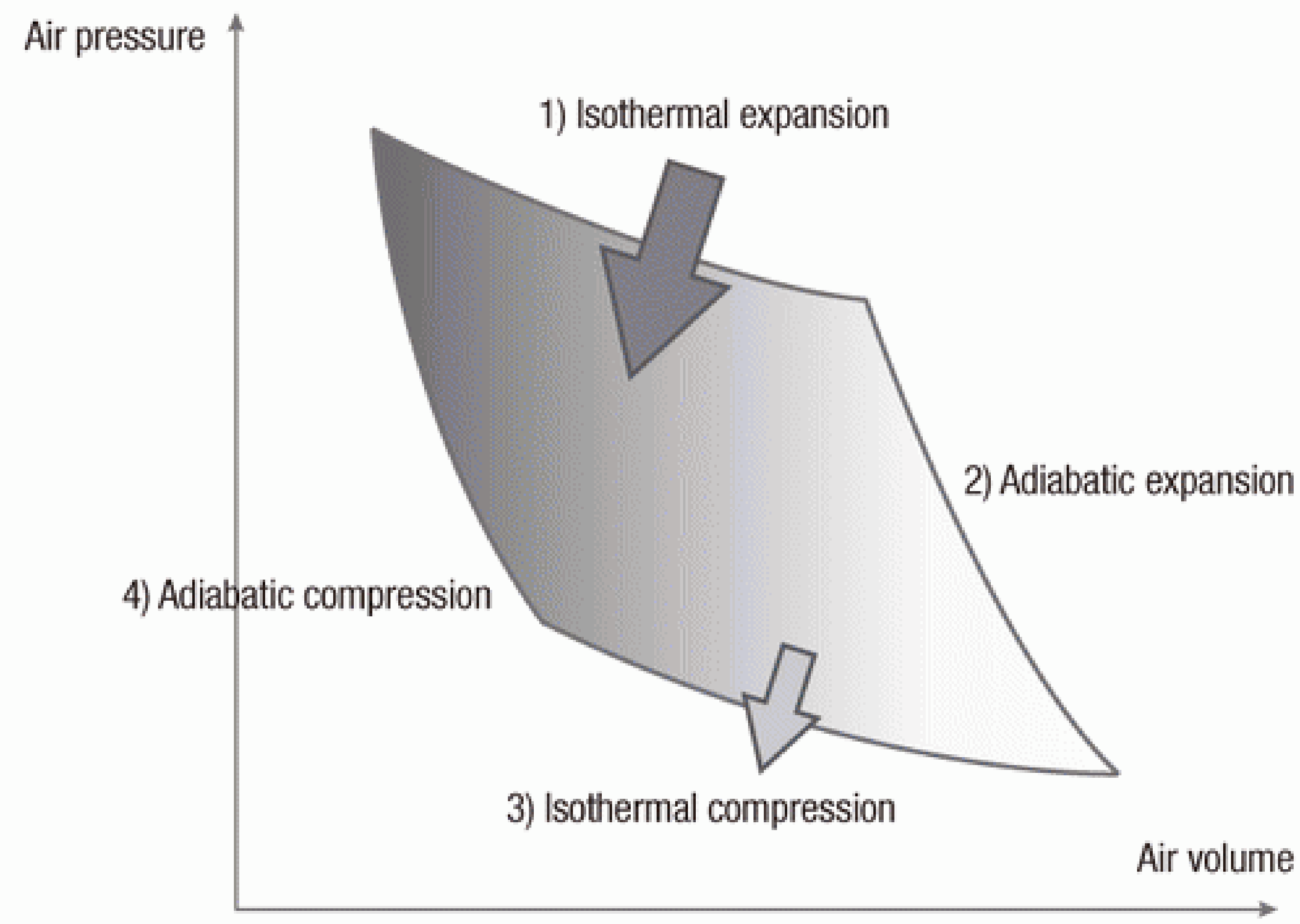
3) When the air temperature inside has come down to that of the low temperature heat reservoir, the cylinder is made to come in contact with the reservoir, thereby transferring the heat in the air to the reservoir while compressing the air. Again, differences in temperature must be avoided, so heat is transferred slowly and gradually using isothermal change.

4) After isothermal change, the air is compressed applying adiabatic change to increase the temperature. When compressed so that the air temperature matches that of the high temperature heat reservoir, the process can return to isothermal expansion described in Item (1) to repeat the cycle.

As noted above, after cycling through (1) isothermal expansion from the high temperature heat reservoir, (2) cooling through adiabatic expansion, (3) isothermal compression from the low temperature heat reservoir, and (4) heating through adiabatic compression, the air in the cylinder returns to its original state, converting heat into energy without the occurrence of unnecessary thermal transfer. Named after its founder, this thermodynamic cycle is called the Carnot Cycle.

Fifty years after Carnot's passing, the first vehicle equipped with a gasoline engine is born. Pictured here is a 3-wheel vehicle that was made by Karl Benz.

Diagram 3-2-2 Change in air pressure and volume in the Carnot Cycle



3-3 Carnot's conclusion

▶ Surprising abstraction of the heat engine

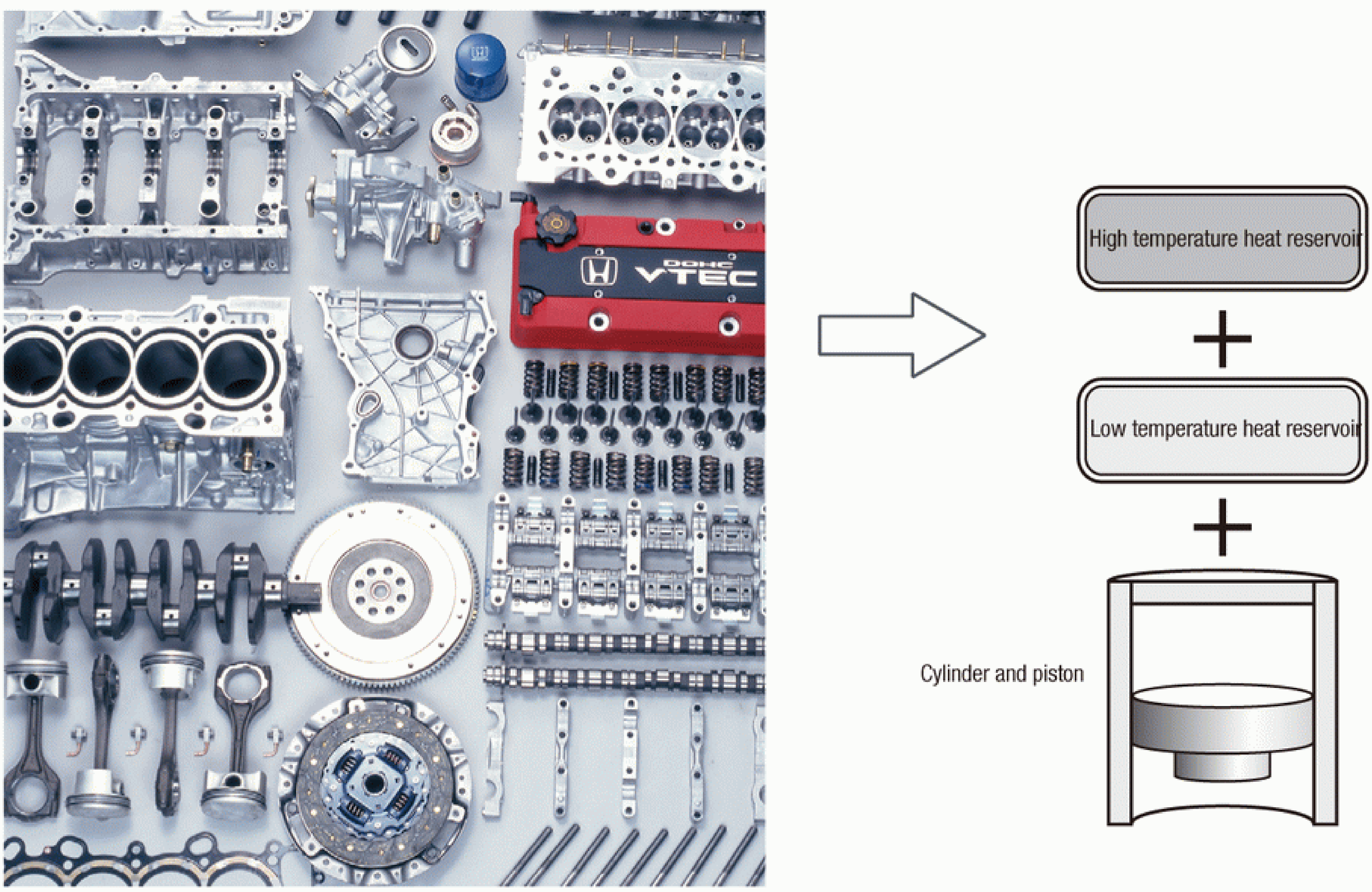
Only two temperatures of the heat reservoir determines efficiency

Thus far, it is normal to believe that the Carnot Cycle is the most efficient thermodynamic cycle for use with a heat engine. But, what Carnot excelled at was that he used sane logic to come to the conclusion that, with the Carnot Cycle, no two different temperatures would come in contact with each other within a cylinder, and that his thermodynamic cycle is indeed the ideal engine. What is even more surprising is that Carnot concluded that the efficiency of the thermodynamic cycle is solely determined by the high and low temperatures of the heat reservoir. Carnot did not put this into a formula, but in later years, the British engineer, William Thompson created the following mathematical expression.

Temperature of the low temperature heat reservoir
Ideal Efficiency of the Carnot Cycle

$$= 1 - \frac{\text{Temp of low res}}{\text{Temp of high res}}$$

Diagram 3-3-1 **The Carnot heat engine precisely identifies the main component from the intricate engine structure in relation to heat transfer and then applied abstraction to the heat engine, thereby proving that the Carnot Cycle was the ideal heat engine.**



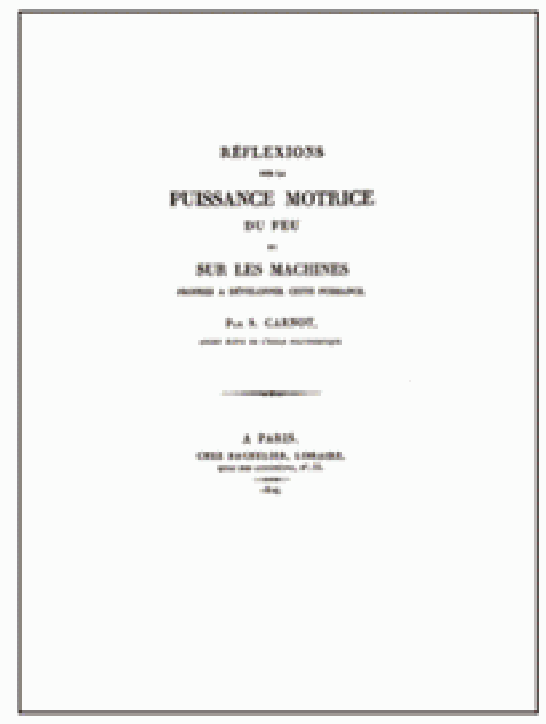
Despite the engine being built from various parts, Carnot was not swayed by such intricacies, but instead applied the Carnot Cycle on heat efficiency and theorized that the high and low temperatures of the heat reservoir were the only determining factors for efficiency. (The picture is a BMW brand twin power turbo V-8 gasoline engine)

The ultimate abstraction of the heat engine

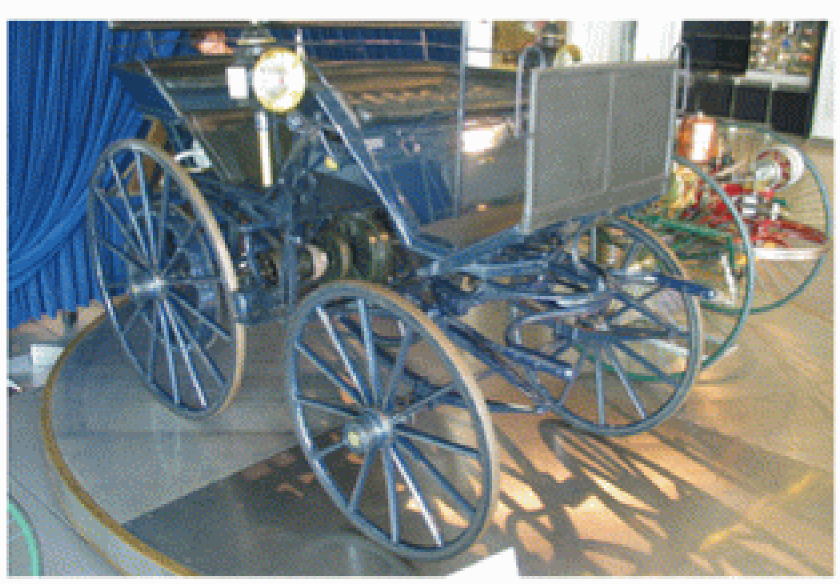
Thus, the relationship between the theoretical efficiency of the Carnot Cycle, heat reservoir, and temperature has been made clear, but the conclusion that Carnot came to also brings to light a very interesting engineering point. As the above formula shows, the theoretical efficiency of the Carnot Cycle is determined only by the temperature differences of the heat reservoir and neither the engine structure nor air or steam or any other derived substances are part of the cause. In other words, the Carnot Cycle is determined by natural causes only and not by how an engine is built.

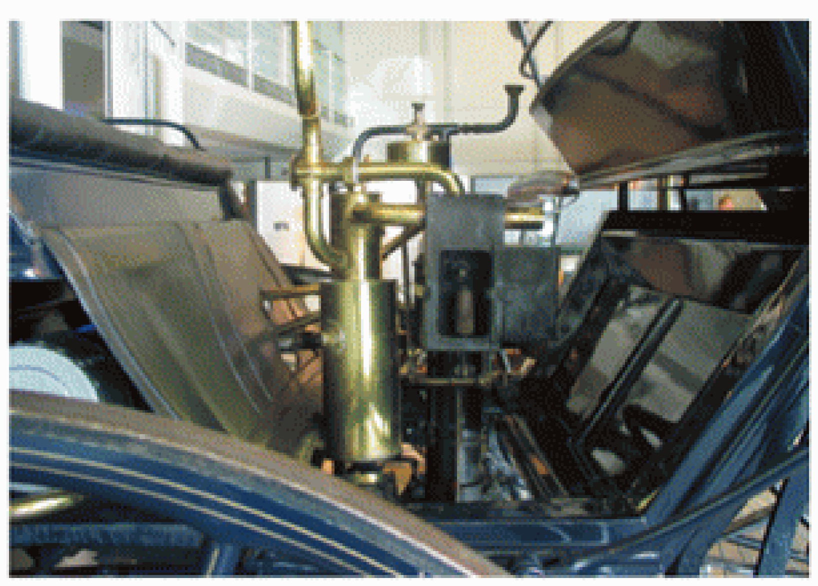
It is interesting to note that the Carnot heat engine precisely identifies the main component from the intricate engine structure in relation to heat transfer and applies abstraction to the heat engine. Nothing was missed and everything necessary is there. It is, in a way to state, an absolute form of abstraction.

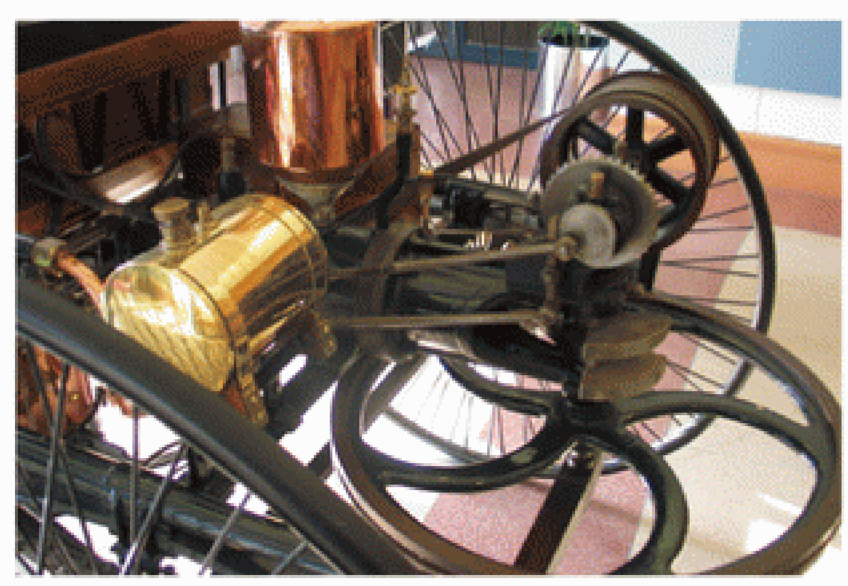
TIPS In the year 1824, Carnot released a technical essay titled “Reflections on the Motive Power of Fire,” where he went into detail of the Carnot Cycle. His motive for releasing this was to approach improvements towards steam engines from an engineering point of view.
Back then, steam engines were widely used and were also consistently improved to the point that steamships had already succeeded in crossing the Atlantic five years before Carnot’s essay. But hardly any thought was placed towards the scientific reasoning behind the steam engine. As such, improvements were solely based upon the experience and “guesses” by mechanics. With that, Carnot decided to explore what characteristic the heat engine held in relation to natural causes, and not what was caused by Carnot’s engine structure, mechanism, or work objects.
But, despite the release of Carnot’s “reflection,” its importance was not immediately recognized. To add to the misery, in the year 1832, while Carnot was researching cholera, he himself became infected with the disease, and within a short number of hours, passed away at the young age of 36. As was customaryback then when a person passes away from cholera, Carnot’s research results and papers were mostly destroyed after his passing.
But even after Carnot’s death, his “reflection” was supplemented by one of his classmates named Clapeyron, from back when Carnot attended ÉcolePolytechnique. This led to wide spread acknowledgement of Carnot’s “reflection,”and soon it greatly contributed to him being considered a pioneer and founder to new fields such as thermodynamics and statistical mechanics within the field of physics.


RÉFLEXIONS
PUISSANCE MOTRICE
DU FEU
SUR LES MACHINES
Par S. CARNOT,
A PARIS.

TIPS Note that William Thompson, the man who made the theoretical efficiency of the Carnot Cycle into a mathematical formula, defined absolute temperature through derivation of the theoretical efficiency of the Carnot Cycle.


A 4-wheeled vehicle born in 1886 by Gottlieb Daimler


The gasoline engine equipped on Daimler’s 4-wheeled vehicle, with 462cc displacement, 680rpm and 1.1ps


The engine part of the aforementioned 3-wheeled vehicle made by Karl Benz. Where Daimler’s engine had the cylinder vertically placed, this was placed horizontally. 984cc displacement, 400rpm and 0.96ps

3-4 Theoretical efficiency of car engines

▶ Investigating the theoretical efficiencies of the Otto Cycle and Diesel Cycle

Otto Cycle

Now that we are aware of what is an ideal heat engine, let us look at a standard car engine. Gasoline engines of today are based on the four-stroke or cycle, usually not both. engine (Otto Cycle) invented by Nikolaus Otto. The four cycles in the Otto Cycle are (1) adiabatic compression, (2) isovolumic heat addition, (3) adiabatic expansion, (4) isovolumic heat rejection. Isovolumic heat addition and isovolumic heat rejection refers to the heating and cooling of the working substance inside the cylinder without changing the cylinder's volume.

Like the Carnot Cycle, how the maximum efficiency of the Otto Cycle is attained can be illustrated by using an air engine with high and low temperature reservoirs, and by moving the pistons very slowly. However with the Otto Cycle, imbalance in temperature during the isovolumic cycles of (2) and (4) cannot be avoided. Because the Otto cycle does not include an isothermal change, thermal transfer cannot occur from the high temperature heat reservoir to the air or from the air to the low temperature heat reservoir without a difference in temperature which causes a wasteful thermal transfer. As such, this thermal transfer makes the theoretical efficiency of the Otto Cycle relatively inefficient compared to the Carnot Cycle.

The theoretical heat efficiency of the Otto Cycle is mathematically represented as…

$$\text{Theoretical efficiency of the Otto Cycle} = 1 - \frac{1}{\text{Compression}^{\text{Ratio of specific heat} - 1}}$$

As shown by the formula, the theoretical efficiency of the Otto Cycle is different from the Carnot Cycle. It is determined by the engine's mechanism and the characteristics of the working substance in relation to the compression and specific heat ratio, but there is no limit to what mechanism should be used for compression or what working substances should be specifically used. Although the engine has many variables and sophisticated mechanisms, the compression ratio and the ratio of specific heat determine the theoretical efficiency of the engine.

Diagram 3-4-2 Change in air pressure and volume in the Otto Cycle

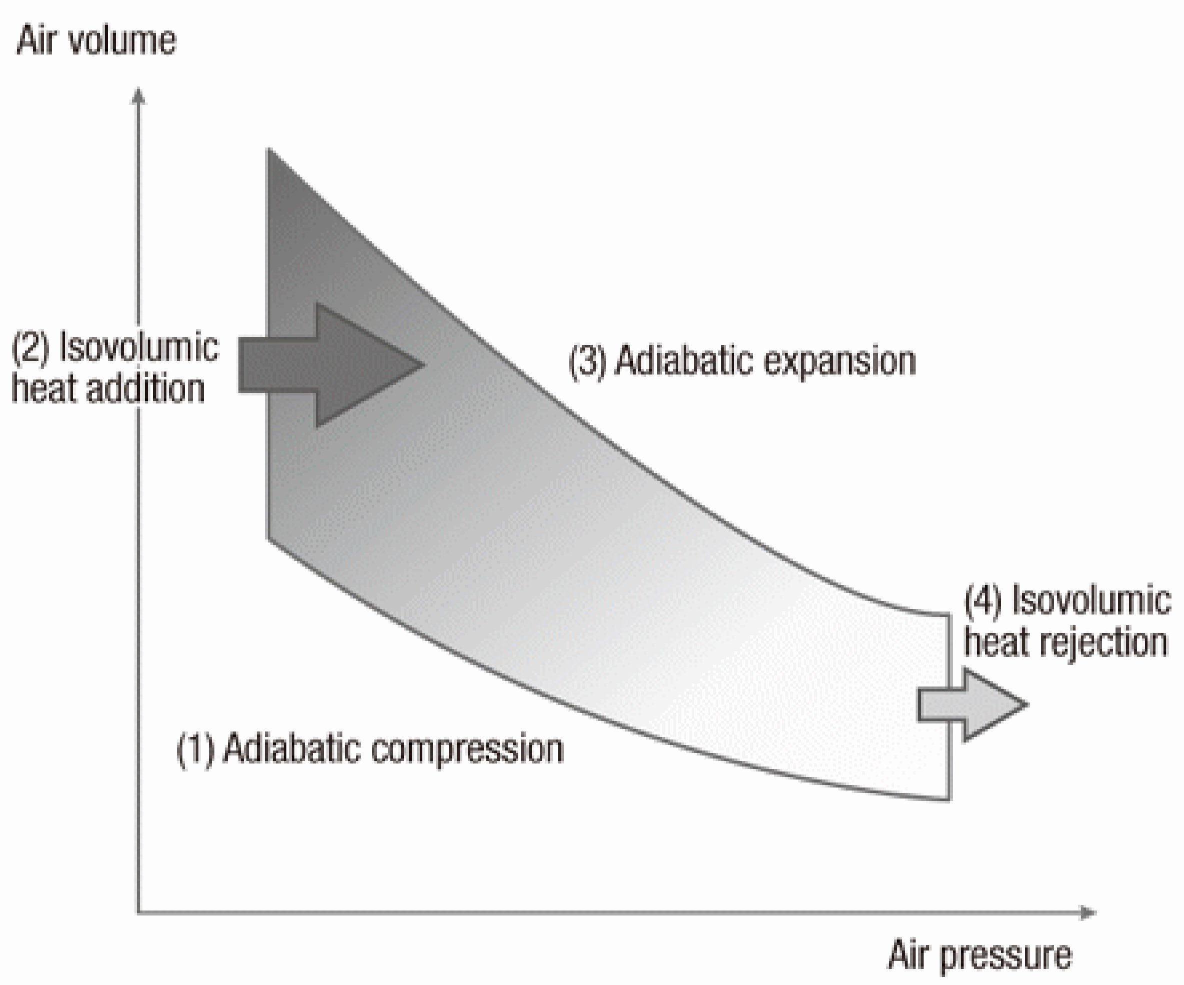
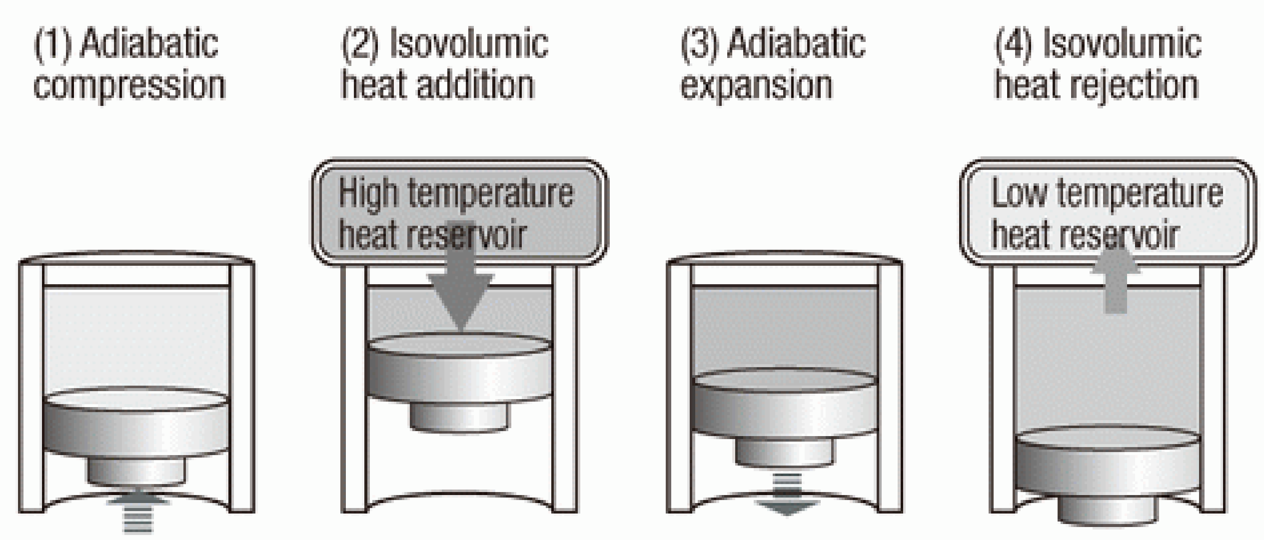


Diagram 3-4-1 Processes of the Otto Cycle



Otto Cycle sample. BMW brand twin power turbo V8 gasoline engine

TIPS The thermodynamic cycle of the Atkinson Cycle, which is most often used in hybrid cars, is the same as the Otto Cycle. Please see the "Tips!" at 3-7.

Theoretical efficiency of the Diesel Cycle

The Diesel Cycle is the thermodynamic cycle of the diesel engine invented by Rudolf Diesel. The four processes of the Diesel Cycle are (1) adiabatic compression, (2) isobaric heat addition, (3) adiabatic expansion and (4) isovolumic heat rejection. Isobaric heat addition refers to the heating of the working substance within the cylinder without changing the air pressure.

The theoretical thermal efficiency can be derived from the formula below.

Diagram 3-4-3 Processes of the Diesel Cycle

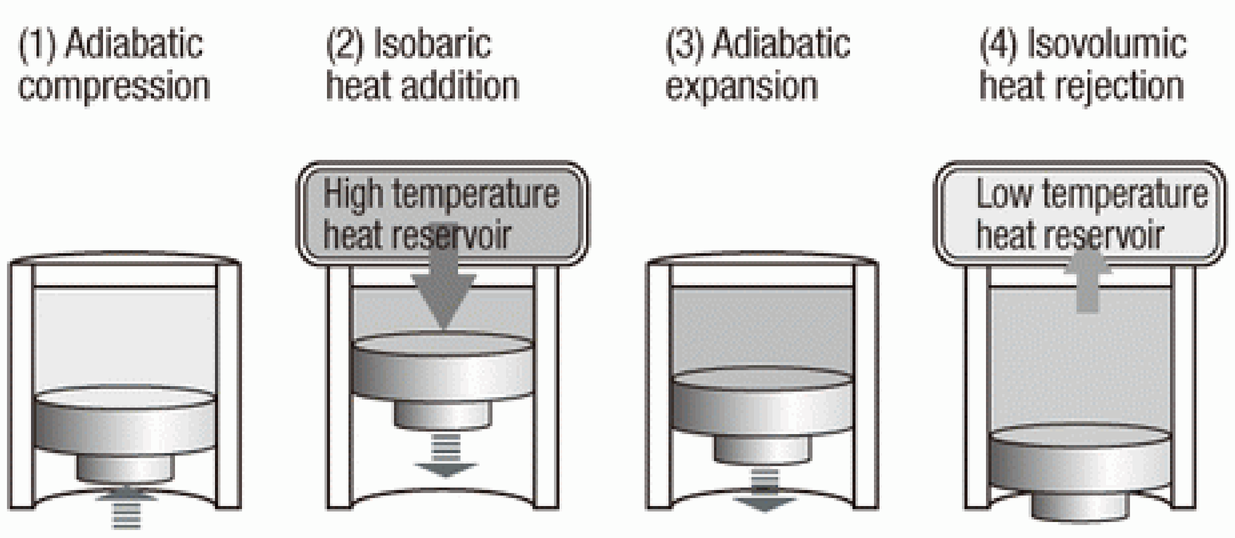
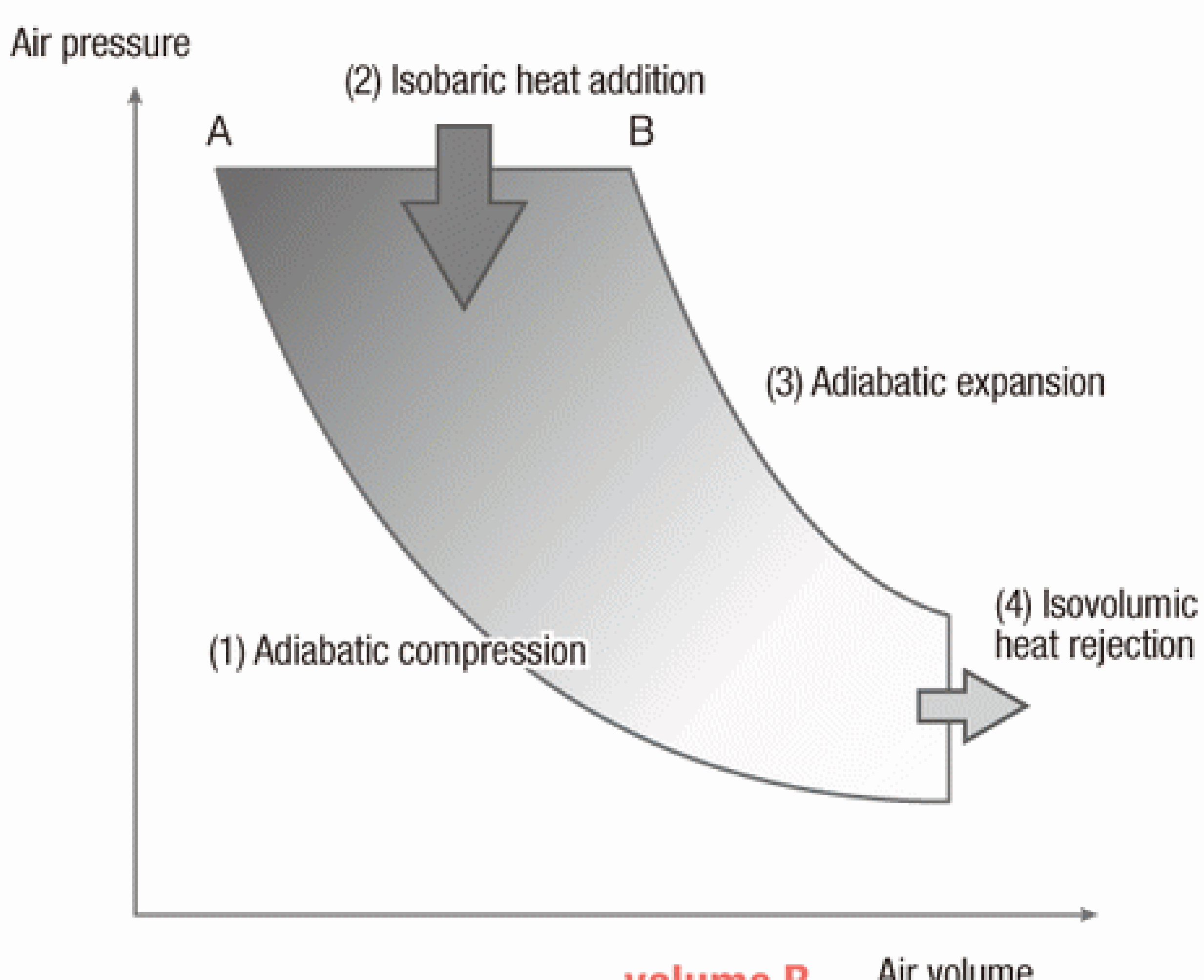


Diagram 3-4-4 Change in air pressure and volume in the Otto Cycle



$$\text{Cut-off ratio of fuel injection} = \frac{\text{volume B}}{\text{volume A}}$$

$$\text{Theoretical efficiency of the Diesel Cycle} = 1 - \frac{1}{\text{Compression}^{\text{Ratio of specific heat} - 1}} \cdot \frac{\text{Cut-off ratio of fuel injection}^{\text{Ratio of specific heat}} - 1}{\text{Ratio of specific heat}\left(\text{cut-off ratio of fuel injection} - 1\right)}$$

It is determined by only three measures: compression ratio, ratio of specific heat and the cut-off ratio of the fuel injection. To maximize the efficiency of the Diesel Cycle, the piston must again be moved very slowly. However, thermal transfer is inevitable in cycles (2) and (4). Therefore, the thermal transfer of the Diesel Cycle is relatively inefficient compared to the Carnot Cycle.

Diesel Cycle sample. Mazda brand 2.2 liter Diesel engine

All three of the cycles—Carnot Cycle, Otto Cycle and Diesel Cycle—fail to achieve the theoretical efficiency of a thermal engine. In reality, moving the piston slowly as required for maximum efficiency does not create utility value. Also the temperatures of the piston and cylinder cannot be fully insulated, which leads to some kind of wasteful thermal transfer due to temperature differences. Friction cannot be prevented between the piston and cylinder as well. However, clarifying theoretical efficiency illuminates the true nature of each thermal engine, giving the engineers a very valuable guiding principle.

3-5 Reversible change and irreversible change

▶ Natural change has a direction

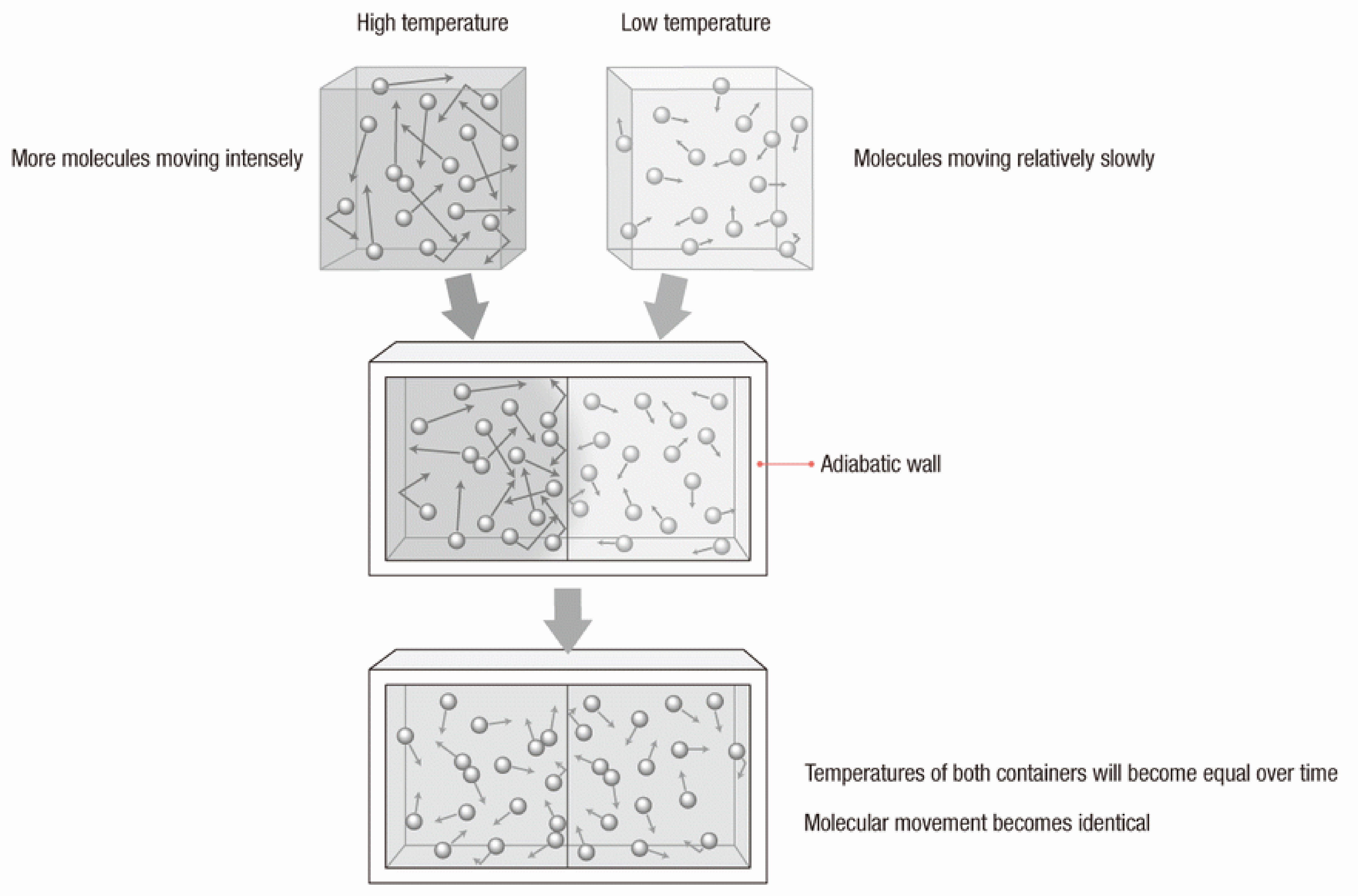
From here, let us examine the inevitable energy loss of engines based on the discussions we've made in the past pages. But before we get into detail, a very important natural law must be explained.

Nature changes from order to disorder

Let's take another look at the gas molecules inside a container. Only this time, we will use one container with high temperature gas and another container with low temperature gas sealed inside. If both containers are put in contact with each other, the heat from the high-temperature container will transfer to the low-temperature container. If left as is, both will soon reach a median temperature, which then stops any further thermal transfer, resulting in the containers to be in an equilibrium state.

From a microscopic perspective, initially, the container with high-temperature gas inside contains relatively greater amounts of fast-moving molecules, whereas the lower-temperature container has relatively fewer amounts of fast moving molecules. When the two containers come in contact with each other, the kinetic energy from the molecules inside the high-temperature container transfers to the low-temperature container, increasing the molecular kinetic energy inside the low-temperature container. When each of the molecules in both containers reaches the median kinetic energy (temperature), the transfer of kinetic energy (thermal energy) between the containers will cease.

Diagram 3-5-1 Contact between two containers with different temperatures



No changes occur between "disorder" and "order"

The same example can be viewed from a different perspective. Inside one container are molecules of high kinetic energy and the other contains molecules of lower kinetic energy, making it possible to distinguish the difference of molecular motion inside the high-temperature and lower-temperature containers. It can be said that there was distinguishable information within the containers. However, when the containers reached the equilibrium state, the distinctive information between the two containers were no longer present. The containers were now in a state of "disorder."

In nature, transformation from an "order" to "disorder" state is actually natural. Meanwhile, the reverse transformation of a state of "disorder" to "order" does not occur in nature. For example, when the high- and low-temperature containers were in contact with each other, the high-temperature cooled and the low-temperature container warmed, which is natural. On the other hand, we know by experience that when two containers with different temperatures are put together, the container with the higher-temperature container will not heat up and the lower-temperature container will not cool down. Furthermore, no matter what people do, we cannot go against nature and revert the two containers in equilibrium back to their "exact" original temperatures, like how you would rewind a video. When the resulting change cannot be undone to recover the original state, we call this irreversible change. If the change can be undone and recovered to its original state, we call it reversible change.

Diagram 3-5-2 **A natural direction of change in nature**

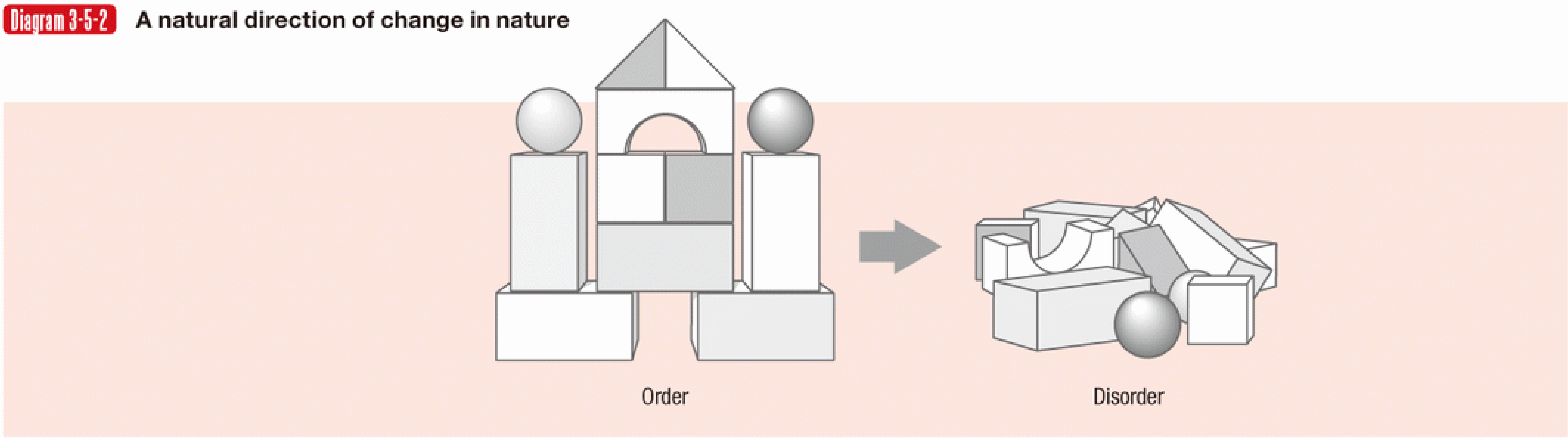
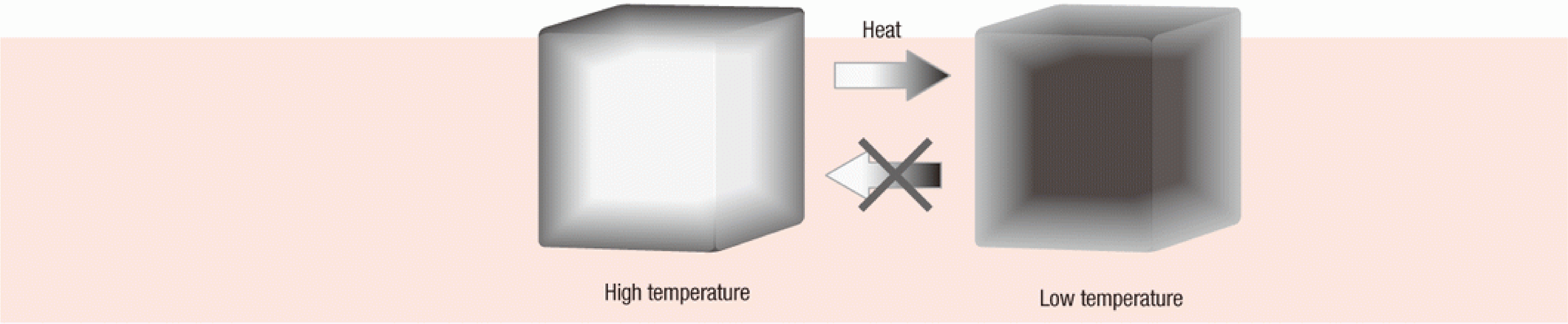


Diagram 3-5-3 **Thermal transfer from low to high temperature does not occur naturally. (* to be specific, such phenomenon occurring naturally is not impossible, but is close to impossible, and is something which humans cannot observe.) If thermal transfer from low to higher temperature is done artificially, there will always be a trace left of the transfer. Therefore, perfect reversal to the original high and low temperature conditions is not possible.**



3-6 Reversing the heat engine

▶ Differences in reversible and irreversible cycles

Despite explaining the theoretical efficiency of the Carnot Cycle, Otto Cycle and Diesel Cycle, why can't actual engines achieve such theoretical efficiency? Why does energy loss occur in an actual engine? The answer to that is hidden in the fact that theoretical efficiency of the thermodynamic cycle can only be achieved by the gradual and slow speed of the piston.

The reversible process of the Carnot Cycle

Let us go back to the Carnot Cycle. Let us call the Carnot Cycle processed in the order of (1) → (2) → (3) → (4) a [progressive cycle], and a reversed process of (4) → (3) → (2) → (1) a [reversed cycle]. Let us then assume that, through progressive cycle of the Carnot Cycle, a certain amount of heat is transferred from the high-temperature heat reservoir to the low-temperature heat reservoir, and that during the process, the derived work is reserved somewhere. Next, if that reserved work is used to do a reversed cycle of the Carnot Cycle, the heat transferred by the progressive cycle to the low-temperature heat reservoir is returned exactly back to the high-temperature heat reservoir. At this point, the reserved work will be depleted by the reversed cycle, leaving nothing behind. In other words, the work derived by the progressive cycle of the Carnot Cycle can be reserved and when that reserved work is used for the reversed cycle, the entire cycle is "reverted back into its perfect, original state." This is possible due to the Carnot Cycle not having objects with temperature differences coming in contact with each other, which prevents unnecessary thermal movement. In other words, all processes of the Carnot Cycle are reversible changes, so a reversed cycle is possible.

Diagram 3-6-1 Reversed cycle of the Carnot Cycle

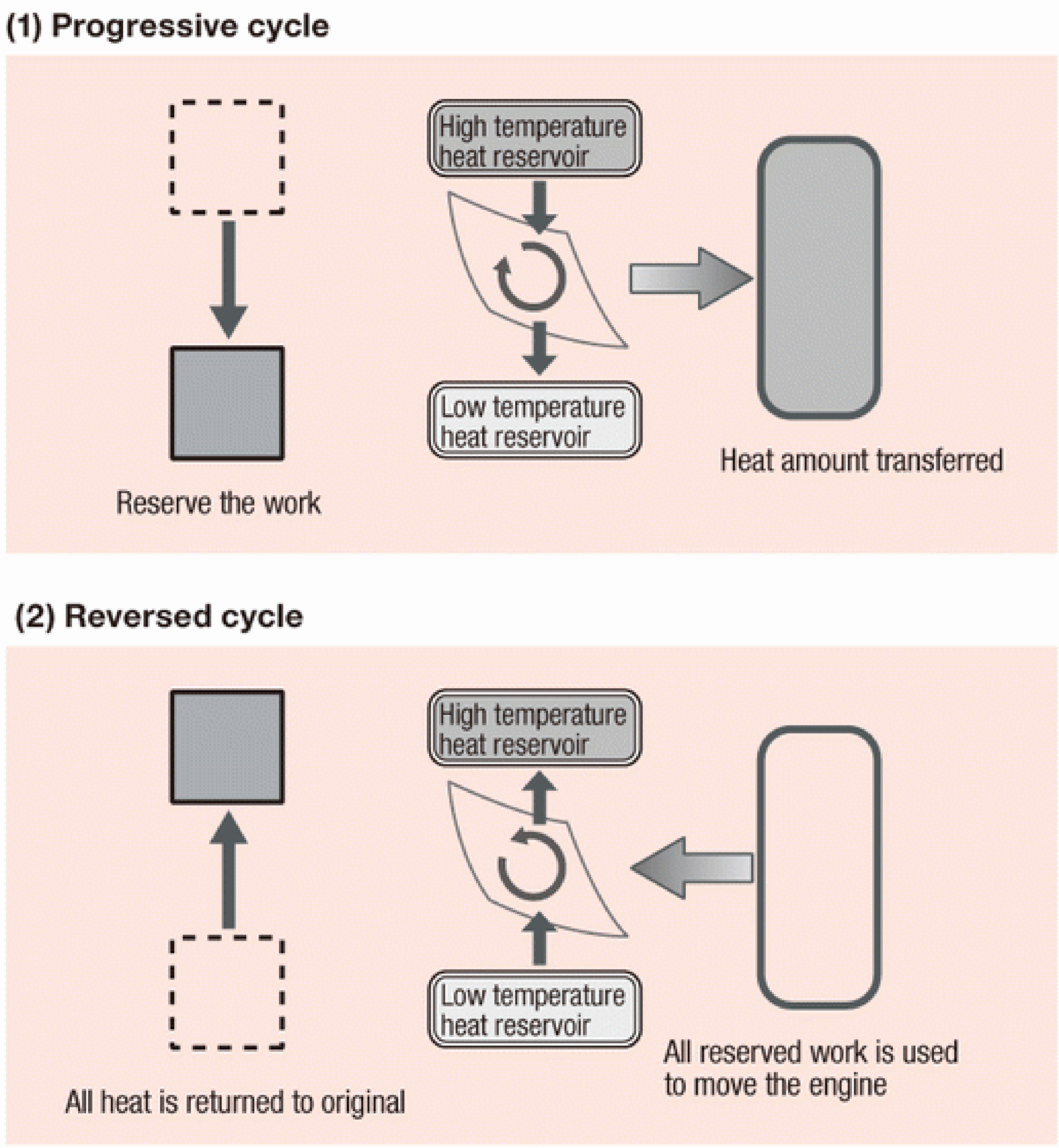
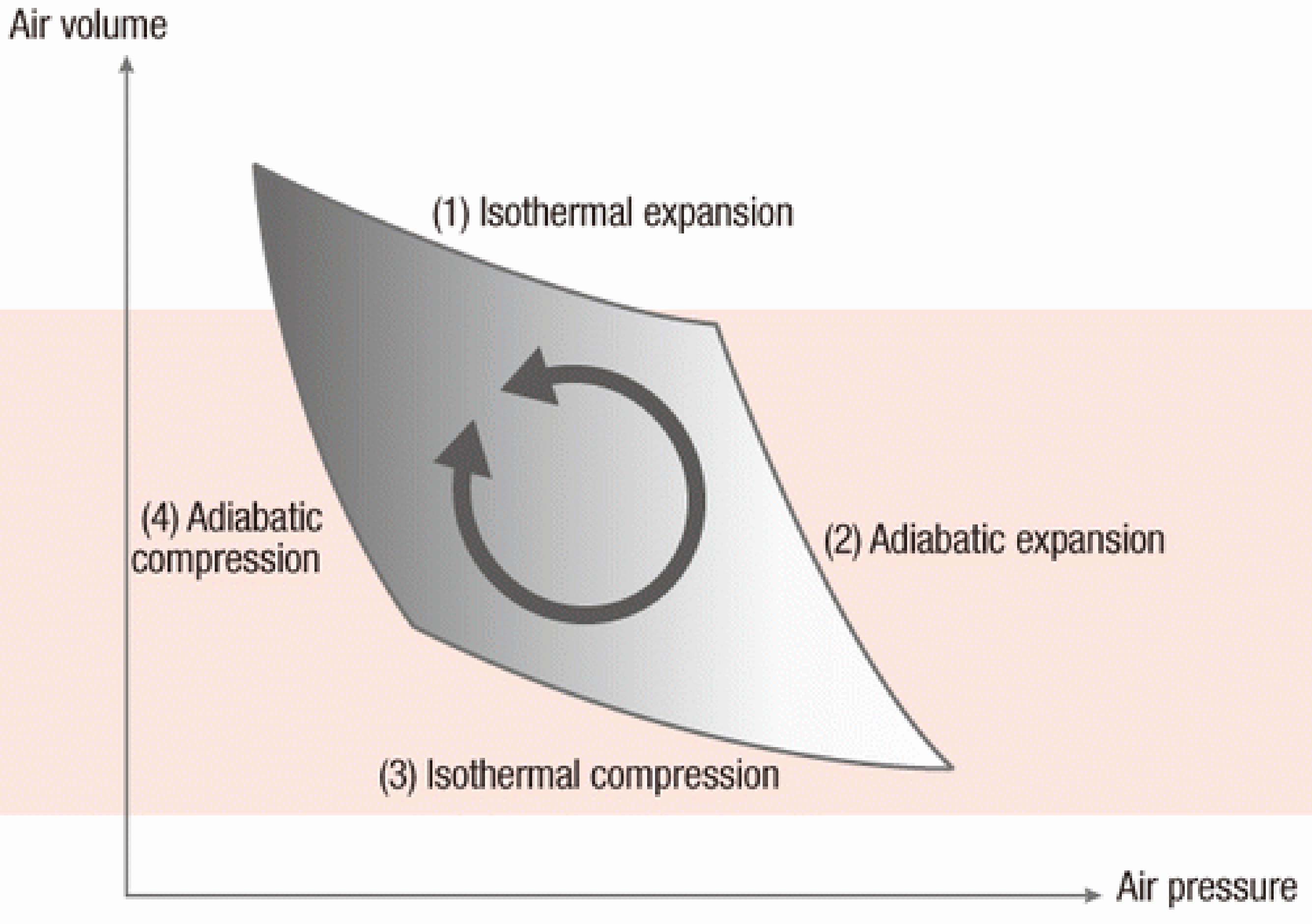


Diagram 3-6-2 Reversible nature of the Carnot Cycle

All the cycles of the Carnot Cycle are reversible, hence a [reversible] reversed cycle is possible.



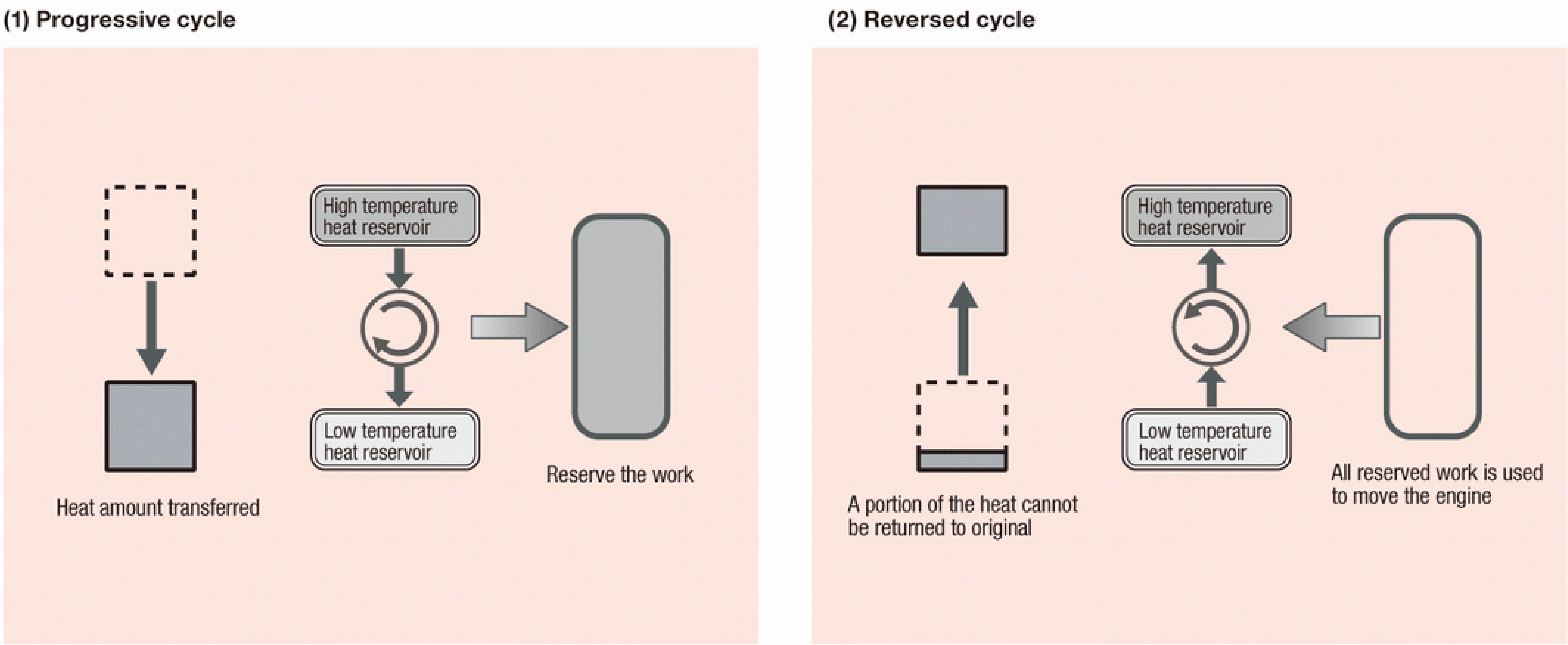
Reversed cycle of car engines is irreversible

Let us now consider the Otto Cycle and the Diesel Cycle. Similar to previous cases, let us reserve the work from the progressive cycle, and apply the reserved work to the reversed cycle. Even if we deplete the reserved work for the reversed cycle, all the heat cannot be transferred from the low-temperature heat reservoir to the high-temperature heat reservoir and only a portion of the heat will be reverted to original,

The reason this occurs is because, for the Otto Cycle and the Diesel Cycle, a level of temperature difference is needed to conduct (2) isovolumic heat addition and (4) isovolumic heat rejection, and (2) isobaric heat addition and (4) isobaric heat rejection respectively. These processes do not create work and causes wasted thermal transfer between high to low temperature. Hence, compared to the Carnot Cycle, the derived work amount from a progressive cycle is reduced by the same amount of wasted thermal transfer. Also, during the process of temperature differences in a reversed cycle, it goes against the natural order by transferring heat from low temperature to high temperature, so again, more work is needed.

This actually points to something very important. If a heat engine cannot conduct a reversible reversed cycle, it is proof that there is wasted thermal transfer occurring within the process of the cycle's work output. We will touch on this at a later time.

Diagram 3-6-3 Reversed cycle of the Carnot Cycle



TIPS With Carnot assuming his Carnot Cycle as being reversible, what is left behind after conducting a progressive cycle and then a reversed cycle? With this, conclusion was logically made based on the concept that "the Carnot Cycle is the most efficient heat engine." Carnot understood that his Carnot Cycle, which leaves nothing behind, is the ideal engine. If there is an engine which is more efficient than the Carnot Cycle, it would have to utilize perpetual motion. But, it is assumed that perpetual motion does not exist and that the aforementioned possibility is moot.

37 Engine's loss of energy

▶ The loss of energy is due to irreversible change

When explaining the theoretical efficiency of the heat engine, we have repeatedly mentioned that "the piston must be moved gradually and at slow speeds." Such was actually necessary to avoid any irreversible changes. We will explore further on the nature of energy loss due to irreversible change.

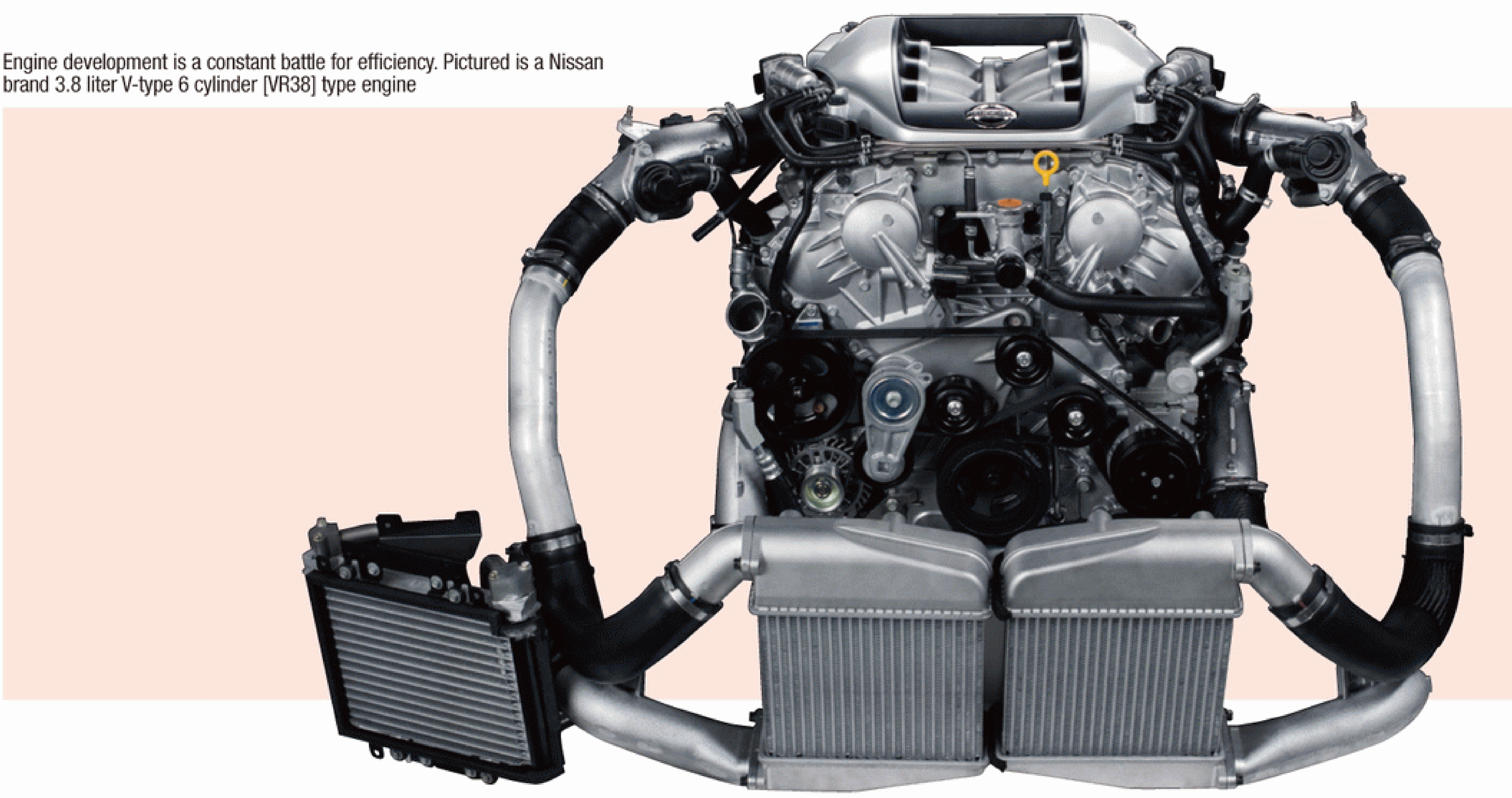
Engine's loss of energy

As shown previously, the Carnot Cycle does not transfer heat through temperature differences, so a reversible reversed cycle is possible. But for the Otto Cycle and the Diesel Cycle, there are irreversible processes using temperature differences for thermal transfer within its cycle, so a reversible reversed cycle is not possible.

Thus far, we have focused on the concept of irreversible change due to thermal transfer by use of temperature differences, but if there is a phenomenon of irreversible change within the process of a heat engine cycle, the thermal transfer cannot be extracted for work and is instead something that reduces the amount of work possible.

When the actual engine is in motion, heat is created from the chemical change of the fuel within the cylinder, thereby using the energy created to move the piston for work output. At this point, the heat creates differences in temperature, which causes unnecessary waste of thermal transfer. Friction between the cylinder and piston causes noise and turbulence, and the chemical change of the fuel is also irreversible. Of course, due to these phenomena being irreversible changes, when they do occur, they cannot be perfectly reversed back to its original state—like a rewound video. In other words, wasteful thermal transfer has occurred.

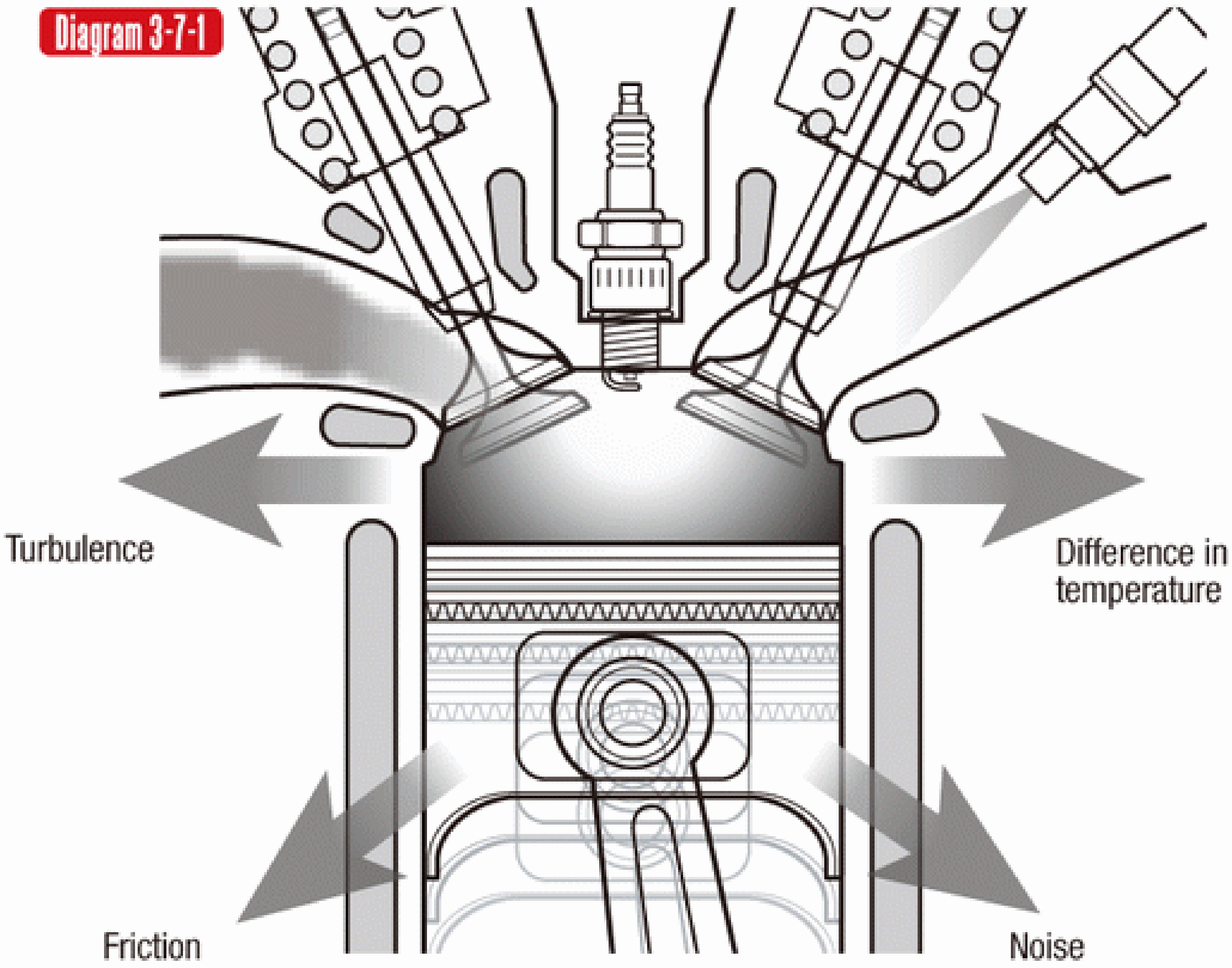
Engine development is a constant battle for efficiency. Pictured is a Nissan brand 3.8 liter V-type 6 cylinder [VR38] type engine



Mechanical energy loss

Up to now, the focus has been in relation to heat engines, but mechanical energy loss occurs entirely due to irreversible change. On the flipside, an efficient machine is one where irreversible change does not occur as much. Hence, in order to create an efficient machine, understanding what irreversible change is and preventing it from occurring as much as possible is very important.

Diagram 3-7-1



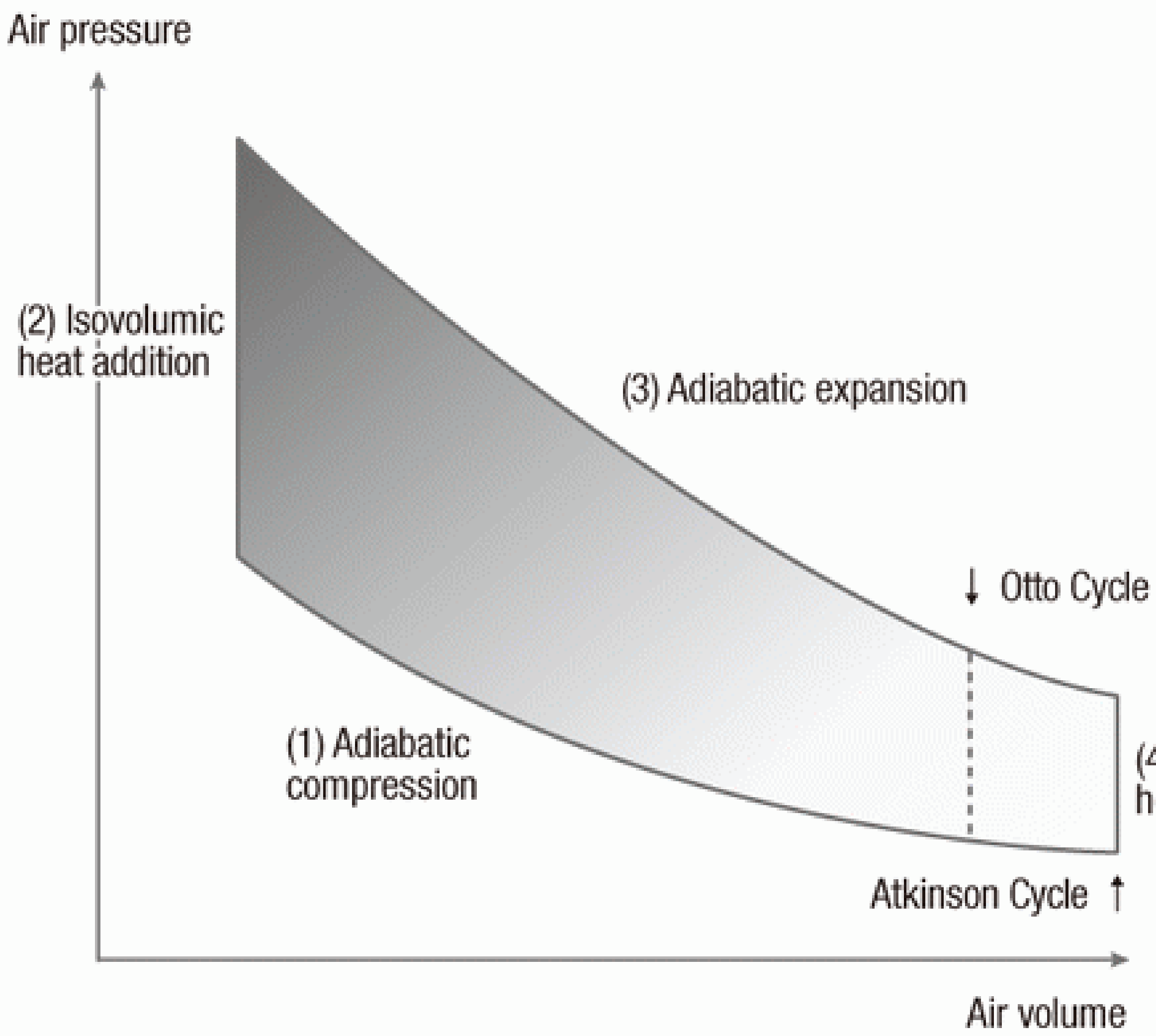
When the piston is moved quickly, various irreversible energy is lost from the engine.

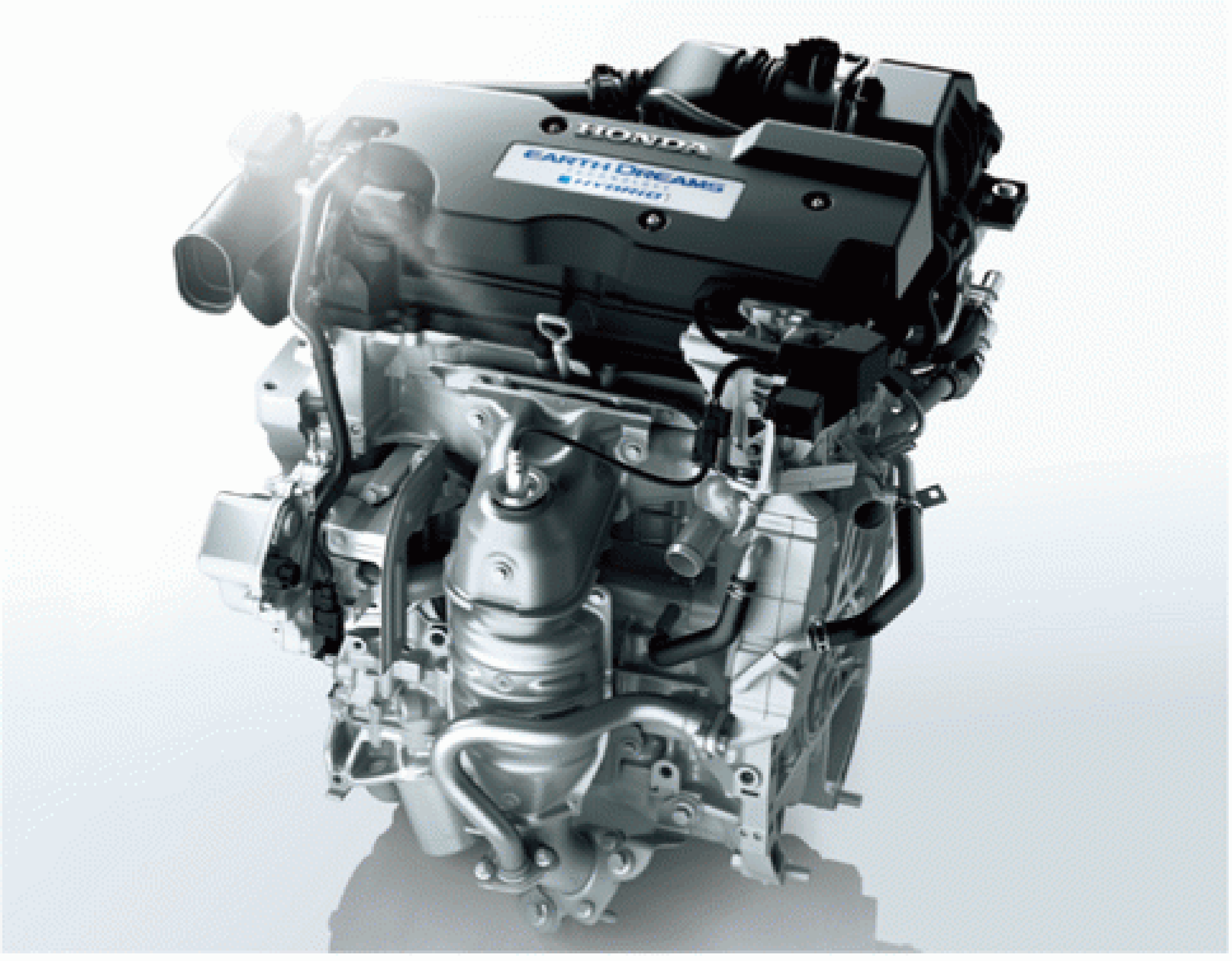
TIPS It is commonly explained that the Atkinson Cycle uses the same thermodynamic cycle as the Otto Cycle, and by making the expansion process longer, the work output is increased. With the concept of creating an engine that does not cause much irreversible change, the Atkinson Cycle is a thermodynamic cycle that goes through the process of lengthening the adiabatic change of (1) and (3), and shortening the isobaric heat rejection of the irreversible change process at (4). Note that high temperature adiabatic expansion and low temperature adiabatic compression will never intersect, so there is a need for an isovolumic cycle to act as a conductor.

In similar manner, when optimizing the efficiency of engines or any other machines, it can be said that all thought is placed in "ensuring prevention of irreversible change."

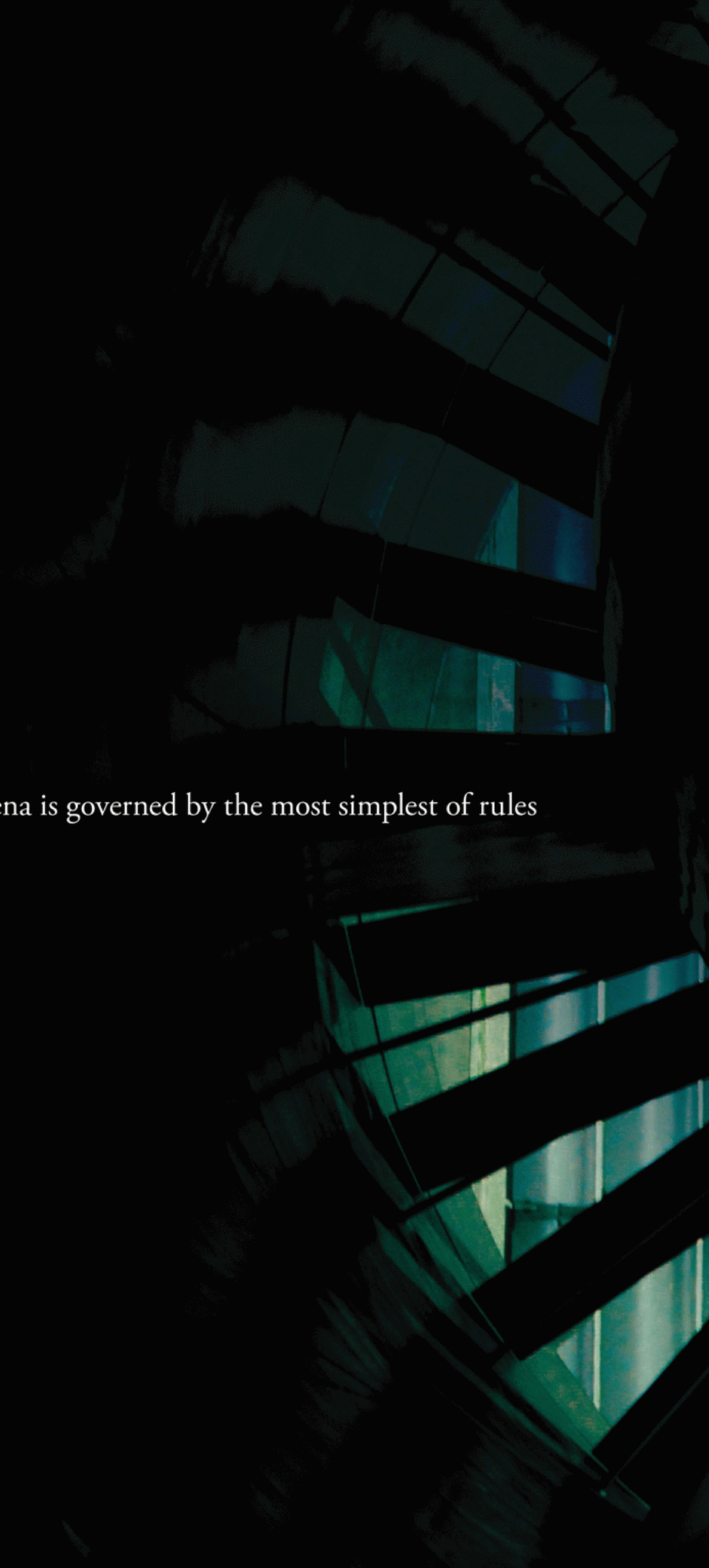
Diagram 3-7-2 **Atkinson Cycle**

The Atkinson Cycle is a thermodynamic cycle that lengthens the adiabatic process and shortens the isobaric heat rejection.





Equipped on the Honda Accord hybrid is the 2 liter Atkinson Cycle DOHC i-VTEC engine



Even the most complex phenomena is governed by the most simplest of rules

4-1 Bernoulli's Theory

▶ Relativity of fluid pressure and speed

How does the air surrounding the automobile affect its performance? In order to answer that question we need to understand the theory of aerodynamics. In this section, we will introduce the basics of aerodynamics.

Molecular movement in the presence of flow (current)

In the previous section, we have explained that measurement of pressure will be the same regardless of direction under an equilibrium state. A macroscopic perspective shows us that the countless number of molecules moving in a disorderly fashion are actually colliding evenly in all directions. From an energy standpoint, it can be rephrased that kinetic energy of the molecules are being evenly dispersed. This is called the law of equipartition of energy (hereafter, equipartition).

However, if there is a flow to the movement of molecules, equipartition becomes valid. There will be more kinetic energy in the direction of flow, while there will be less kinetic energy perpendicular to the direction of the flow. When pressure is measured in the region of flow, ...

It should be noted that the sum of the kinetic energy, before and after a change in the direction of flow, will not change. For example, if a flow current should occur from an equilibrium state, the sum of kinetic energy after the occurrence of flow and the sum at the equilibrium state are the same. In other words, when a change in flow rate occurs, the dispersion of kinetic energy changes but the sum of the total kinetic energy does not change.

Diagram 4-1-1 Movement of molecules. If there is a flow to the movement of molecules, the highest pressure is at the direction of flow, and the lowest pressure is at a point perpendicular to the direction of flow.

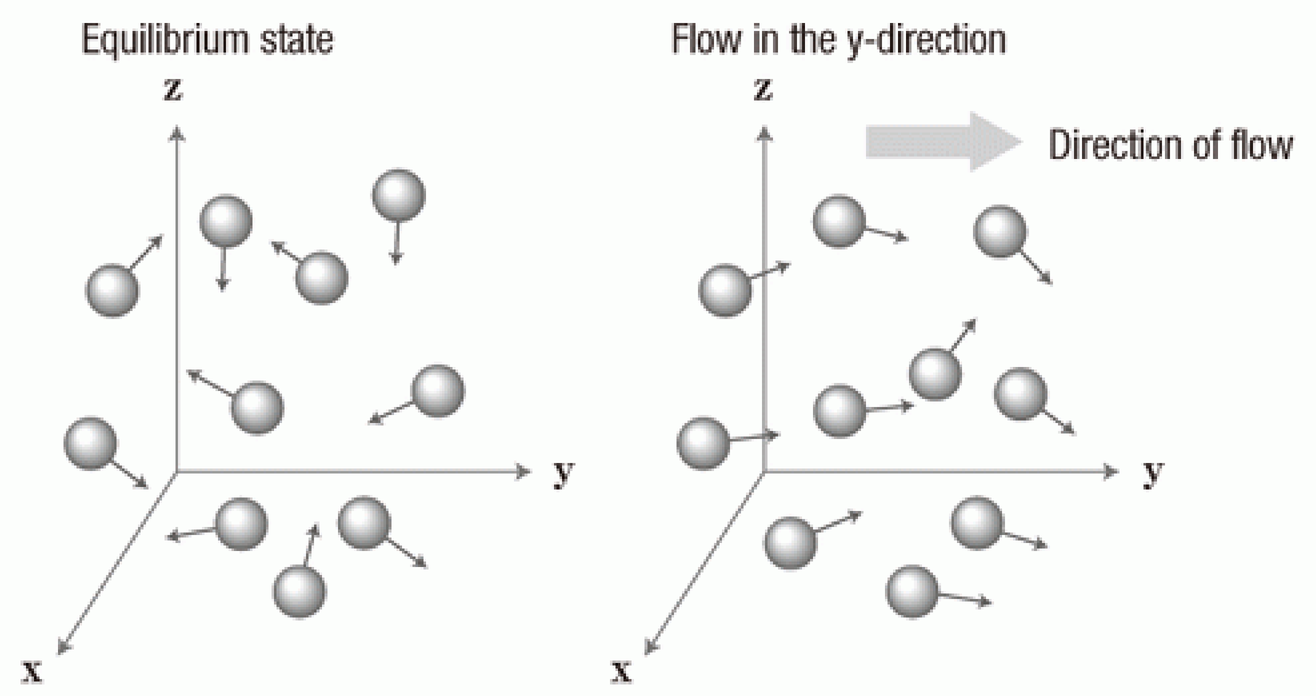
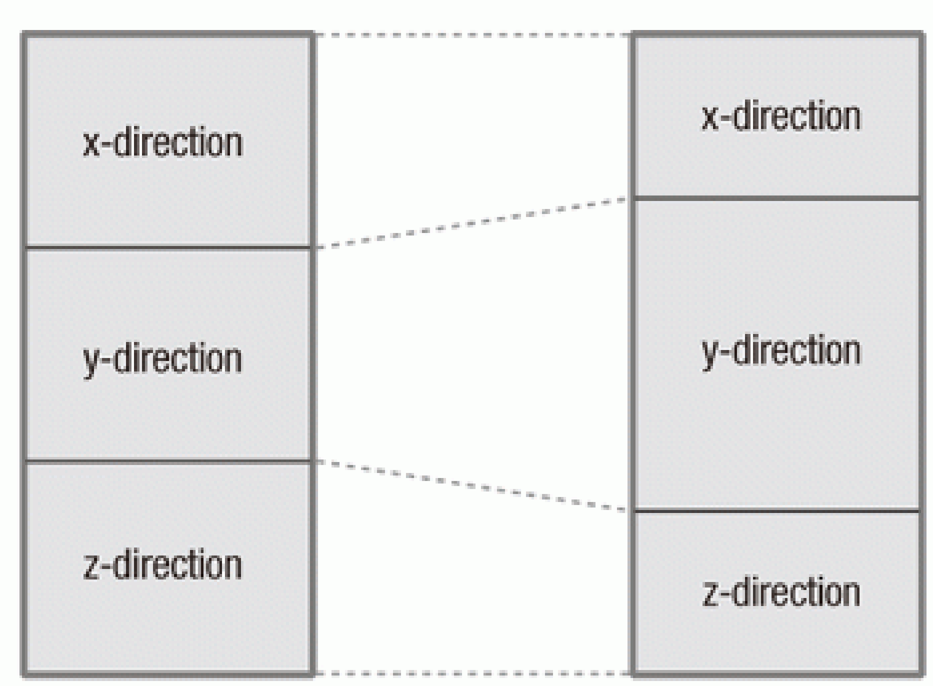
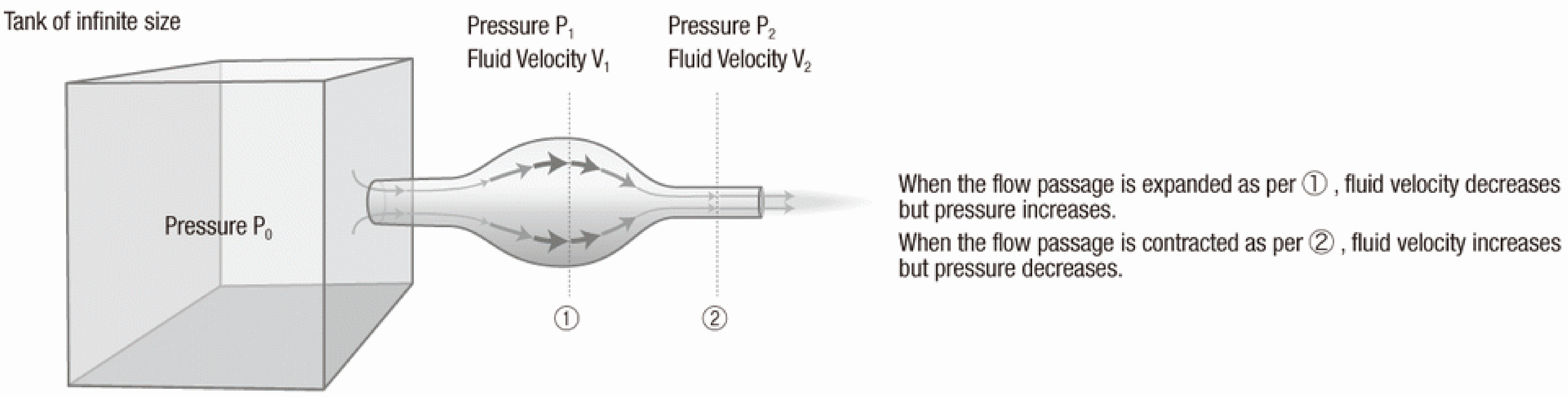


Diagram 4-1-2 Dispersion of molecular kinetic energy



The sum of the kinetic energy does not change even when the direction of flow changes.

Diagram 4-1-3 **Example of Bernoulli's Theory**



Bernoulli's Theory

Bernoulli's Theory defines the relationship between velocity of flow and pressure, when dissipation of energy occurs due to the change in flux. Bernoulli's Theory can be mathematically expressed as follows.

Here P is pressure, ρ is fluid density and V is fluid velocity. Bernoulli had recognized the relationship between fluid velocity and pressure from the concept of "vis viva" (Latin for "living force"), which is a concept very much similar to that of energy. However, it is often believed that he did not have full understanding of the relationship between pressure and velocity. The person who gave Bernoulli's Theory a full and correct mathematical meaning was his close friend, Leonhard Euler.

$$P_0=P_1+\frac{1}{2}\rho V_1^2=P_2+\frac{1}{2}\rho V_2^2$$

Lift generating mechanism

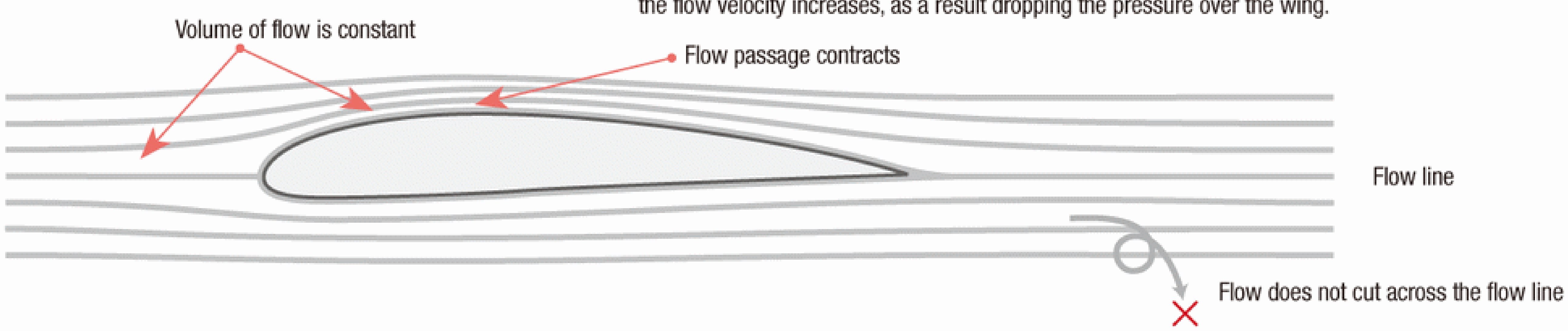
This section will explain the mechanism of how an airfoil generates lift using the Bernoulli Theory.

Diagram 4-1-4 illustrates the flow line around an airfoil. A flow line is a curve based on the tangent line of the velocity vector. It is the line of flow or the streamline. The definition of a flow line states that a flow does not cut across the flow line; therefore, an area that is between the same flow line will have the same flow volume in any part of the flow. Note that a location where the fluid exists is called a flow field.

Looking at the flow field in Diagram 4-1-4, we see that the flow line in front of the airfoil is evenly spaced, but we can tell that the spacing of the flow line is constricted on top of the airfoil. Since the flow will not cross the flow line, it can be assumed that the passage of flow is limited on top of an airfoil. But, the volume of flow between the flow line should not change. Hence, if the flow path is limited, the velocity of flow on top of the airfoil should accelerate. Therefore, according to Bernoulli's Theory, pressure on top of the airfoil should decline proportionally to the square of the flow velocity. In contrast, if the flow underneath the airfoil should expand, the flow velocity will decrease and the pressure will increase. This difference in pressure between the top and bottom surface of the airfoil is what generates lift.

Diagram 4-1-4 **Lift generating mechanism of an airfoil**

Flow passage narrows on top of the wing. Since the volume of flow does not change, the flow velocity increases, as a result dropping the pressure over the wing.



4-2 Law of fluid motion

▶ The meaning of the equation of fluid motion

Euler equation – without considering viscosity

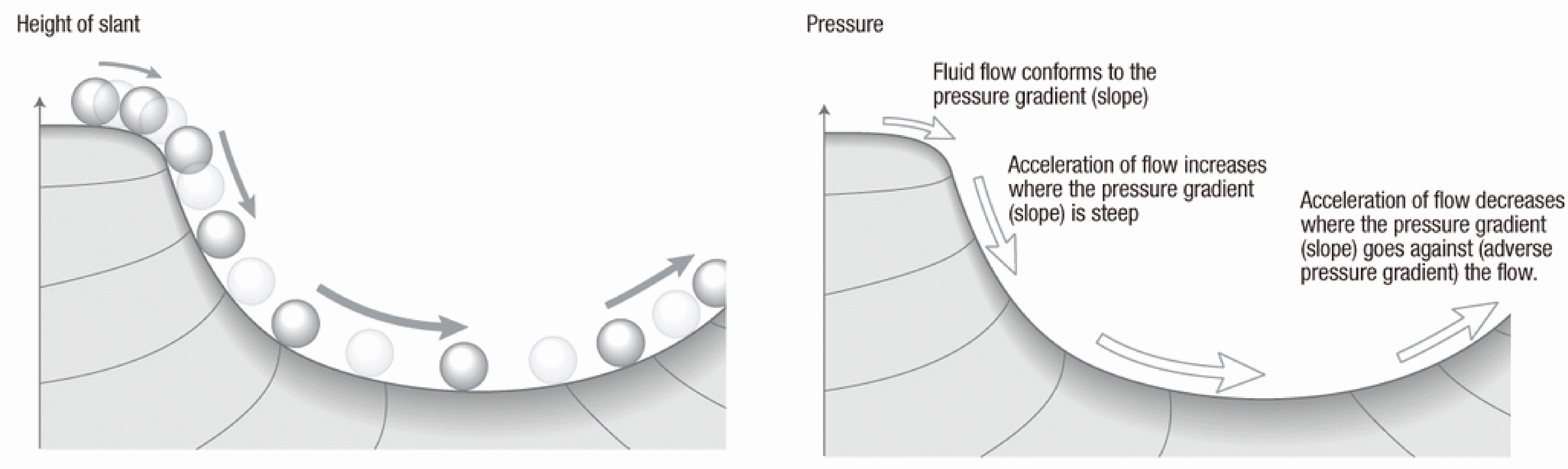
The first person to derive the fluid equation of motion was Euler, who had also formulated Bernoulli's Theory. In terms of advancement of hydrodynamics, this revelation was much more important than Bernoulli's Theory. The equation of motion that Euler had derived is called the Euler equation shown below.

$$\rho \frac{Du}{Dt} = -\nabla P$$

The left-hand member of the equation is called the advective or convection term representing the advection effect of fluid, or in other words, the effect caused by the flow of fluid. Meanwhile, the right-hand member is called the pressure term, expressing the gradient (slope) of pressure. In short, Euler states that "fluid flows according to the pressure gradient.

A good example of a gradient of pressure is pressure distribution charts in meteorology. During the winter season of Japan, cold and dry air flows in from the Eurasian continent because the gradient of pressure around Japan is high in the west, and low in the east. If the pressure lines are cluttered together, it means the gradient of pressure is substantially steep; therefore, winds in those areas are strong. If the pressure lines are spread apart showing a mild gradient of pressure, the winds in those areas can be forecast to be mild. This very intuitive understanding of flow is what the Euler equation had successfully formulated.

Diagram 4-2-1 **Pressure gradient**



TIPS Equation of motion for fluid with zero viscosity is called the Euler equation. The equation mentioned in the passage is for non-compressed fluid with no consideration to change in density. Euler has also formulated an equation of motion for compressive fluid.

Navier-Stokes Equation – with consideration to viscosity

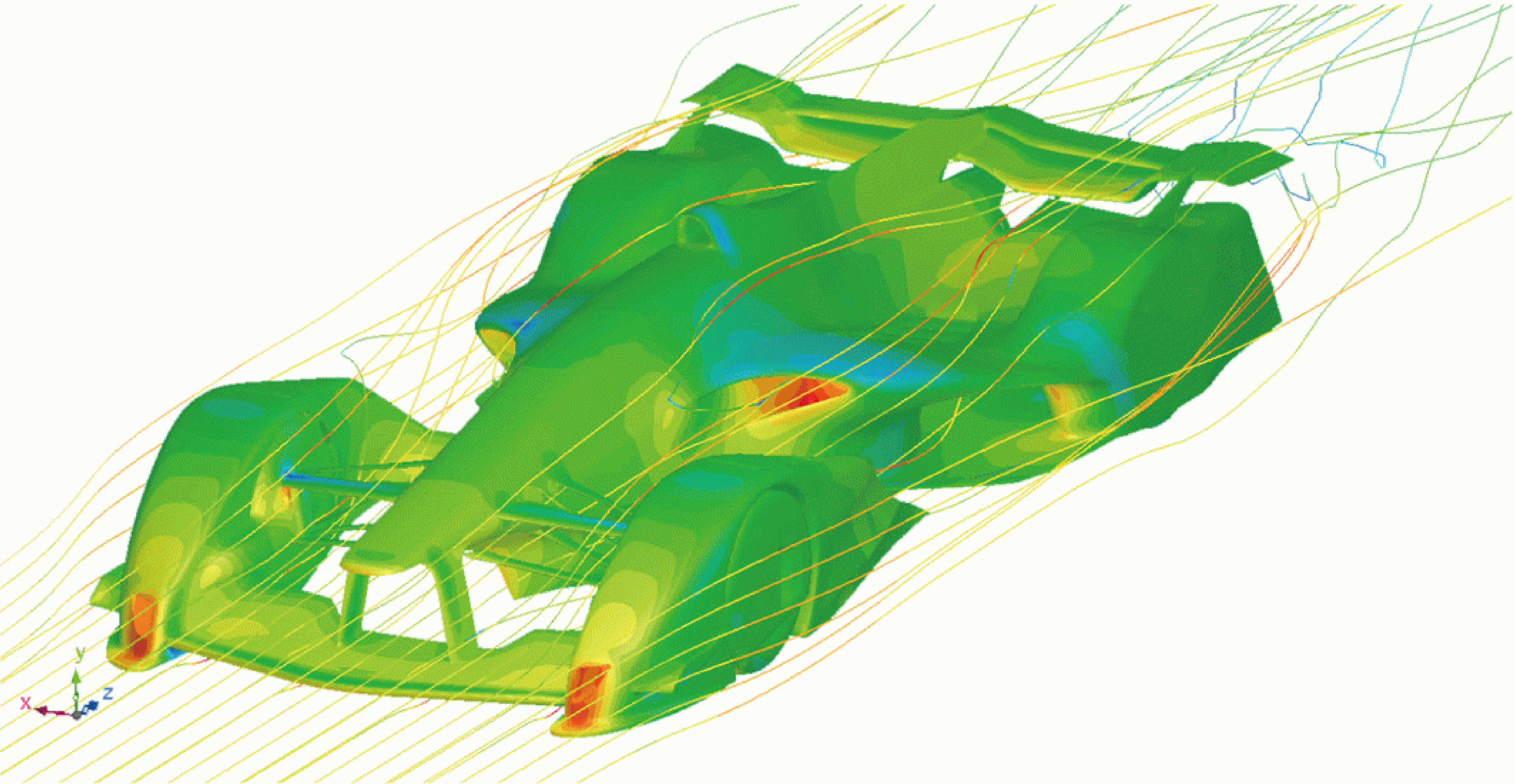
The Euler equation expressed a mathematical formula for the effect of fluid flow and its relation to pressure; however, it did not express the effects of viscosity which fluids in real life would have. The equation of motion which considered the effects of viscosity was derived in the 19th century by Claude-Louis Navier and George Gabriel Stokes. The Navier-Stokes equation is expressed as below.

$$\rho \frac{Du}{Dt} = -\nabla P + \nabla \cdot \tau$$

Identical to the Euler equation, the left-hand member of the equation is the advective (convection) term representing the advection effect of fluid. The first variable on the right side of the equal mark is the pressure term (above), expressing the gradient of pressure. The newly added second variable is called the viscosity or diffusion term, expressing the property of viscosity. In short, the Navier-Stokes equation states that "fluid flows according to the pressure gradient, but viscosity also has an effect on fluid momentum." The aforementioned Navier-Stokes equation is for non-compressed fluid that does not consider changes in density.

TIPS For both the Euler equation and Navier-Stokes equation, a generalized solution has yet to be found. The equations can only be applied to very specific and specialized currents (flow). In order to apply these equations to general flow-fields, a computer must be used to numerically solve the equations. Not only is the Navier-Stokes equation an important research topic in hydrodynamics, but it is also a mathematically important model question used in the research of non-linear partial differential equation. In the year 2000, the Clay Mathematics Institute in the United States offered a million dollar prize to anyone who could solve any of the seven unsolved problems in mathematics, also known as the Millennium Problems (Millennium Prize). One of the seven unsolved problems was to prove the existence of a solution to the Navier-Stokes equation and to prove the concept of smoothness through it.

Computer generated solution to the Navier-Stokes Equation



4-3 Plane of discontinuity and vortex filament

▶ Avoidance strategy of equation of fluid motion

Although both the Euler equation and the Navier-Stokes equation are correctly expressing the motion of fluids, because of their extreme mathematical difficulties, they could not be practically applied to the actual flow of fluid. Since the solution seemed distant, an analytical approach was made without the use of these known equations.

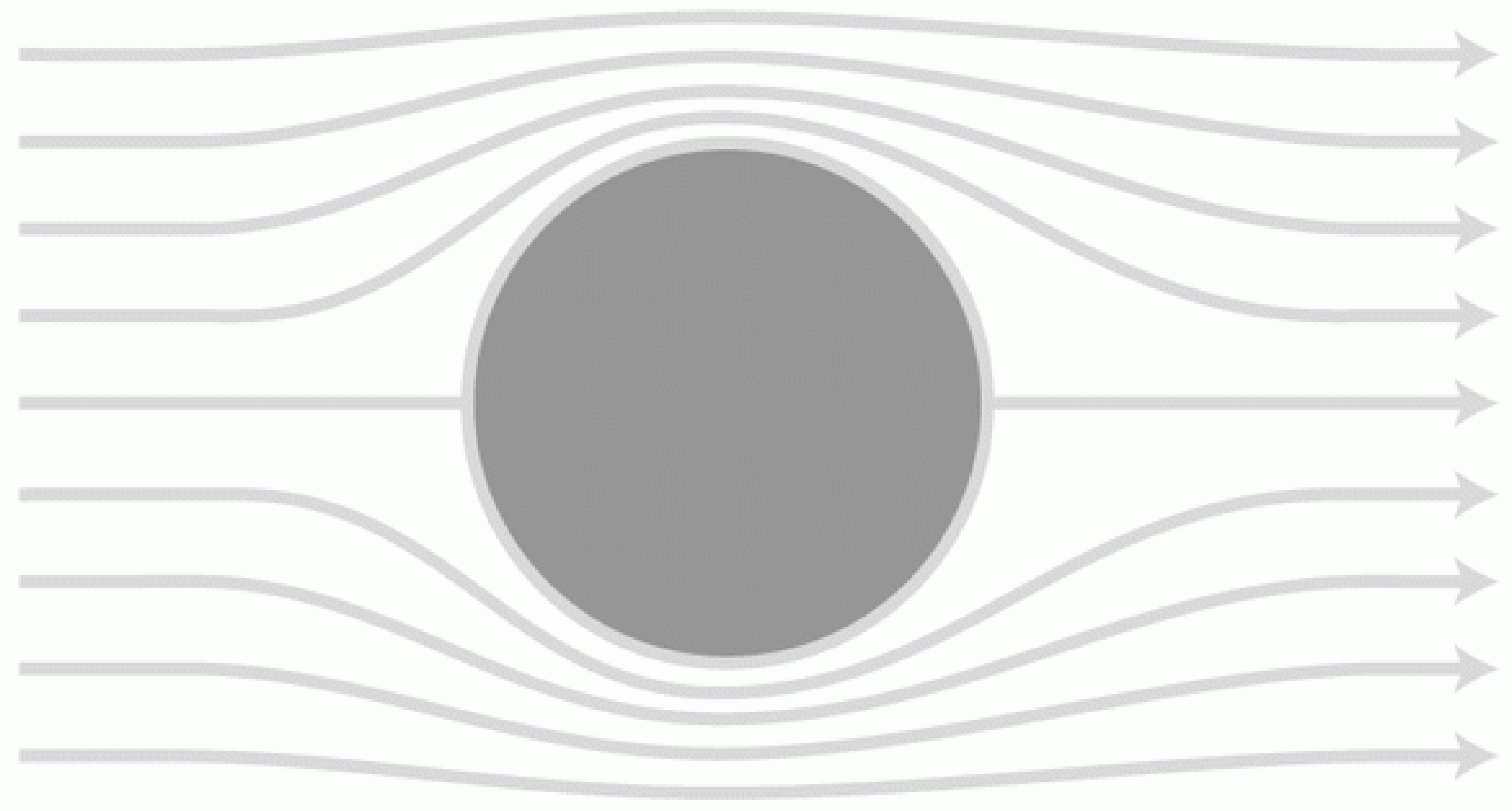
D'Alembert's Paradox

D'Alembert, who was acquainted with both Bernoulli and Euler, sought the theoretical solution to drag (a force that occurs parallel to the velocity of flow in the opposite direction) created by a circular cylinder placed in a two-dimensional uniform on flow. However, the solution he derived was zero, while in reality drag could never be zero. There was no calculation mistakes to his formula and the same answer of zero were repeated numerously by everyone who tried. For the next 160 years, the equation became one of the biggest problems in hydrodynamics, and soon came to be known as "d'Alembert's Paradox."

With today's knowledge, we can understand that none of his calculations were incorrect, and that the answer it derived was logical since the equation did not consider fluid viscosity. Under steady uniform flow conditions where viscosity is not a factor, the flow in front of and behind the circular cylinder would become symmetrical. Therefore, pressure in front of and behind would also be symmetrical which would cancel each other out, resulting in zero drag.

At the time, the Navier-Stokes equation was yet to be found, hence the application of viscosity was not clear. D'Alembert's Paradox was only resolved in 1904 by Ludwig Prandtl with the introduction of the boundary layer concept.

Diagram 4-3-1 D'Alembert's Paradox



Since flow is symmetrical against the center of the cylinder, drag becomes 0.

TIPS The concepts of vortex filaments and discontinuous surfaces expanded to multiple fields of lift force: circulating theory, boundary layer theory and the lifting line theory, all of which will be discussed in the sections to follow. The vortex in hydrodynamics is different from the general image of a spiral. In hydrodynamics, a vortex is defined as a form of movement, that of a rigidly-constrained rotation.

The concept of vortex filament and the plane of discontinuity

The first person to pioneer the way to understand fluid motion mathematically was the German physicist, Hermann von Helmholtz. He expanded the concept of vortex to invent a new understanding of flow.

Think of a fluid element flowing from left to right as per diagram 4-3-2. When the surface of the fluid element is exposed to shearing stress (a force that works to shear a material. See 2-1), a difference in the speed of the fluid element travelling across the surface emerges. As a result, the fluid element begins to rotate creating a vortex. If such vortex is seen from a cross sectional view, it would look like conceptual filaments with infinitesimal size. These are called vortex filaments. The layer created from the gathering of these vortex filaments is called the vortex layer.

By implementing the concept of vortex filaments, as illustrated in diagram 4-3-3, discontinuous planes of speed which occur when flows of different velocity merges (a plane where the continuity of value changes drastically), and boundary layers where the fluid velocity changes drastically around objects can be dealt with in mathematical terms. Such flow can be interpreted as being formed from the rotational movement of fine fluid elements, therefore applying the same mathematical approach already existent to a vortex.

When Helmholtz introduced the concepts of vortex filaments and vortex layers, a light of hope to solve the century's biggest mystery, the d'Alembert's paradox was envisioned. Right after Helmholtz presented the surface discontinuity concept, Kirchhoff and Rayleigh began to calculate the force of drag on a flat plane. According to the d'Alembert's paradox, the drag force on a flat plane is zero. However, if an assumption could be made that a discontinuous surface existed beyond the front and back edges of the plane, the opposite surface can be assumed to have lower fluid velocity, nullifying the existence of the d'Alembert's paradox. Unfortunately, attempts by Kirchhoff and Rayleigh failed since their estimates of pressure on the assumed opposite surface of the flat plane was too high, but the path being taken was certainly headed toward the right direction.

Diagram 4-3-2 **Concept of vortex filament and vortex layer. In order to better illustrate the concept of vortex filaments, the vortex filaments are drawn in a certain size; however, the cross sectional area of a vortex filament is infinitesimal.**

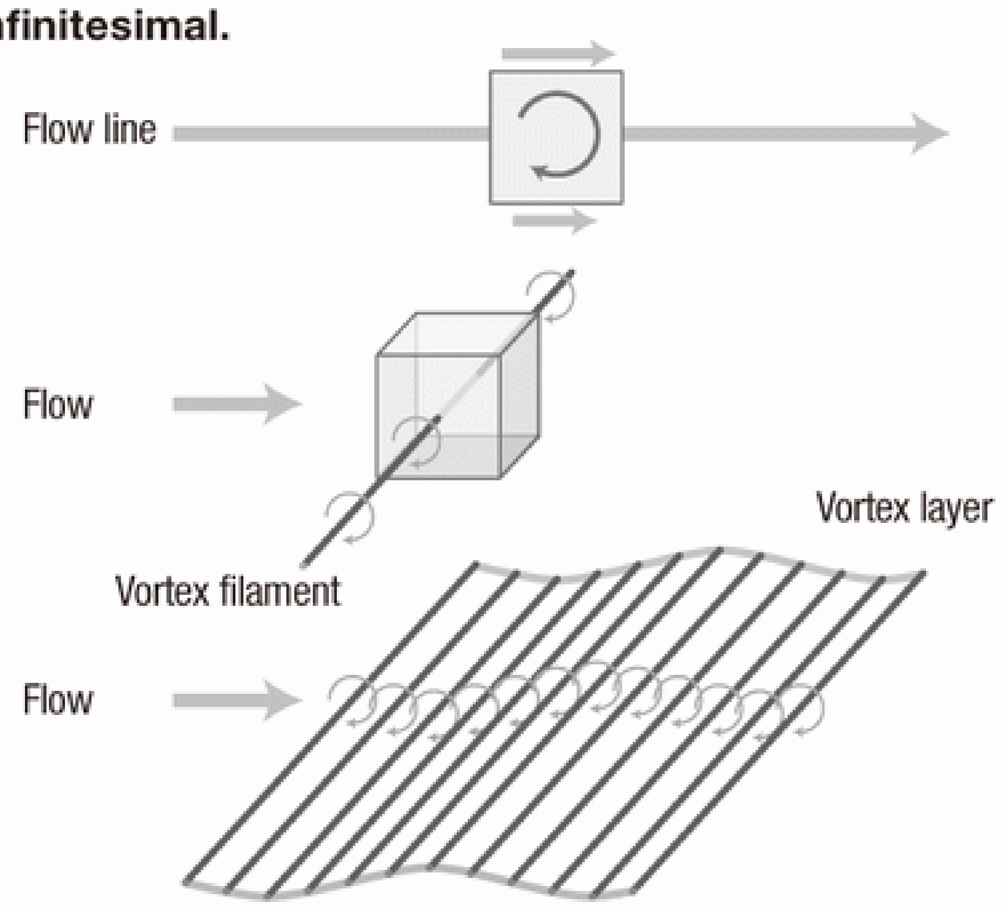


Diagram 4-3-3 **Difference in force from high and low velocities on a discontinuous surface**

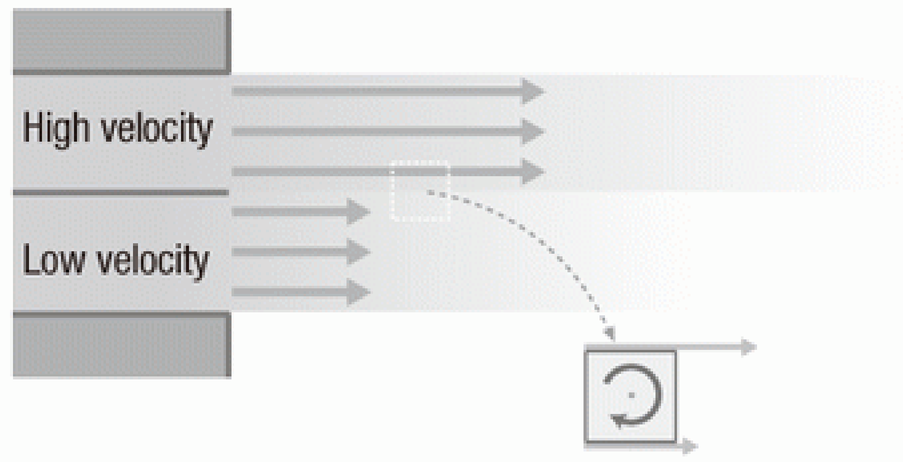
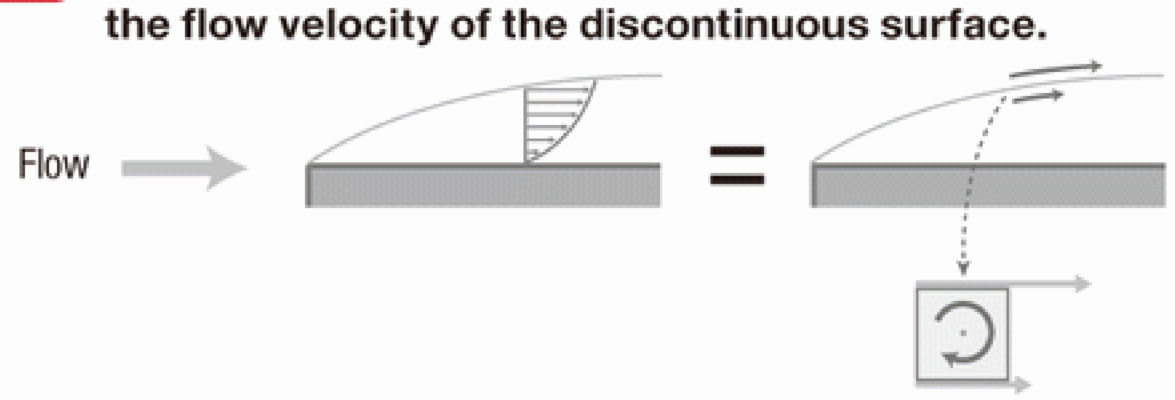
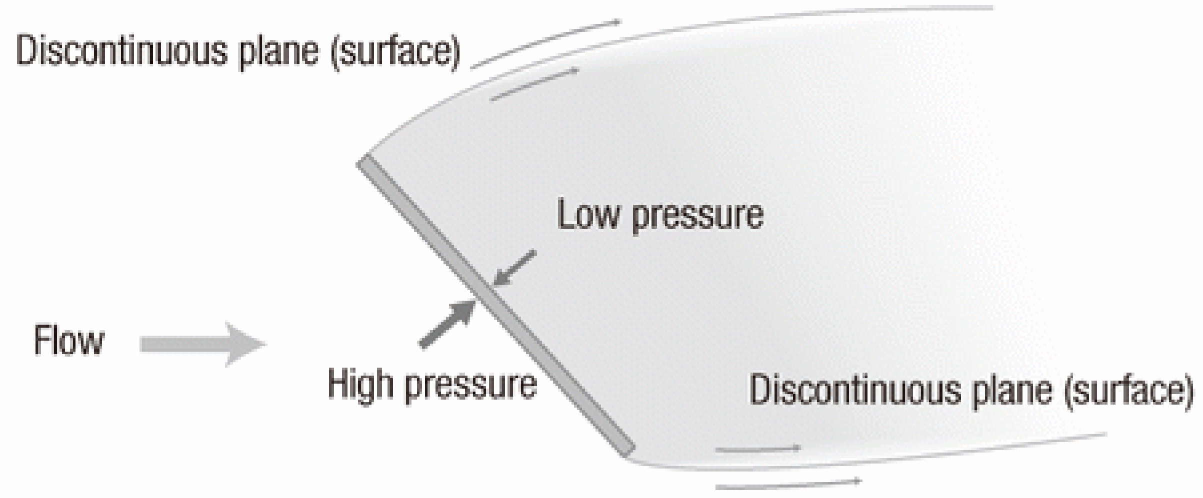


Diagram 4-3-4 **Applying the vortex filament (vortex layer) concept to the flow velocity of the discontinuous surface.**



The boundary layer can be considered as part of the flow velocity for the discontinuous surface.

Diagram 4-3-5 **Conceptual diagram of a flow field around a flat plane (surface). If the discontinuous planes of the front and back edges of a flat plane could be assumed to exist, then d'Alembert's paradox would not come into play.**



4-4 Kutta-Zhkovsky's Theorem

▶ Circulation theory of lift

Kirchhoff and Rayleigh made a hypothesis that the discontinuous surface forms around the part of the acute angle. That said, such discontinuous surface can be formed from anywhere on the surface of an object, and an argument can also be made that the surface of an object is covered withvortex layers. Truth is, the theory of lift is significantly related to the circulation theory of lift.

Kutta-Zhkovsky's Theorem

Flow velocity dramatically changes due to the viscosity on the surface of an object, hence leading to vortex filaments that become vortex layers which envelop the surface of the said object. The strength of such vortex layers that covers the object surface is called "circulation." On such premises, flow around the perimeter of the material can be separated into two artificial flows; one is the uniform flow (stream) and the other is circulation flow (from a different perspective, circulation is the amount derived by integrating flow velocity along the arbitrarily selected horizontal curve).

As discussed in the previous paragraph, based on the existence of an uniform flow and circulation flow, let's consider a flow with both types occurring simultaneously overlapping each other. In this example, the top part of the circulation flow is flowing in the same direction as the uniform flow,, hence flow velocity at the top increases. On the other hand, the circulation flow at the bottom is flowing in the opposite direction to the uniform flow, so when overlapped, the flow velocity decreases. As a result, according to Bernoulli's Theory, pressure decreases at the top while pressure increases at the bottom of the circulation flow,, thus generating an upward lift. (Diagram 4-4-1).

This model actually resembles the flow field surrounding an airfoil. The airfoil is made to correspond to the flow velocity rise on the top surface, which decreases pressure and the decrease in flow velocity on the bottom surface increases pressure. The flow field around the airfoil can be considered to be an overlap of uniform flow and circulation flow, and if there is circulation, the lift can be calculated with the following equation. (Diagram 4-4-2)

Lift = Flow density x Velocity of uniform flow x Vortex circulation ($L=\rho V\Gamma$)

This theory was introduced independently by Martin Wilhelm Kutta and Nikolai Zhkovsky, and hence is called the Kutta-Zhkovsky Theory. This theory tells us that, regardless of the shape and size of the object, if there is circulation, the lift from the object can be determined.

Diagram 4-4-1 Flow field with overlapping uniform flow and circulation flow

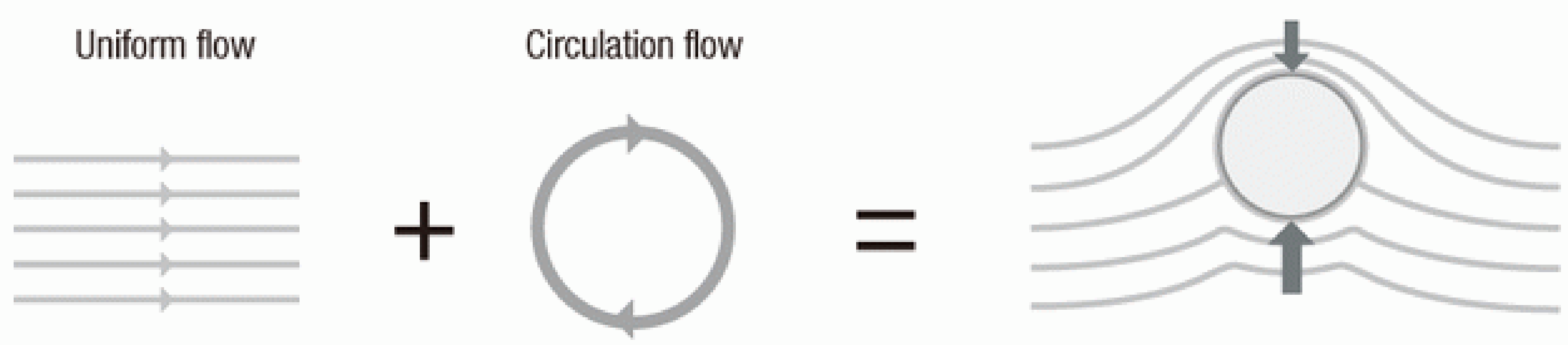
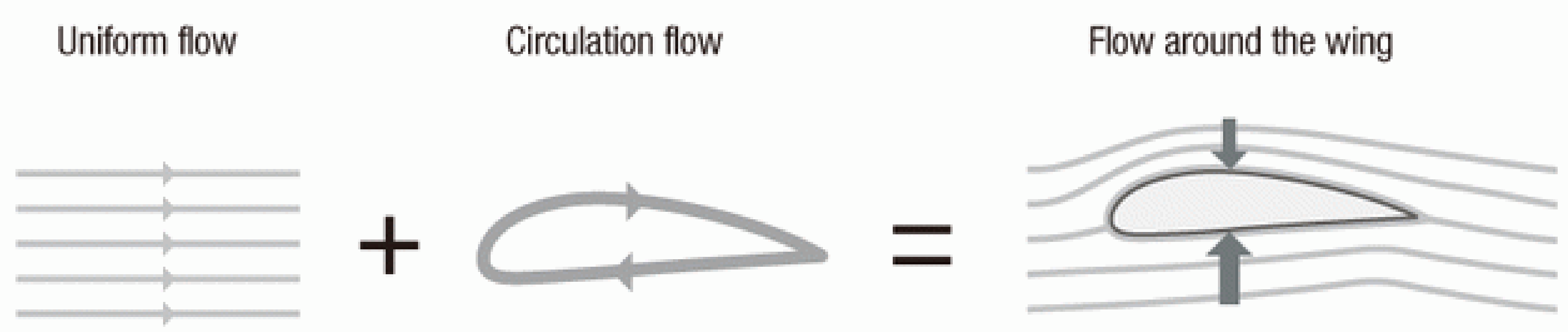


Diagram 4-4-2 The flow field around an airfoil can be said to be a combination of uniform flow and circulation flow



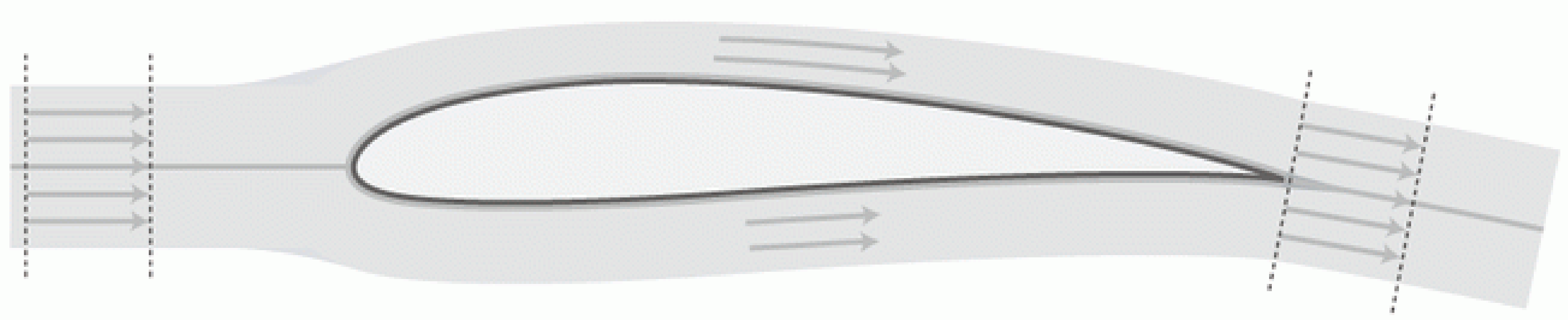
Kutta's Condition

From the Kutta-Zhukovsky Theorem, we have found that the lift of an object can be calculated if the circulation around the object is known. However, to implement this theory to an airfoil, one factor must be considered. In general, fluid equation is based on the concept that the flow is smooth, and that special consideration needs to be taken if the object is sharp or the flow is discontinuous.

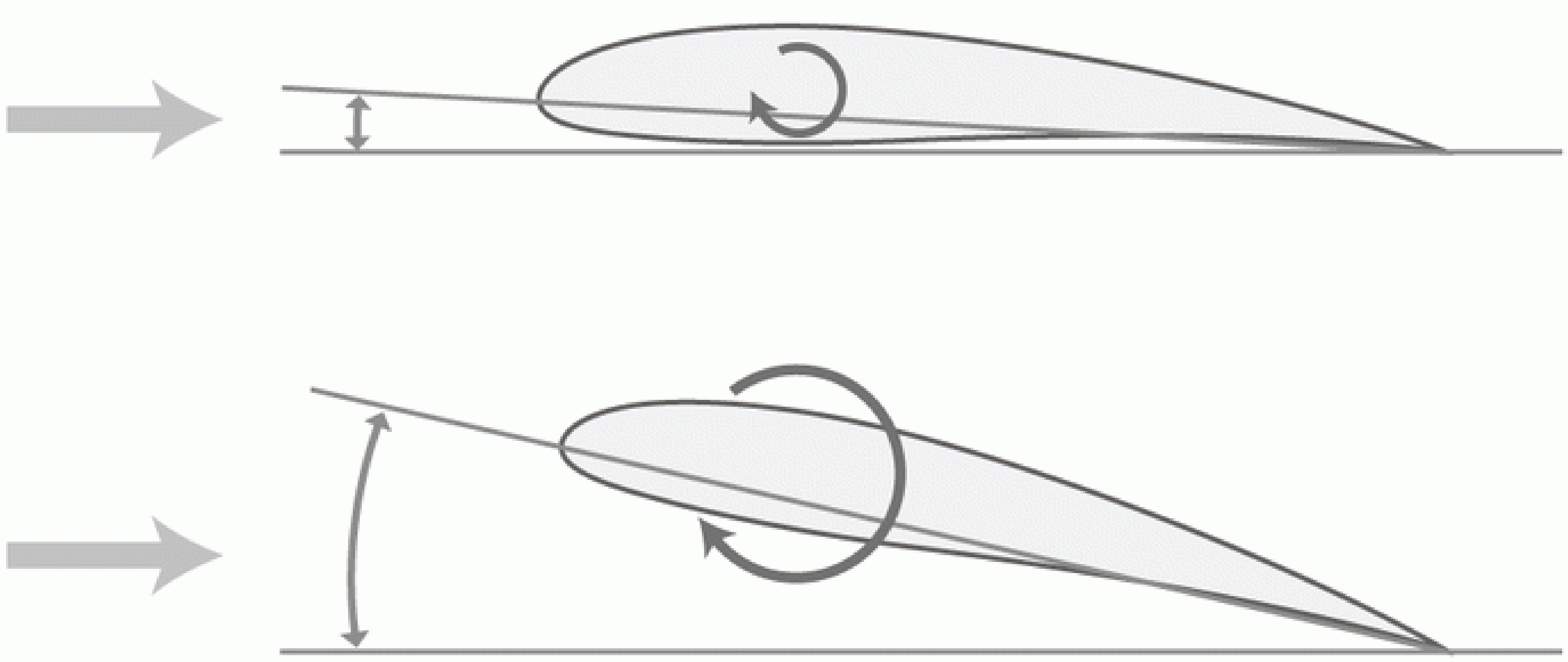
When an airfoil is taken as an example, the back edge of the airfoil is sharp. Thus, unless the flow over the top and the flow underneath the airfoil can converge smoothly at the back edge, the Kutta-Zhukovsky Theorum cannot be applied to an airfoil. This required condition that the top and bottom flow must converge smoothly is called Kutta's Condition. By applying Kutta's Condition, circulation can be finally determined and lift can then be mathematically calculated.

If an angle of attack is set on a wing against the flow, the larger the angle is, the more the circulation is required to meet Kutta's Condition. Hence, the greater the angle of attack, the larger the circulation; thus greater lift is naturally created.

Diagram 4-4-3 **Kutta's Condition and circulation**



Kutta's Condition: The flow on top and at the bottom of the wing converge at the back edge smoothly and at the same velocity.



The larger the angle of attack, the more circulation is required to meet Kutta's Condition.

4-5 Prandtl's Boundary Layer Theory

▶ Friction only affects the vicinity of an object's surface

Although the drag calculations of Kirchhoff and Rayleigh were not successful, they were in fact on the right track. Here we will introduce Prandtl's Boundary Layer Theory which finally solved d'Alembert's paradox.

Prandtl's Boundary Layer Theory

In order to correctly estimate drag, not only is the pressure important, but also crucial is how the frictional force is handled. To understand frictional force, one must correctly know the flow condition on the object's surface. However, in order to properly calculate frictional force, the question of whether a fluid can completely adhere to an object's surface when the fluid velocity is zero, or whether the fluid slides atop the surface at any given speed, remains to be answered.

Ludwig Prandtl approached this difficult issue by being the first to apply the concept of boundary layer. He found that the effects of viscosity made flow velocity on an object's surface zero—the effects of friction only affected the vicinity of the object's surface. Outside of this, the flow is not affected by viscosity and it could be defined as an inviscid fluid. The area of the object's surface vicinity that is affected by viscosity is currently known as the boundary layer.

In 1904, Prandtl published a short 8 page paper titled "Flussigkeitsbewegung Bei Sehr Kleiner Reibung" (Fluid Flow in Very Little Friction) in which he first introduced the concept of boundary layer. He applied the Navier-Stokes equation to only a particular flow in the boundary layer. This led to the birth of the boundery layer equation, a simplified equation of the Navier-Stokes Equation. This equation was much easier to handle than the complete Navier-Stokes Equation and allowed a more logical and accurate calculation of drag.

The boundary layer theory also helped to better estimate the point of flow exfoliation (detachment). With these findings, d'Alembert's paradox was finally solved with Prandtl's Boundary Layer Theory. The 1904 paper by Prandtl expanded a new scope in hydromechanics and is now considered to be one of the most important papers in the hydromechanics academia.

Diagram 4-5-1 **Boundary layer velocity distribution of an airfoil surface. The range of the boundary layer is defined as less than 99% of the fluid velocity outside the object's surface vicinity.**

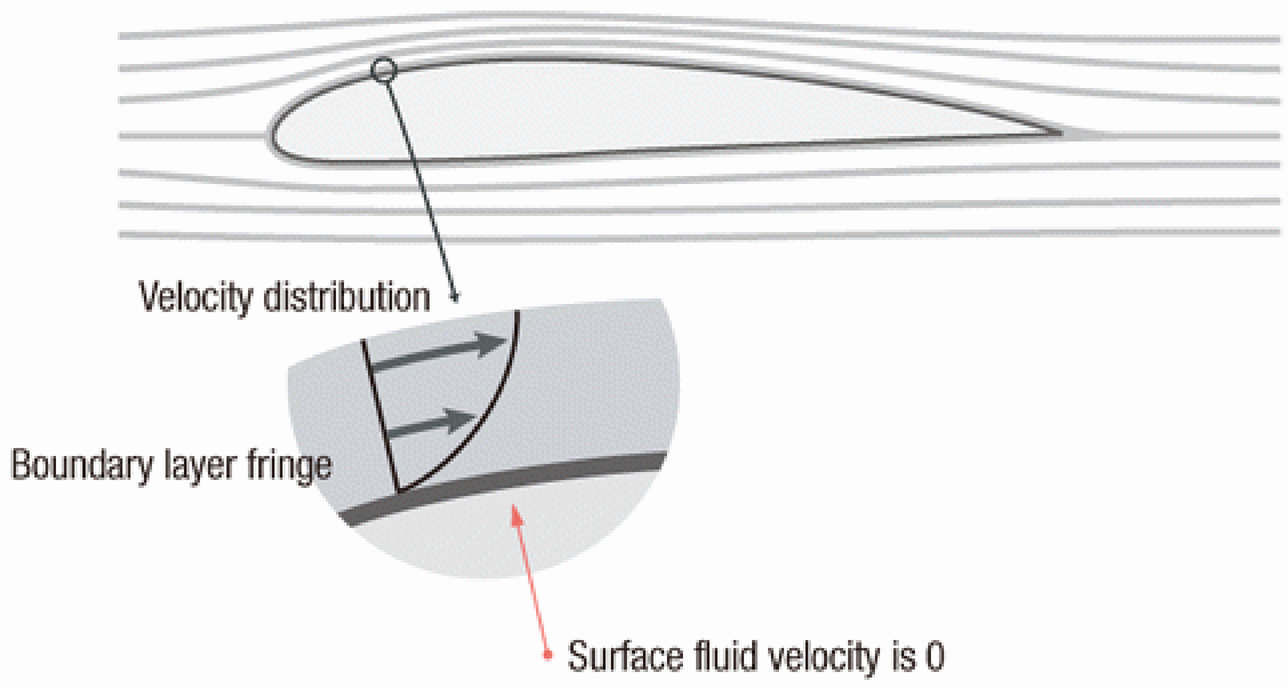


Diagram 4-5-2 **Point of exfoliation on an airfoil and velocity distribution in the boundary layer.**

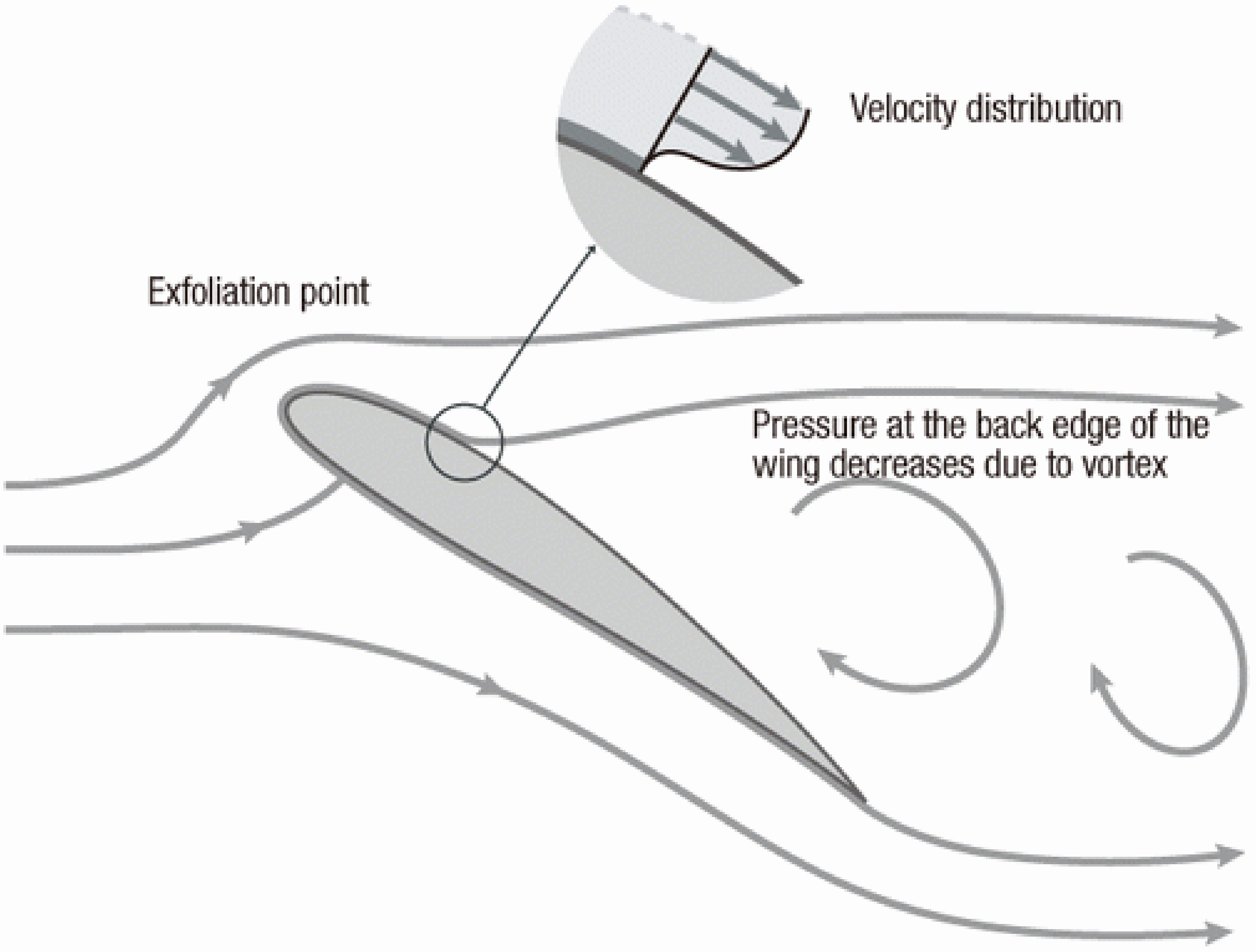
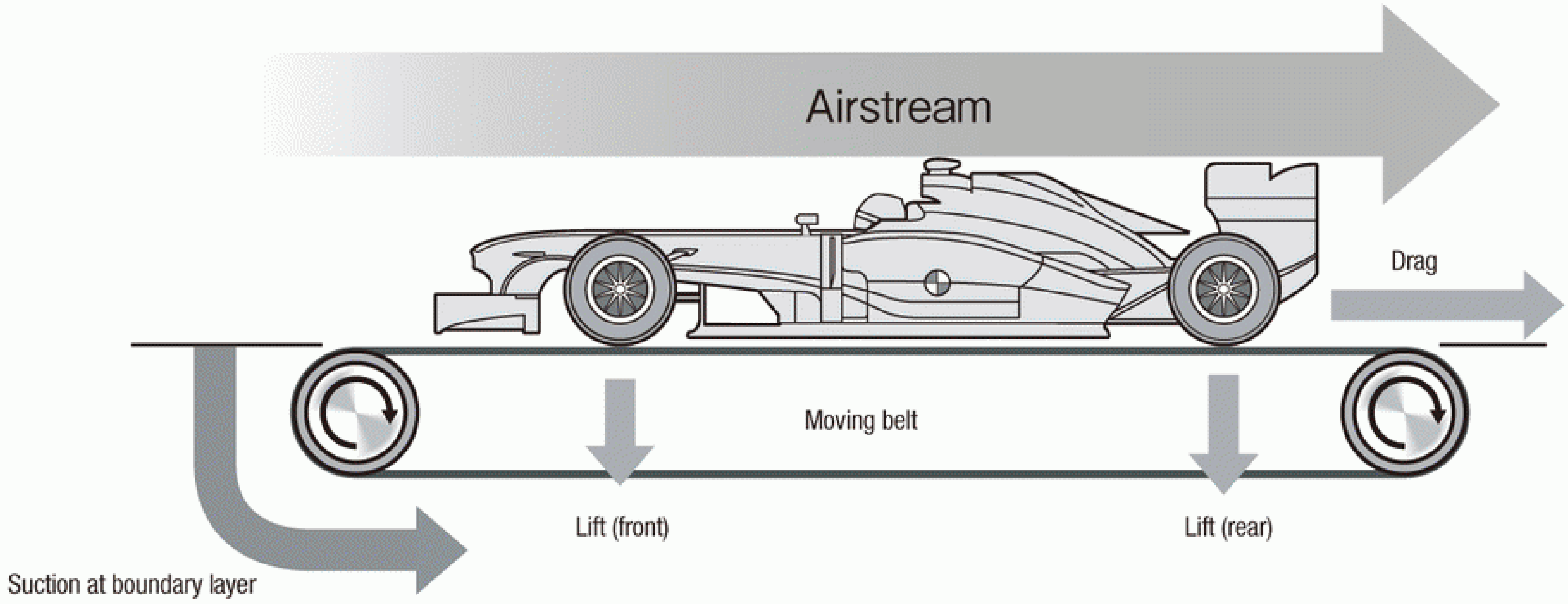


Diagram 4-5-3 **A vehicle that runs on land is greatly affected by the ground in terms of aerodynamics. In a natural outdoor environment, a boundary layer would not exist around the surface vicinity underneath the vehicle. However, in a wind tunnel test, boundary layers are formed along the tunnel walls. Flow velocity is slow in the boundary layer, and as a result, it essentially blocks the flow passage underneath the vehicle. This creates a completely different flow field in the tunnel, compared to the outdoor environment. For racing cars that are delicately designed to create down force between the bottom of the car and the ground, such difference in flow field became a significant issue. As a solution, a moving belt was introduced in the wind tunnel to mimic the outside road surface environment. The moving belt not only helps to replicate the rotational movement of the tires, but it also prevents the formation of a boundary layer beneath the vehicle within the wind tunnel.**



TIPS Originally, Prandtl used two phrases to describe his concept. One was "boundary layer" and the other was "transition layer." He actually used the latter phrase more often. However, Prandtl's students used the phrase "boundary layer" more often and that phrase is the only one that remains of today.

TIPS Prandtl's contribution to hydromechanics cannot be overstated. In addition to the boundary theory, Prandtl introduced the lifting line theory, the mixing length hypothesis and the supersonic shock wave theory, all which have become the structural principles of modern hydromechanics. Furthermore, he has produced quality graduates from his class such as Blasius, Karman, and Munk who all became highly recognized scholars in the field of hydromechanics.

4-6 Prandtl's lifting line theory

▶ Wing tip vortex generation on finite wings

Through Kutta and Zhukovsky, the circulation theory of lift was born and accurate lift calculation of a two-dimensional flow became possible. However, wings and its flow and circulations are three-dimensional, so two-dimensional flow cannot be applied as is. A new theory on the force of lift in a three dimensional field of flow had to be structured.

Flow around a limited wing span

As explained in "4-1 Tips!", an airfoil is a wing with an infinite wing span. A wing with an infinite wing span will have the same sized circulation regardless of location on the wing, and the lift would be constant as well. As such, the Kutta-Zhukowsky Theory can be directly applied to a wing with an infinite wing span.

That said, an actual wing has a limited wing span. At the edge of the wing, flow will try to go from the bottom of the wing where pressure is high to the top of the wing where pressure is lower. Therefore, the pressure distribution on the surface of a limited span wing differs compared to the infinite wing span model, and lift declines as it gets closer to the tip of the wing. Flow circulates from the high pressure side to the low pressure side causing a vertical vortex as it goes downstream. Such vortex that is generated at the wing tip is called the wing tip vortex.

Diagram 4-6-1 Flow around the wing with limited wing span

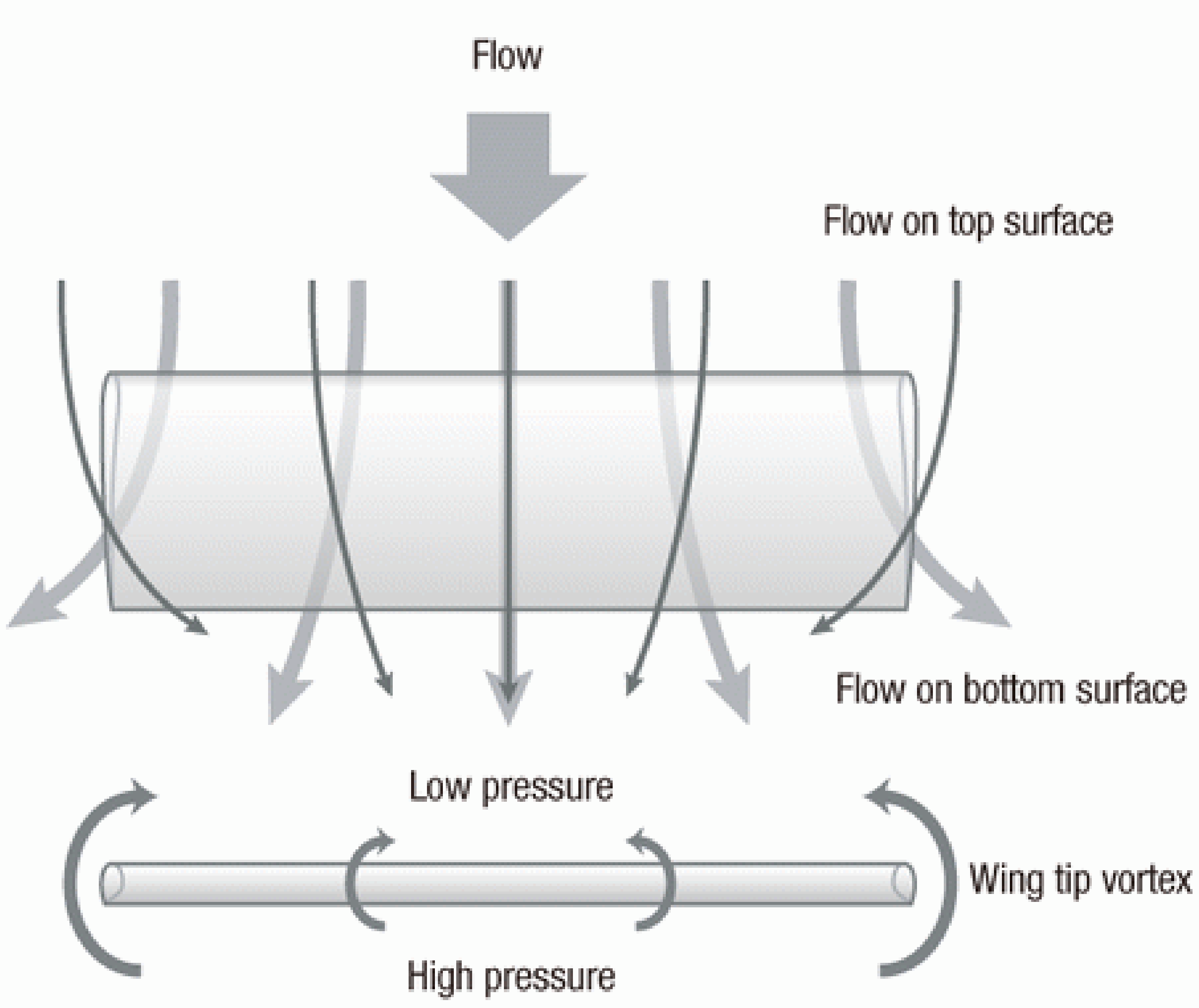


Diagram 4-6-2 Circulation and lift of wings with an infinite wing span and limited wing span

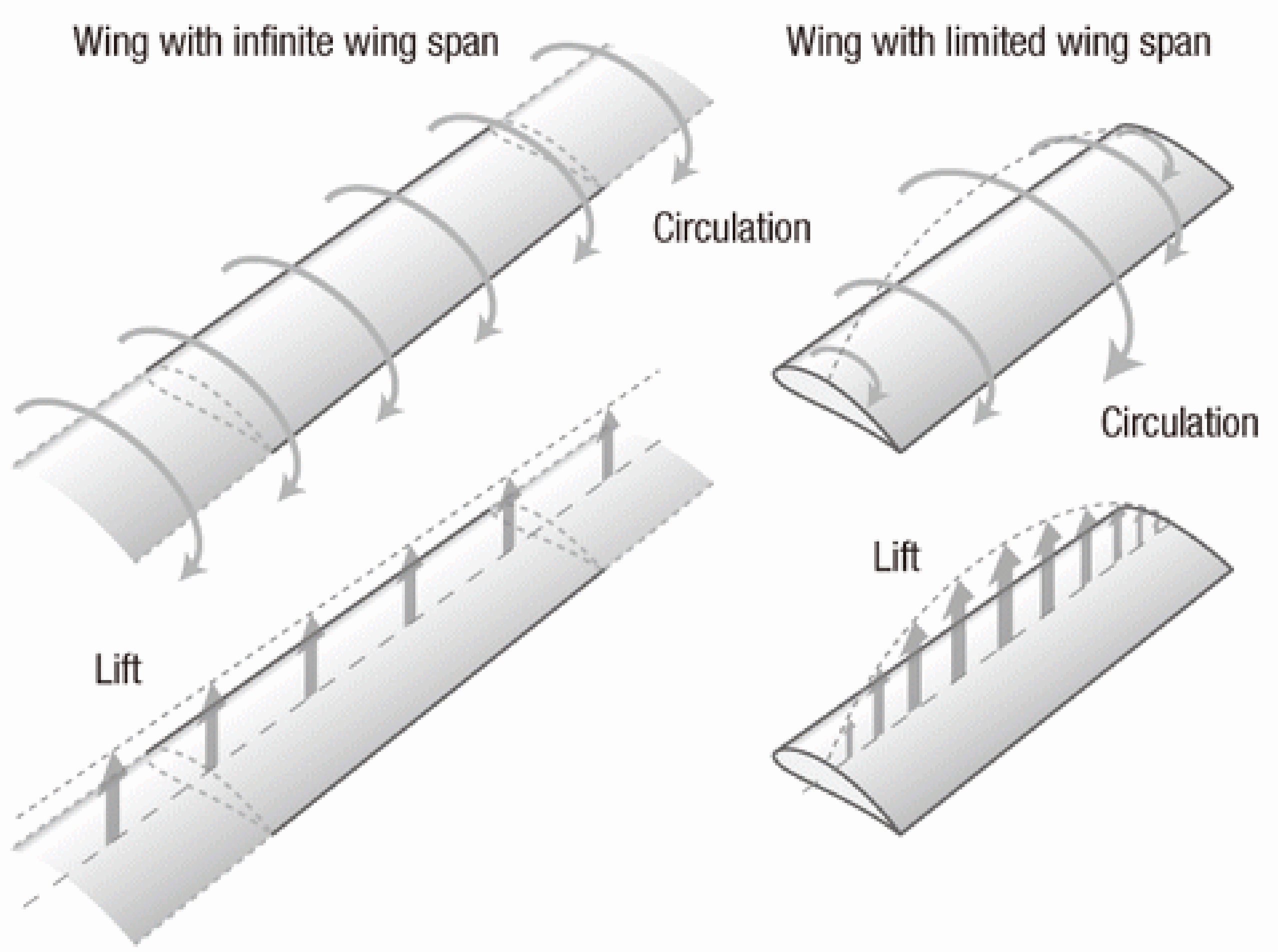
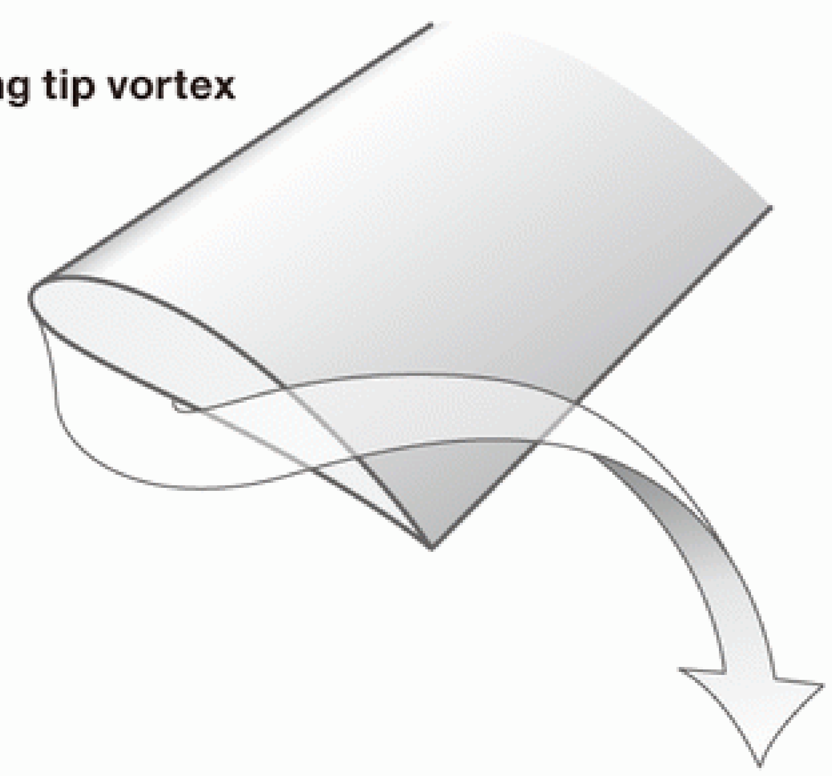


Diagram 4-6-3 Wing tip vortex



Prandtl's lifting line theory

An English man named Frederick Lanchester produced a model of flow around the wing with a limited wing span using Helmholtz's vortex filament concept. He made an assumption that circulation was formed around the wing by vortex filaments, and that the vortex filaments bent toward the downstream of flow at the wing tip, creating a new circulation. He believed that the flow around a wing with a limited wing span consisted of an "uniform flow upstream," a "vortex layer parallel to the wing tip," and a "vortex filament flow going from the wing tip to downstream." By combining these flow elements, Lanchester believed that the lift of a wing with limited wing span can be derived. However, he could not give a precise mathematical expression to his theory, thus it was not approved by the academic community of that time.

The theory for a wing with limited wing span was completed by Prandtl, who had also authored the boundary layer theory. Prandtl's theory of lift for a wing with limited wing span was very similar to Lanchester's model, but he was able to give a mathematical reasoning to back up his theory.

Prandtl's model was based on vortex filaments of infinite weakness, bundled together by an infinite amount, then placed on the wing surface bent downstream. These vortex filaments are called lifting lines.

Prandtl's lifting line theory enabled the calculation of lift force and torque which can be generated from a wing with a limited wing span. Also the existence of induced drag generated by the downwash from the wing tip vortex was confirmed. This helped to theoretically prove that induced drag became smaller when the wing span (aspect ratio) of a wing became larger.

TIPS Wing tip vortex, as illustrated in diagram 4-6-3, occur when high pressure underneath the wing creates a flow going upward to the top surface of the wing where pressure is lower. For the wing tip vortex to be generated, there must be a constant source of energy. If that energy is being made by an engine, it means that there is waste through fuel consumption. In real life, downwash in conjunction with the wing tip vortex affects the pressure field of the wing, causing pressure induced drag. Since this is a drag that is caused from the flow induced by lift, it is called "induced drag." Prandtl has indicated that the wing tip vortex reduces lift. This is because the downwash from the vortex reduces the effect of the angle of attack. It should also be noted that the wing tip vortex was first discovered by Lanchester. (Diagram 4-6-6)

Diagram 4-6-4 Conceptual diagram of the lifting line theory

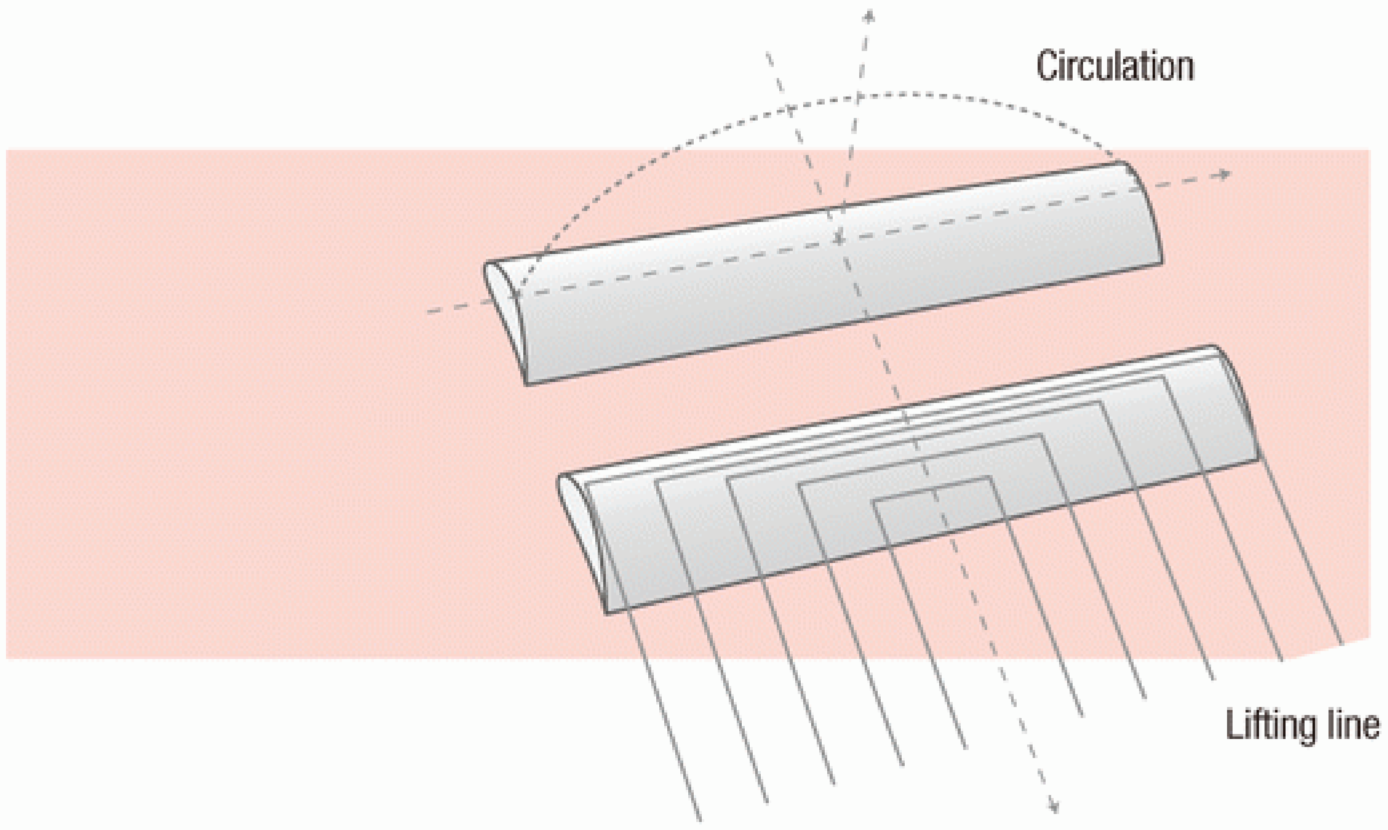


Diagram 4-6-5 Lanchester's illustration of the vortex around the wing

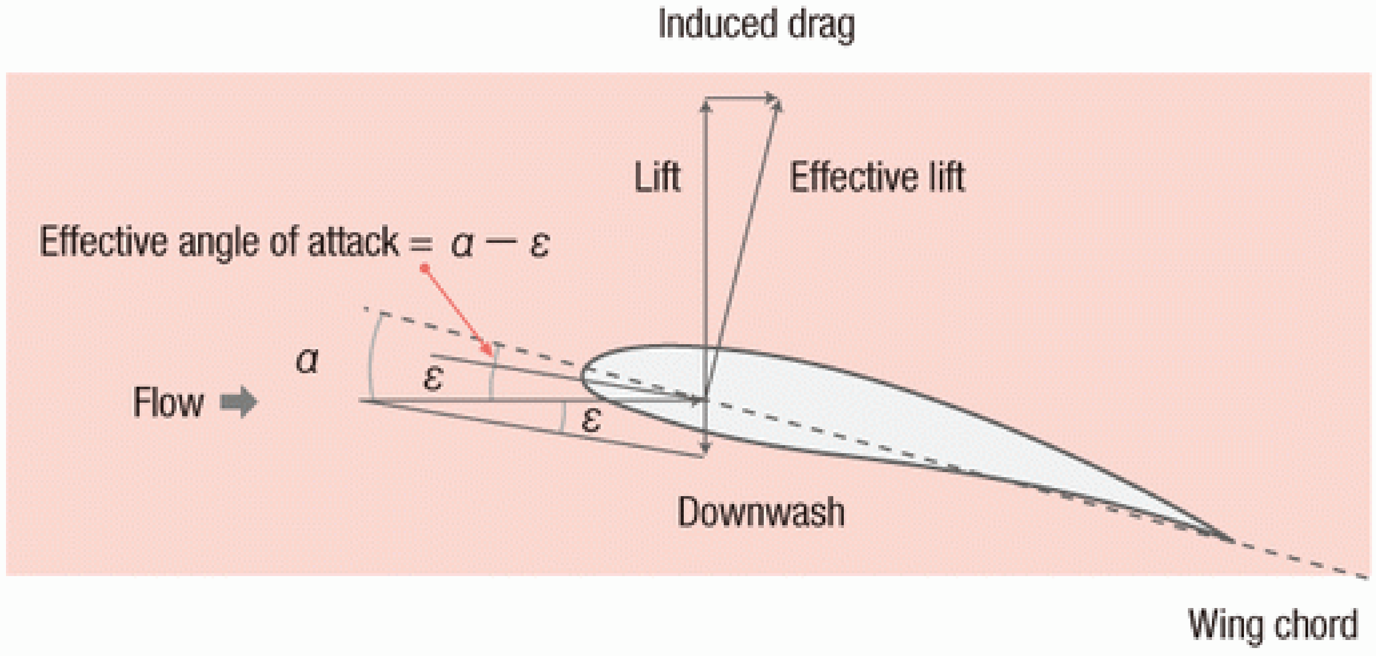
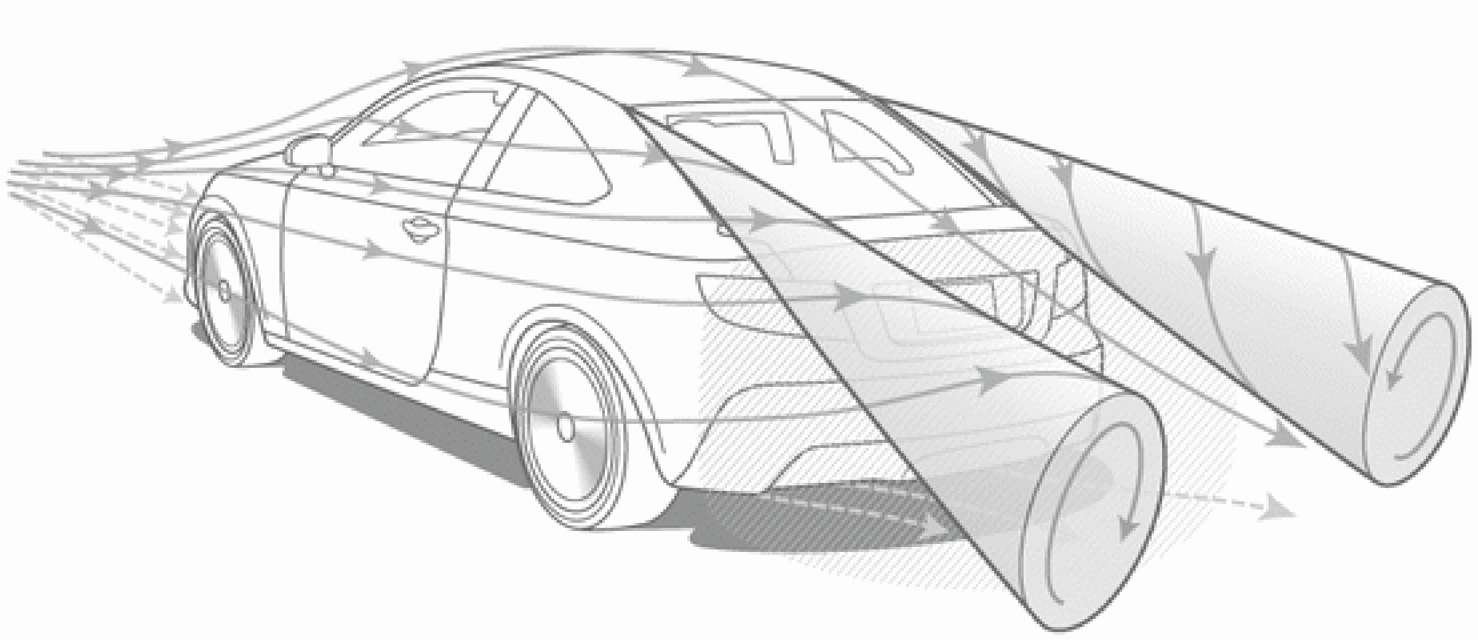


Diagram 4-6-6 Longitudinal vortex generated from a car's chassis



5-1 The World of CFD

▶ CFD—a world of discretization

We've already introduced the theory of aerodynamics in a previous chapter, but those were largely meant to keep us clear of the subjects that were not clarified yet, such as the Navier-Stokes equation. But, in order to further accurately understand the concept of the field of flow, one needs to solve fluid equations such as the Navier-Stokes equation. As such, great advancements in the methods for numerically solving fluid equations through the use of computers were spurred with the breakthroughs in computer technology from the latter part of the 20th century.

This is the field of "Computational Fluid Dynamics" (computational fluid dynamics, or numerical fluid dynamics), often referred to as CFD. CFD has been an essential automotive development tool for some time now, but it is not well known by the general public. To understand the basics of how CFD works, let's take a brief look at its theoretical concepts.

Approximation

The real world is in analog. One way to see it is as a smooth continuum, so that any given point in an infinite space-time continuum produces some kind of physical data. Even in theoretical fluid dynamics, fluid is basically regarded as a smooth, ever-changing continuum. On the other hand, computers are digital, so they can only handle fragmented and/or discontinuous values, and hold limited information. Therefore, CFD splits up the smooth continuum of space and time, and handles it in a discontinuous way. Keep in mind, however; that the goal of CFD is to, as much as possible, represent the smooth continuum that is the real world. In order to do so, information not held by computers needs to be modeled and complemented.

So how do you complement this missing information? It is done by simply connecting the information within the computer with a straight line, and treat missing data as something that changes on this straight line. Or, we can complement using a curved line model that displays changes as a curve where information may be missing. This process of simplifying information without losing the original properties is called an "approximation," and the process of obtaining a value close to the original using this approximation is called an "approximate value." In CFD, the above approximation method is called a "scheme."

Diagram 5-1-1 **The difference between the real world and the world of CFD**

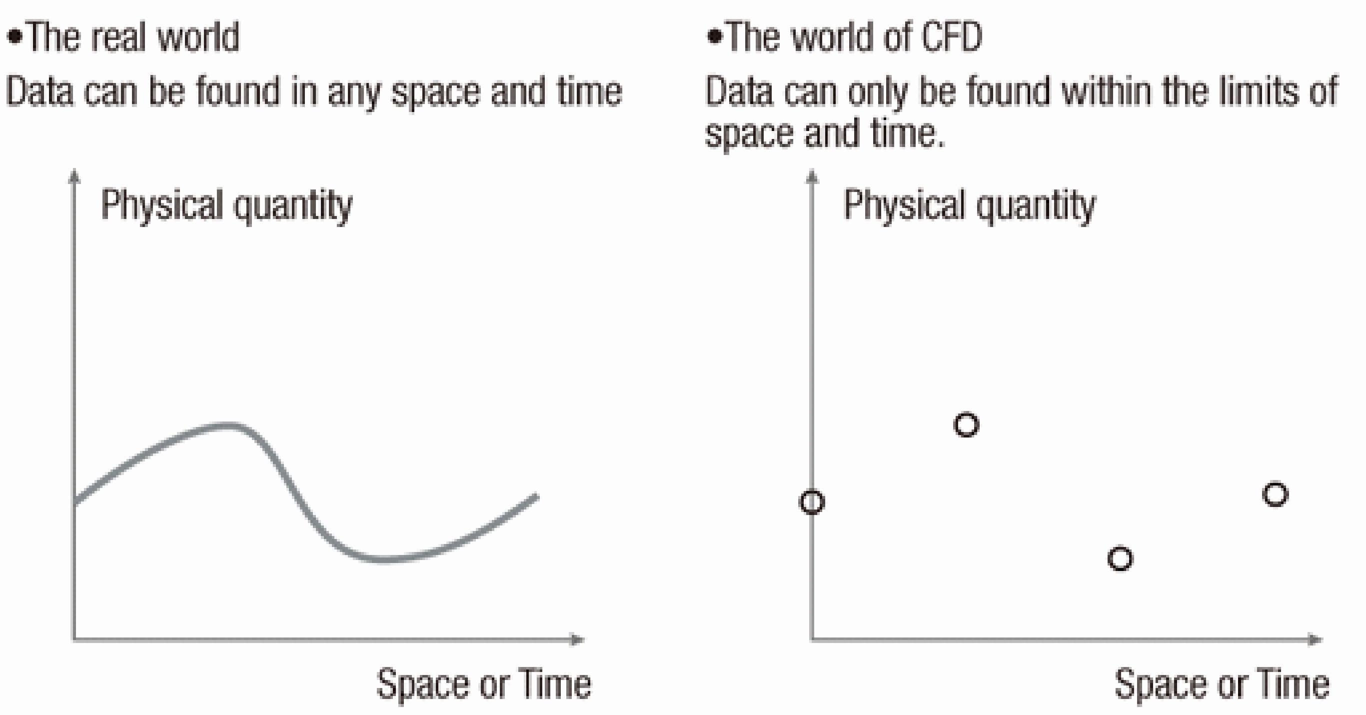
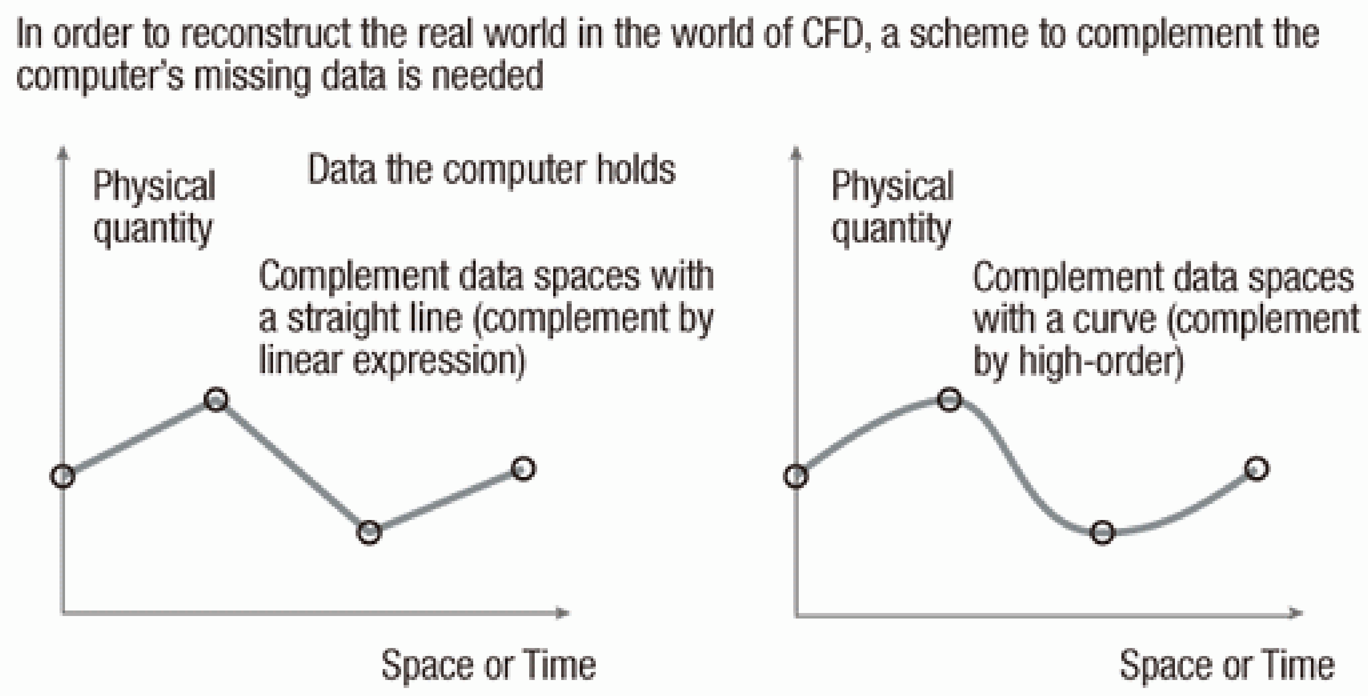


Diagram 5-1-2 **Complement missing data from computers**



The Lax Equivalence Theorem

Since computers cannot contain information about all the time and space in the real world, calculation results obtained by CFD are of an approximate value. However, if the difference from the true value is small enough, from a practical standpoint, there are essentially no issues. For instance, when the average flow velocity in a flow field is 30m/s, it makes no pertinent sense to consider a digit value of 0.000001. A person analyzing a flow between 30m/s and 30.000001m/s would regard them as virtually being the same value. Therefore, such minimal digit values can be ignored, and in like manner, if the results from a simulation produce similar minimal differences, so long as it is minimal enough, it is not of concern. To express this in technical terms, the calculation result from a simulation is acceptable so long as the result is "converged" to the true value.

So let's introduce an important theorem here known as the "Lax Equivalence Theorem" which was demonstrated by Peter Lax. This theorem states that "the only scheme that can converge is a scheme that can conform stably." In other words, the relationship of [stability + conformability = convergence] is the Lax Equivalence Theorem. Please look at diagram 5-1-4 for the meanings of "conformability", "stability" and "convergence."

Diagram 5-1-3

Lax Equivalence Theorem

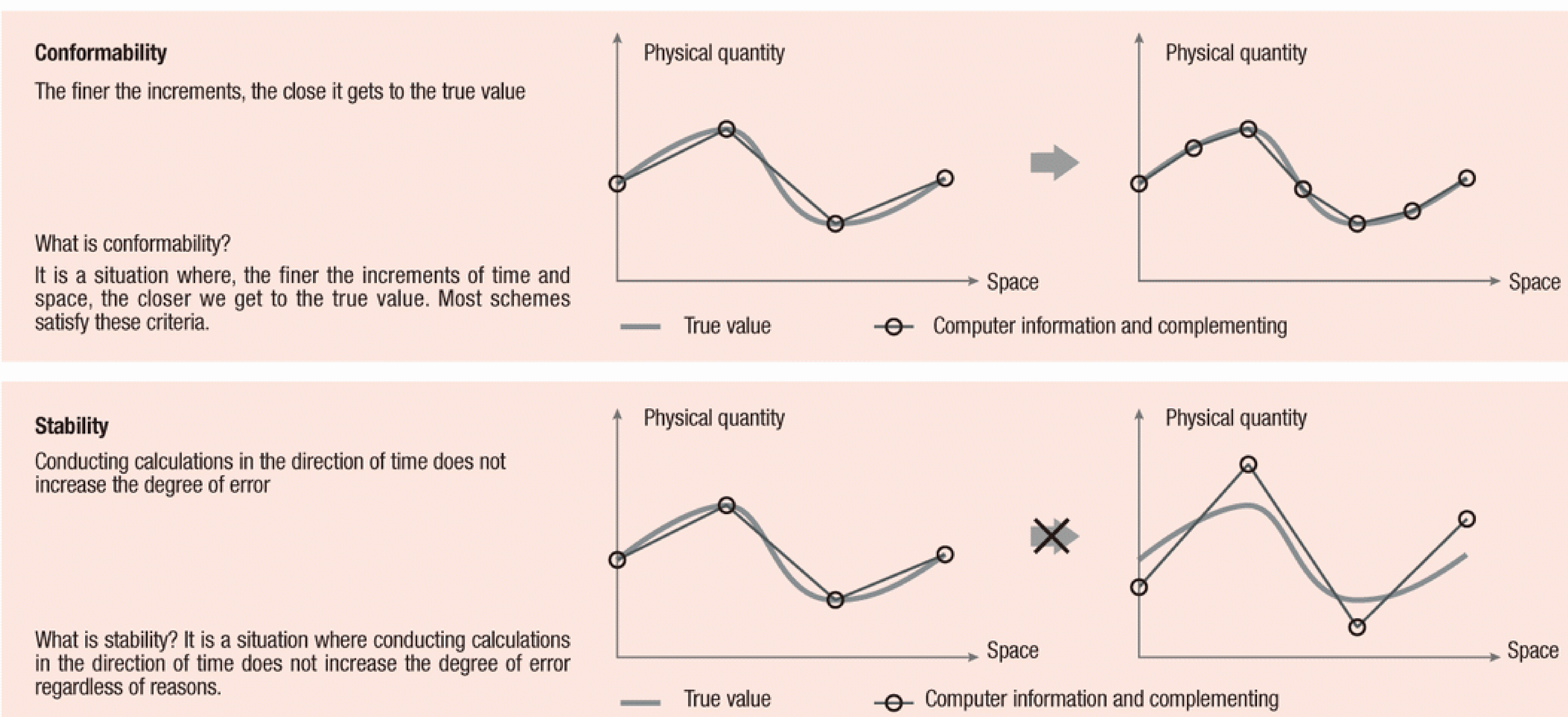
Stability + conformability

⬆⬇

the calculation converges

TIPS The Lax Equivalence Theorem states that both the linear and scalar time evolution equation fulfills the criteria of stability and conformability for convergence through the difference equation. In other words, when convergence is done and the grid increments are fine, the difference solution closes back to its original differential equation.

Diagram 5-1-4 **Conformability and stability. "True value" referred here is the solution that is obtained when analytically solving partial differential equations of fluid.**



5-2 Finite volume method

▶ The most widely used fluid simulation technique

While many fluid simulation techniques have been devised, let's introduce a technique that is currently the most widely used, called the "finite volume method."

Concept of the finite volume method

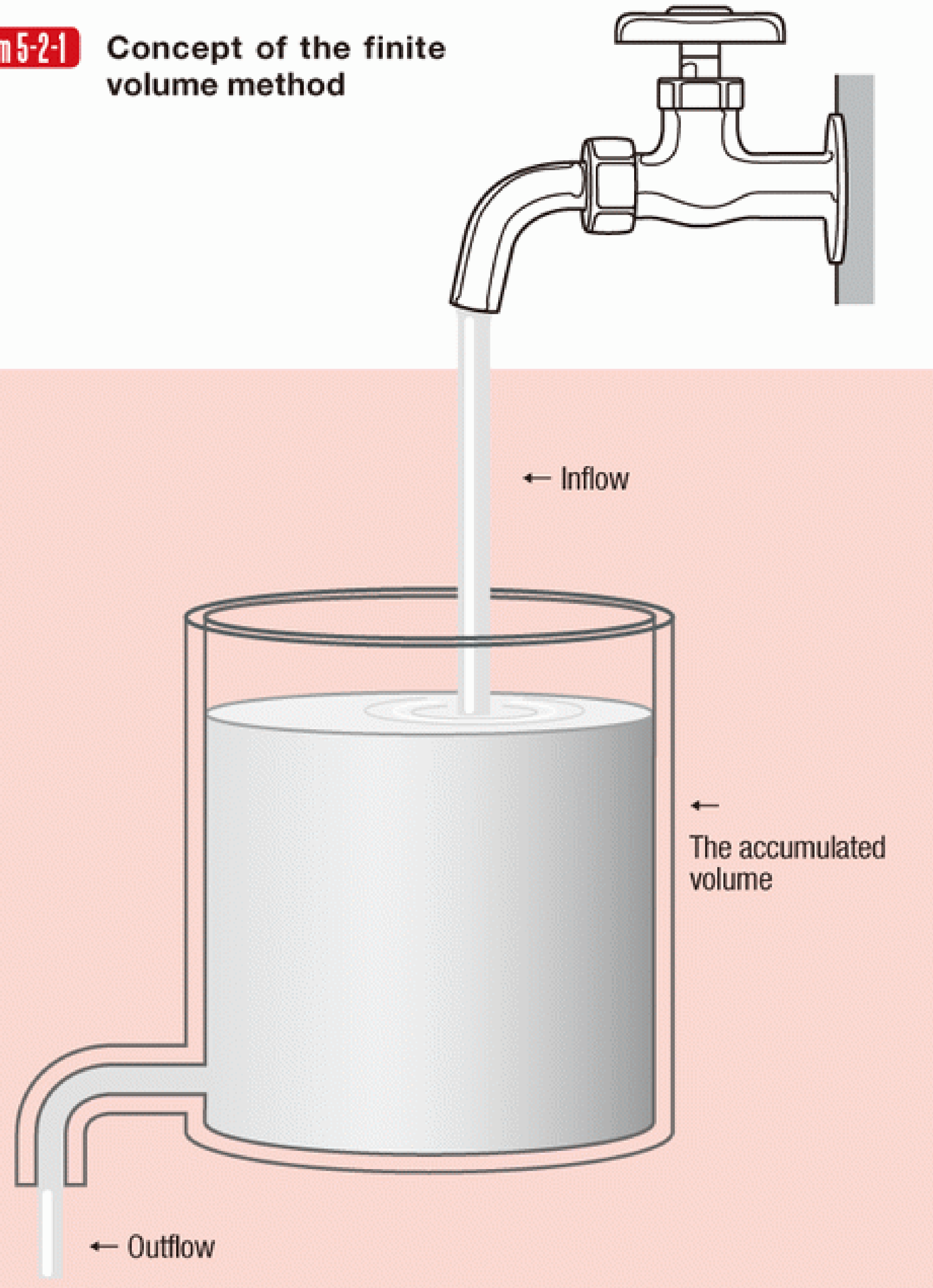
The finite volume method places attention towards the balance of volume which flows in and out of each divided space elements. For instance, consider the volume of water flowing into and out of a container. In order to calculate how much water is in that container one second later, the following equation can be used:

Volume in a container after 1 second = Original volume + Inflow per second - Outflow per second

The basic idea behind the finite volume method is similar in concept to the technique of predicting the volume of water in the future by using the current volume of water and the volume of water flowing in and out. The technique to calculate the volume of fluid in a simulation can also be applied to physical quantities such as pressure and flow rate.

TIPS The approximation (scheme) used for the difference method and finite volume method relies upon the Taylor expansion. The Taylor expansion is a technique that represents a smooth function through a series expansion. Although the Taylor expansion is not described here, it is very important in a variety of mathematical endeavors, including CFD, and we highly recommend that you examine it should you have more interest.

Diagram 5-2-1 **Concept of the finite volume method**



In order to foresee how much water will be in the container, all that needs to be done is to keep watch of the balance of water flowing in and the amount of water flowing out. This is the basic view of the finite volume method. Note though that the volume flowing in and out cannot be clearly defined and an estimate needs to be made in some form of fashion. Hence, the accuracy of the estimate will greatly affect the accuracy of the simulation.

Numerical flux

Let's look a little closer at the concept of the finite volume method through CFD. First, we'll divide the space as in Diagram 5-2-2. This divided space is referred to as the "lattice" (or mesh or grid). Let's now consider a fluid flowing through the lattice.

First, let's assume we know the physical quantity that each lattice element holds at a certain time (see: Tips!). Prediction of the physical quantity held by future elements using the amount of inflow and outflow per unit of time is what the concept of simulating fluid through the finite volume method is about.

So, how is the amount of inflow and outflow per unit of time in each element determined? Actually, those who perform CFD must measure (approximate) a reasonable value from the inflow and outflow amounts based on the distribution of the current physical quantity. However, there is room for choice on how to determine the amount but the inflow and outflow per unit of time cannot be defined uniquely. In this way, the concept of a human choice to determine the physical quantity of inflow and outflow per unit of time is referred to as a "numerical flux", and the accuracy of this would greatly affect the accuracy of calculation results.

Diagram 5-2-2 **Numerical flux going in and out of the element**

Future physical quantity of element j = Original physical quantity of element j
+ Numerical flux j-1/2 flowing into element j
– Numerical flux j + ½ flowing out of the element j

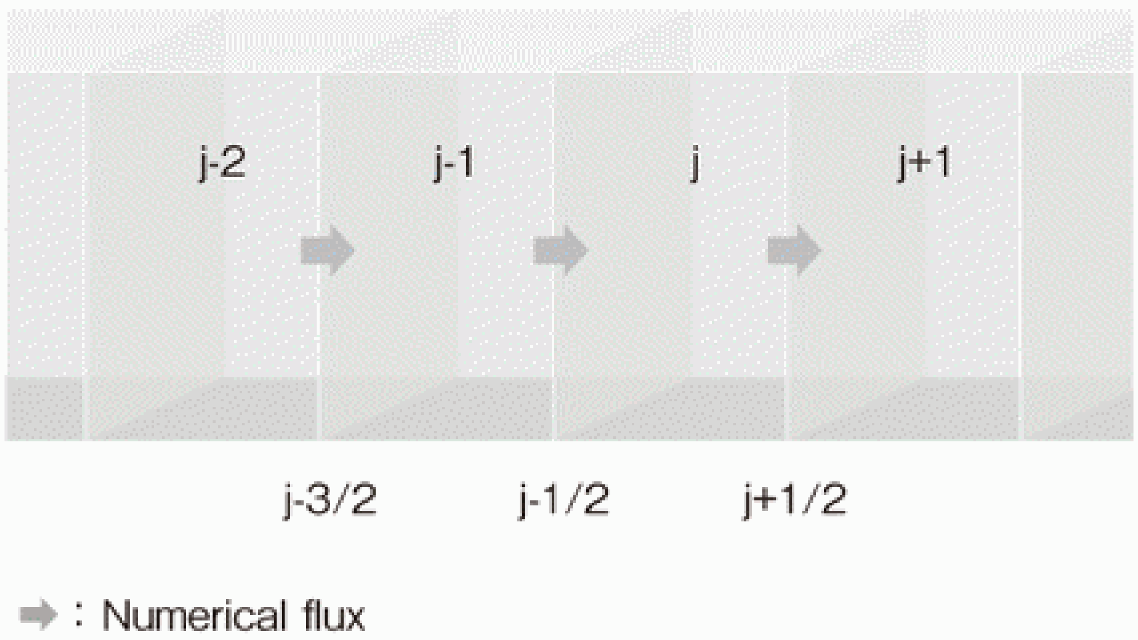
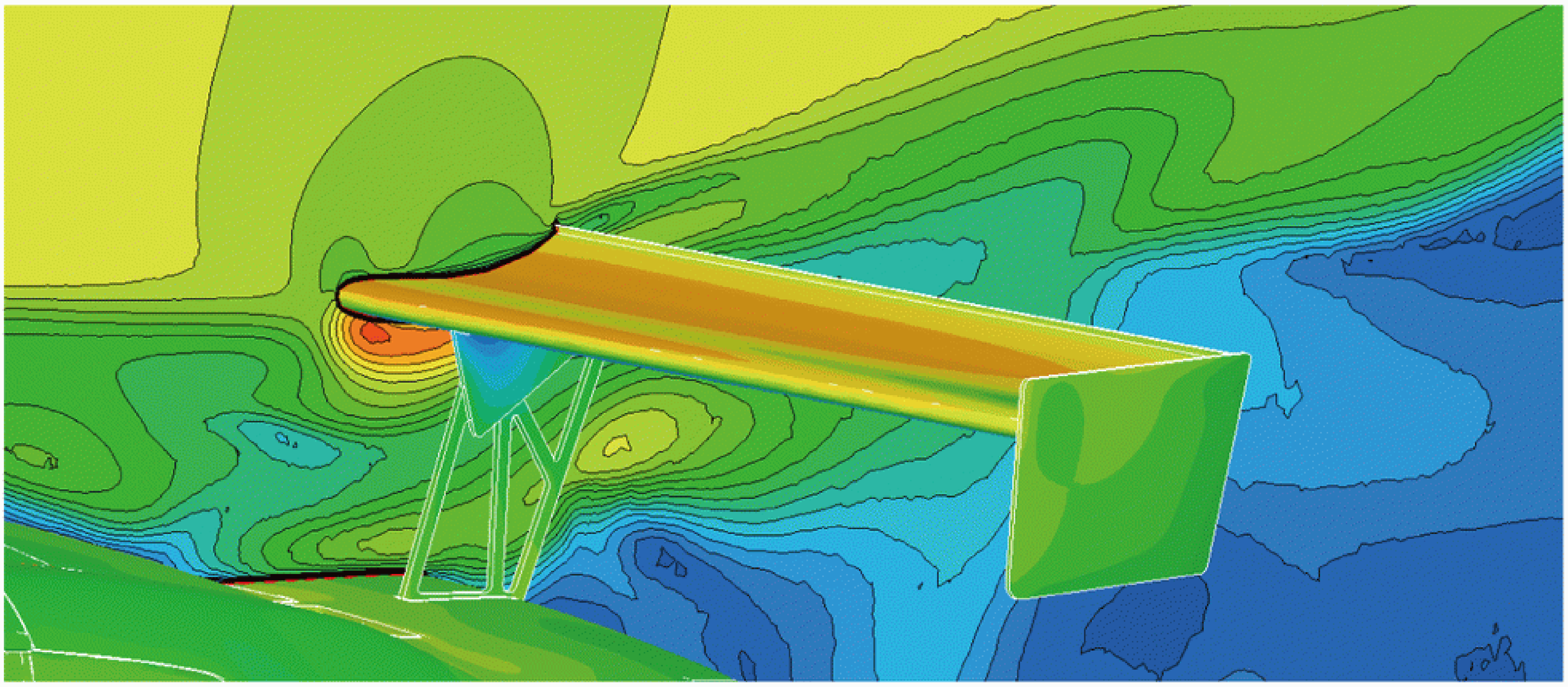


Diagram 5-2-3 **Flow field around the rear wing of a racing car**



5-3 Features of scheme

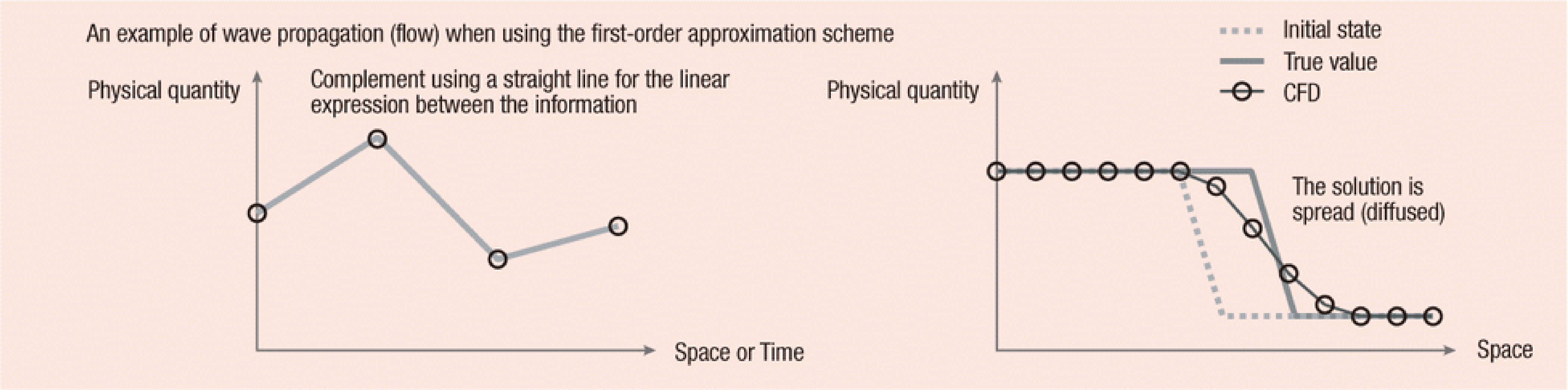
Monotonicity and high accuracy cannot be compatible

There are several ways to determine numerical flux, and a person who performs CFD must determine the appropriate scheme. Of course, one can't just choose any scheme they want. The accuracy of the numerical flux can differ depending on what kind of scheme is employed and will affect the accuracy of the simulation. As the Lax Equivalence Theorem states, using an inappropriate scheme will increase the margin of error and diverge the calculations. Let's briefly examine how the difference in the scheme can affect the results.

The scheme of primary approximation

In order to complement the missing information from a computer, the first thing to do is to approximate using a straight line to represent the changes in physical quantity. When linear expression is used to approximate the linear change, that scheme's accuracy is considered the primary accuracy. The scheme of the first order approximation has the advantage of being able to maintain monotonicity, but has a disadvantage of diffusing the solution.

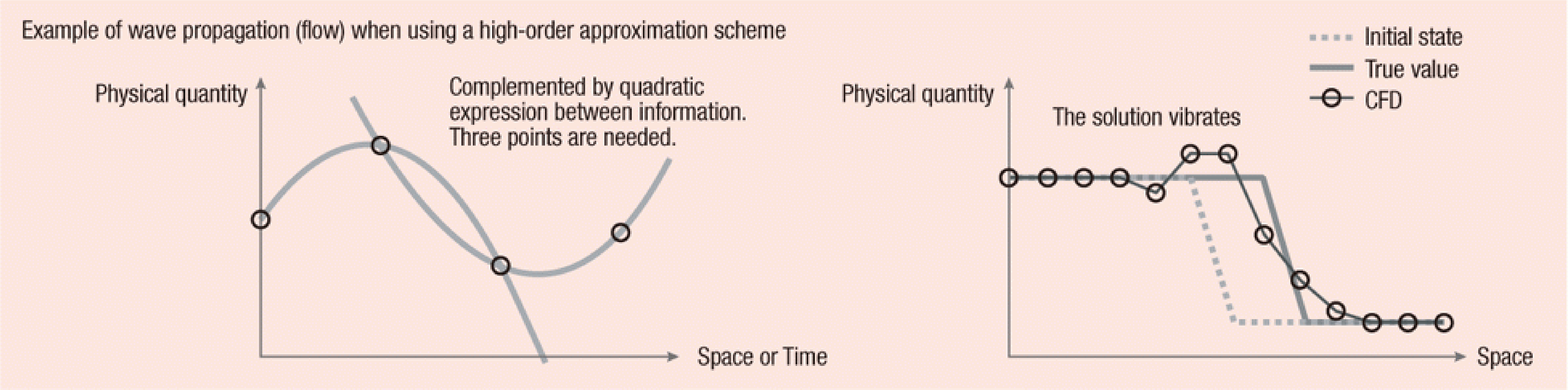
Diagram 5-3-1 Calculation example of wave propagation and the first-order approximation scheme. The solution diffuses because the scheme of first-order approximation can't resolve the high frequency waves.



The scheme of high-order accuracy

It is easy to assume that one could obtain a more accurate result by obtaining information (physical quantity) from more lattice elements and making a high-order curve lined approximation instead of making an approximation from a straight line linear expression. In truth, the high-order accuracy scheme has better this should stay the same. than that of a standard first order approximation scheme. However, the higher the order is, the more the physical quantity is gained from the lattices first-order approximation, thus increasing the computational complexity. There are also other disadvantages where some high-order approximation schemes may have a solution vibrate, thereby reducing the accuracy.

Diagram 5-3-2 A calculation example of a second-order approximation scheme and wave propagation (flow). The wave form is broken because the high-order accuracy wave is different from the speed (phase) of the wave propagation from the frequency.



Godunov's theorem

One can obtain a more accurate calculation result for the majority of the flow field by using the high-order approximation scheme. However, there are disadvantages to the high-order approximation scheme. When using a high-order approximation scheme on areas where there are sudden changes in flow, such as a flow on a surface of discontinuity, the solution becomes susceptible to oscillations which can result in unrealistic values and lack stability. In this kind of flow field, the first-order approximation scheme, which can maintain monotonicity, provides better results.

So why don't we create a high accuracy scheme where the solution does not oscillate? Unfortunately, it has been mathematically proven that both the scheme being of "high accuracy" and that the "solution is monotonic" cannot be compatible. This is called "Godunov's theorem" According to Godunov's theorem, there is no scheme that can satisfy both "high accuracy" and a "solution being monotonic" at the same time, and regardless of how it is handled, there is no way such an ideal high-order approximation scheme can be made.

Diagram 5-3-3 According to Godunov's theorem, any scheme with high-order approximation is not able to maintain the monotony of the solution (the sign of the gradient does not change) for the linear wave equation. That's why a non-linear scheme was constructed to solve this problem. One of them is TVD (described below).

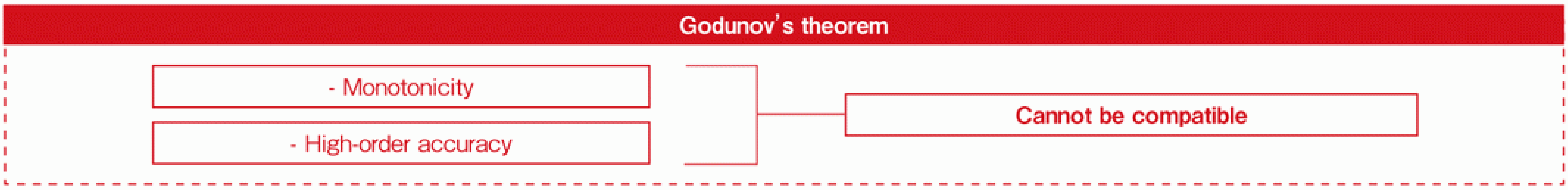
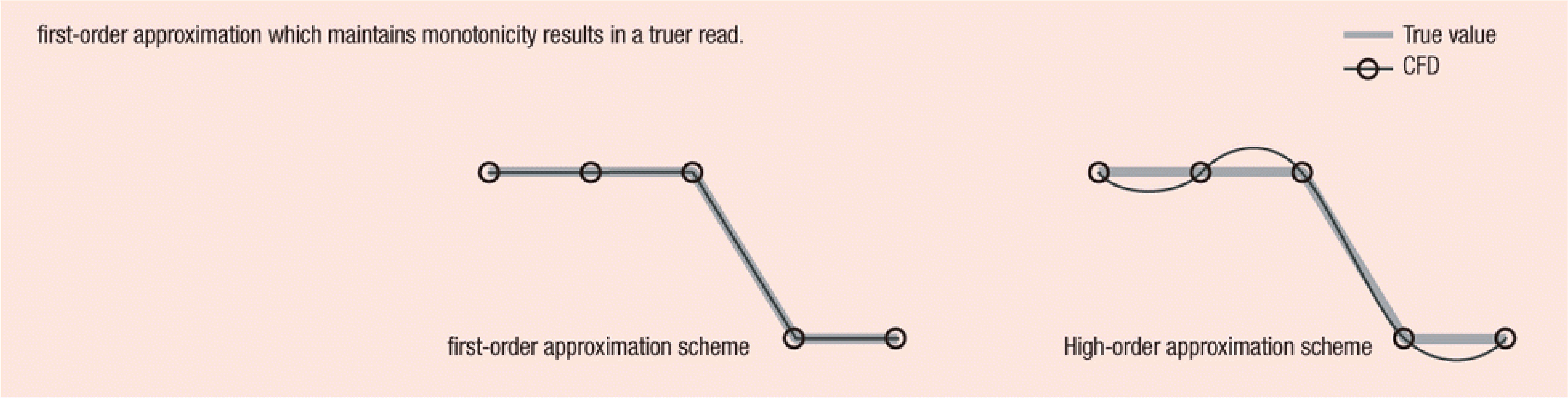
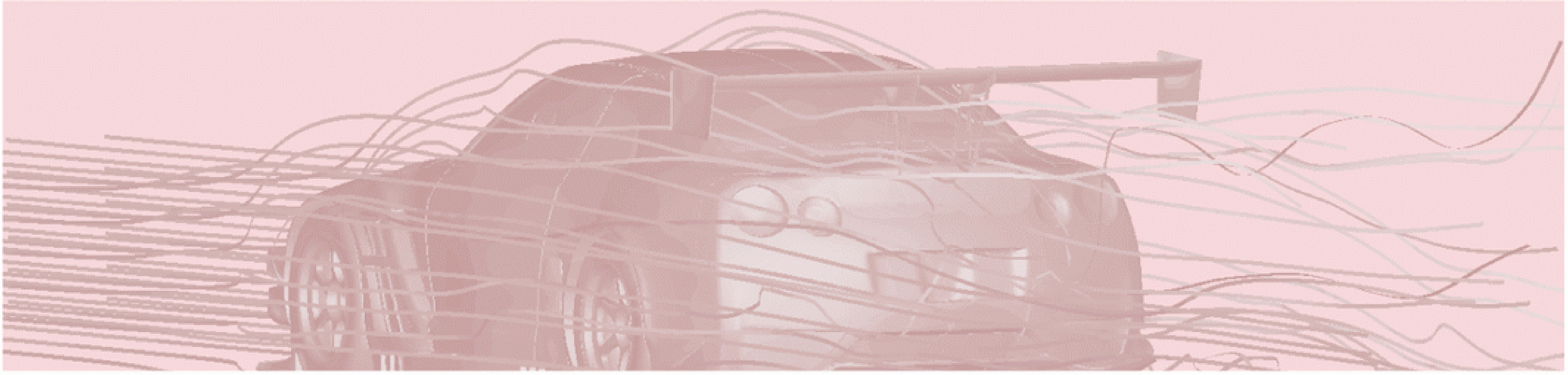


Diagram 5-3-4 The accuracy for dramatic changes in flow, such as a surface of discontinuity





5-4 Compatibility of first-order approximation and high-order appproximation

▶ How to make both first-order approximation and high-order approximation compatible

According to Godunov's Theorem, having a scheme where that it is "high accuracy" and "does not have a oscillation in the solution" cannot be achieved, and regardless of approach, there is no way to eliminate the possibility that the solution will vibrate. Therefore, we must think of a different way to obtain good results without oscillating the solution.

TVD

The first-order approximation solution is easily diffused and the accuracy isn't very high, but the solution will not oscillate and it can maintain monotonicity. On the other hand, while high-order approximation naturally produces more accurate data than first-order approximation, when solving the abrupt change of the flow, such as a discontinuous surface, the solution may oscillate and could lead to unrealistic values and inconsistencies. There is an advantage and a disadvantage for both first-order approximation and high-order approximation. Then why not just use only the advantages of each, depending on the flow, to get the best calculation result? This kind of idea led to a technique called TVD (Total Variation Diminishing).

TVD is a hybrid of first-order approximation and high-order approximation. TVD is an approach that was devised to prevent change in the overall solution. It can determine change of intensity of a flow, and the majority of the flow is calculated using high-order approximation, but in a situation where the flow changes drastically it switches over to first-order approximation, thus maintaining monotonicity.

Diagram 5-4-1 TVD

- Hybrid of first-order approximation and high-order approximation
- Depending on the flow, use either first-order approximation or high-order approximation

	Advantage	Disadvantage
first-order approximation	Monotonicity	Diffusion of the solution
High-order approximation	High precision	Vibration of the solution

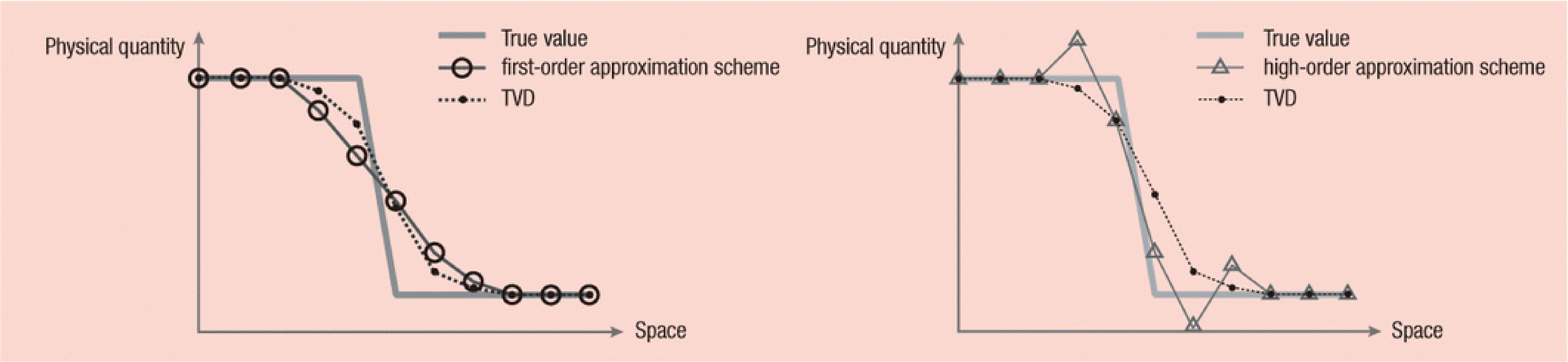
⬇ Using only the advantage of each

TVD

TIPS There are other techniques aside from TVD used to reduce the oscillation that appears when using the high-order approximation scheme. Some notables are one that adds artificial numerical viscosity, while another is called MUSCUL.

TIPS Schemes such as TVD that maintains high-order accuracy in smooth flow areas, but at the same time clearly capture discontinuous areas is commonly called a high-resolution scheme.

Diagram 5-4-2 **The results obtained are much closer to the true value when using TVD.**

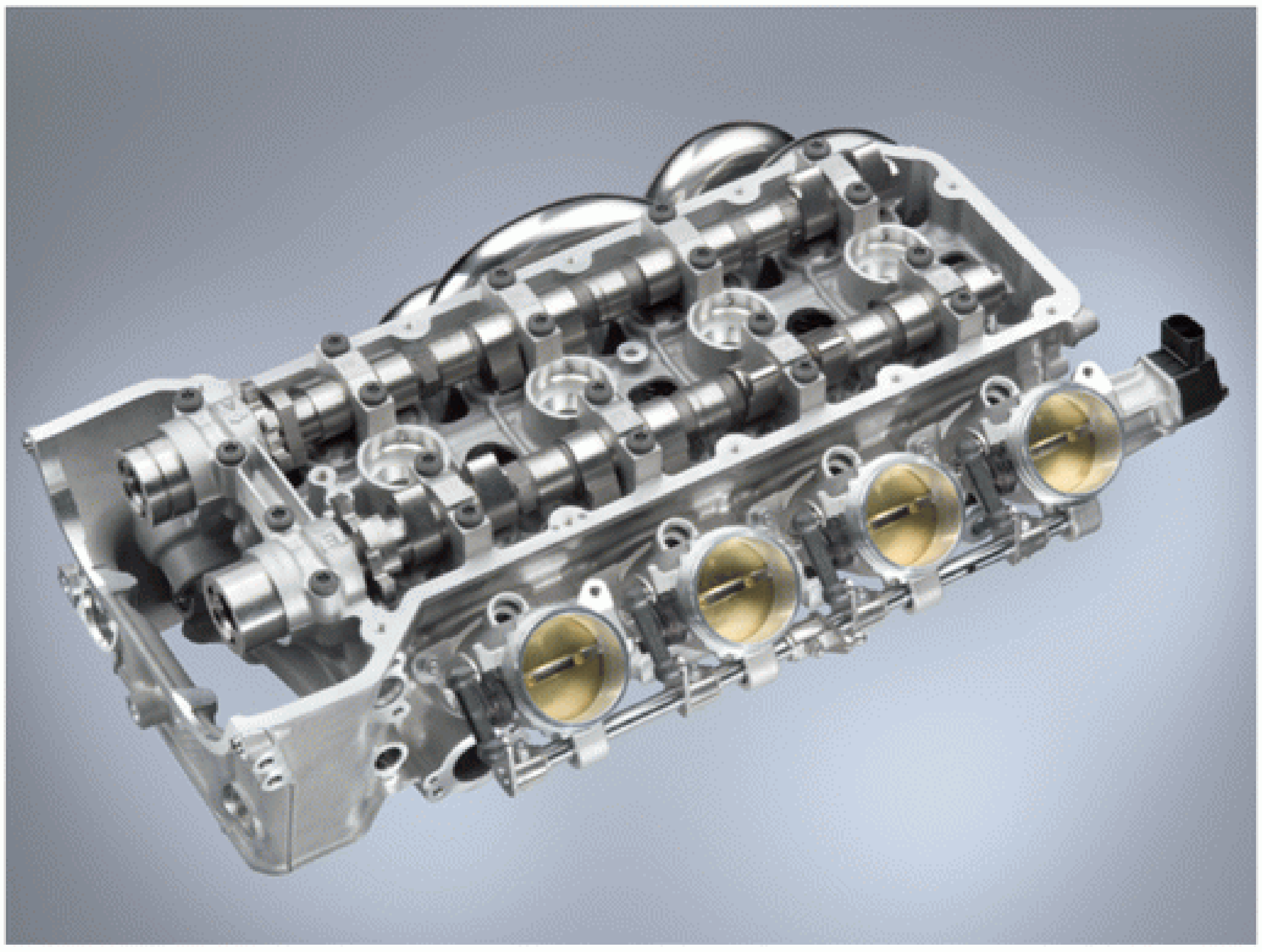


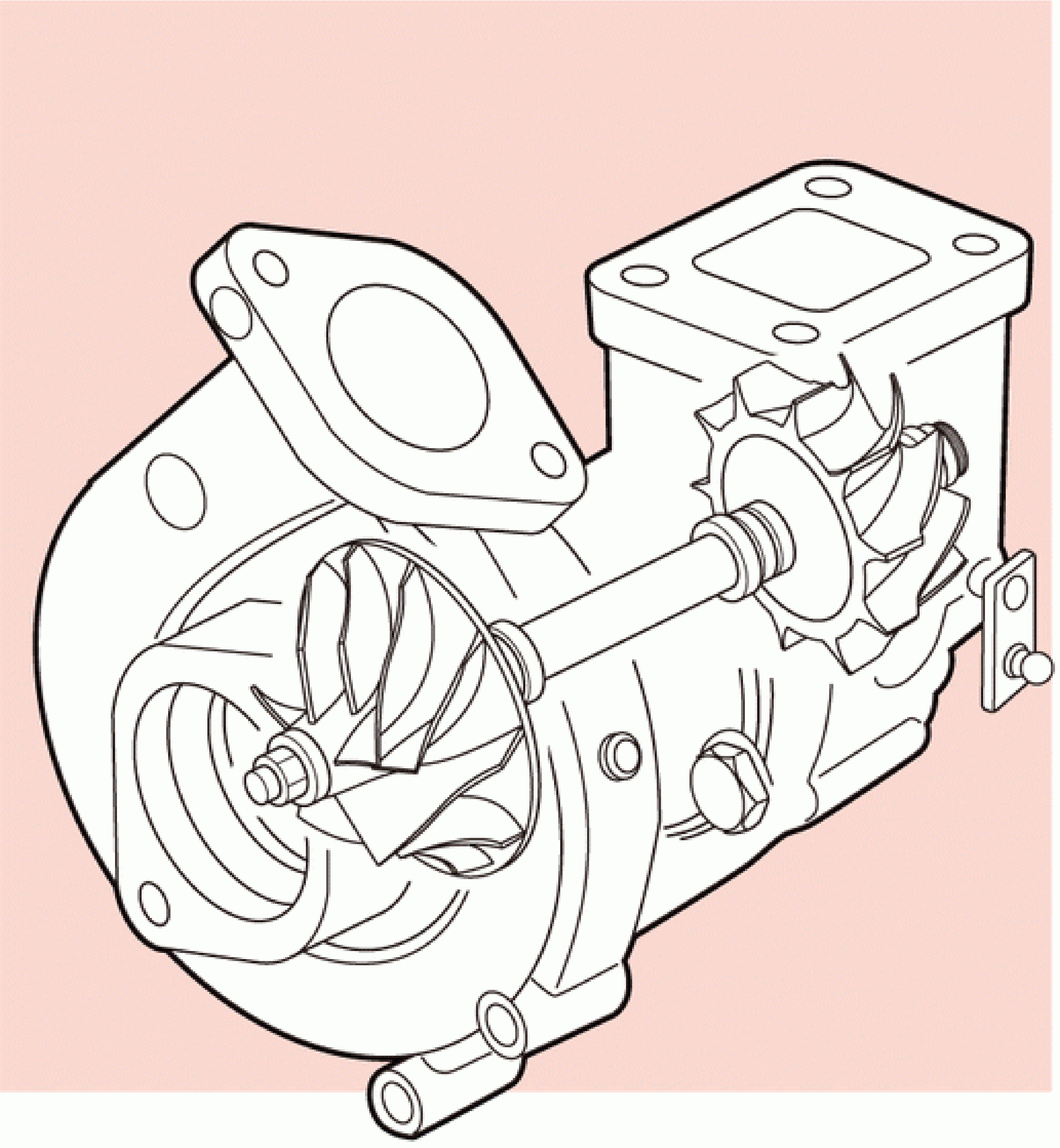
Evaluation of TVD

Diagram 5-4-2 is a calculated result using TVD that is compared with results from the high-order approximation scheme and the first-order approximation scheme. Unlike the first-order approximation scheme, TVD does not waver from non-physical effects such as overshooting and undershooting. Notice also that the spread is better contained than the first-order approximation scheme. In particular, notice that TVD has closer true values (exact solution) than the other schemes.

But, since there is work necessary to determine the change in the flow field when using TVD, it will take that much longer to calculate the results.

TIPS TVD is effective in solving a surface of discontinuity, such as that of a shock wave, and is a technique that is widely used in simulating compressible fluid.





5 5 Solving turbulence

▶ Method of reducing computational complexity

Solving vortexes

When a vehicle is running, turbulence is generated around it. Turbulence is made of both large and small air vortexes;, but to calculate even the simplest vortex we need at least 9 lattice elements or grid elements as shown in diagram 5-5-1. If we want to directly calculate the complete set of vortexes around a vehicle, massive numbers of elements would be necessary.

For example, if we try to solve the vortices that make up turbulence around a vehicle going 100km/h, the number of elements needed would be 10^{13} power. In other words, in the neighborhood of 10 trillion lattice or grid elements would be required! If you're able to use a world-class supercomputer, this might be theoretically possible, but in the real word of automotive engineering, making a massive calculation like this is considered impractical.

Diagram 5-5-1 To resolve two-dimensional vortexes, a minimum of 9 lattice elements will be necessary

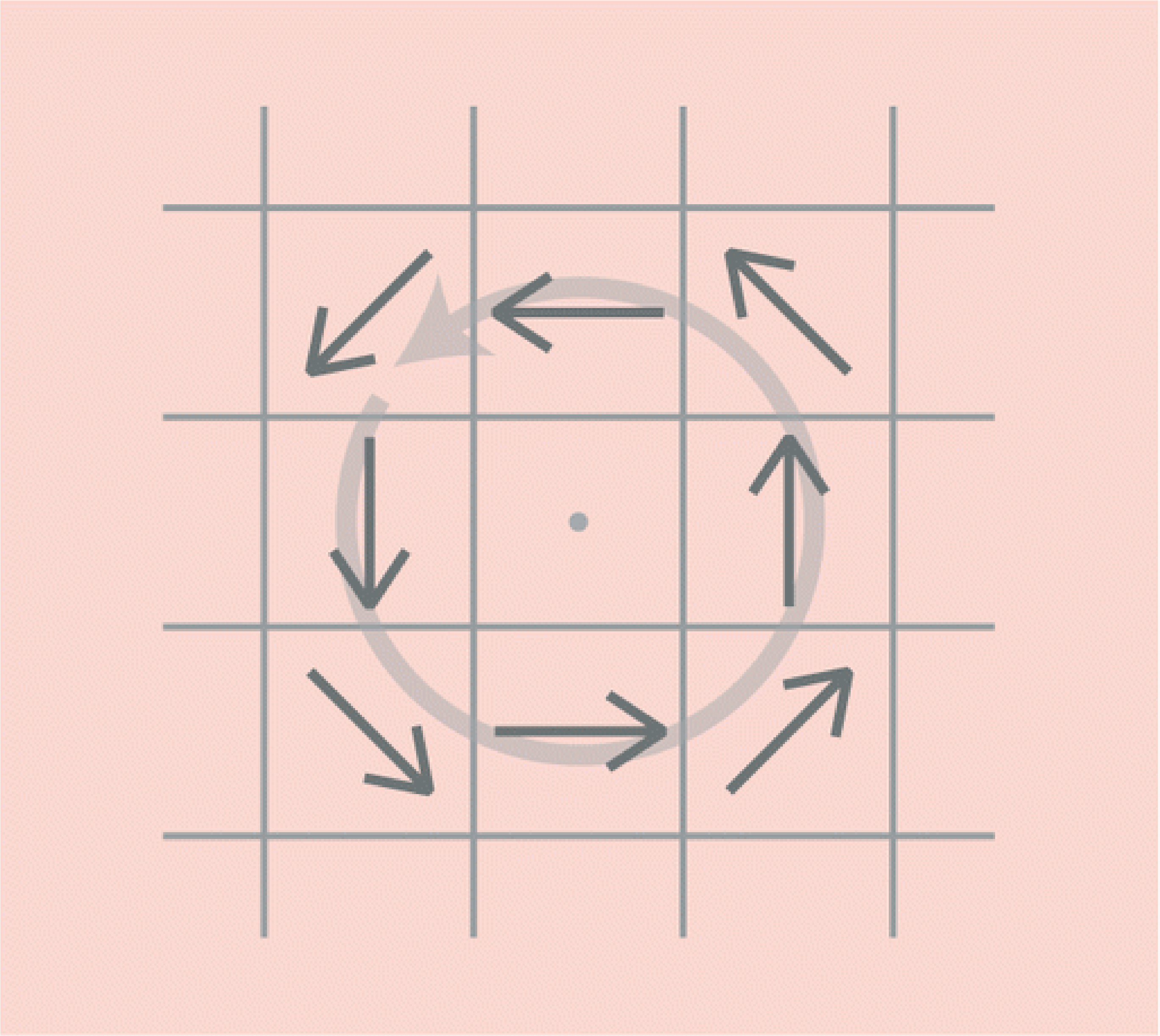
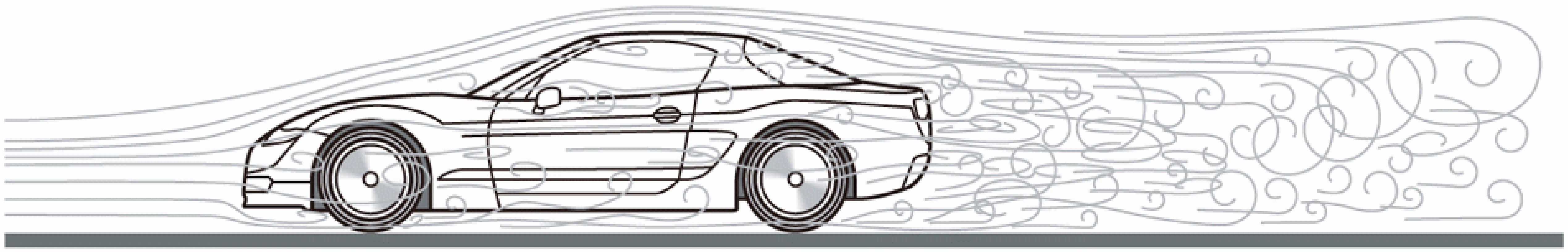


Diagram 5-5-2 The relationship between turbulence and air vortexes

Turbulence is composed of large and small air vortexes.



Turbulence model

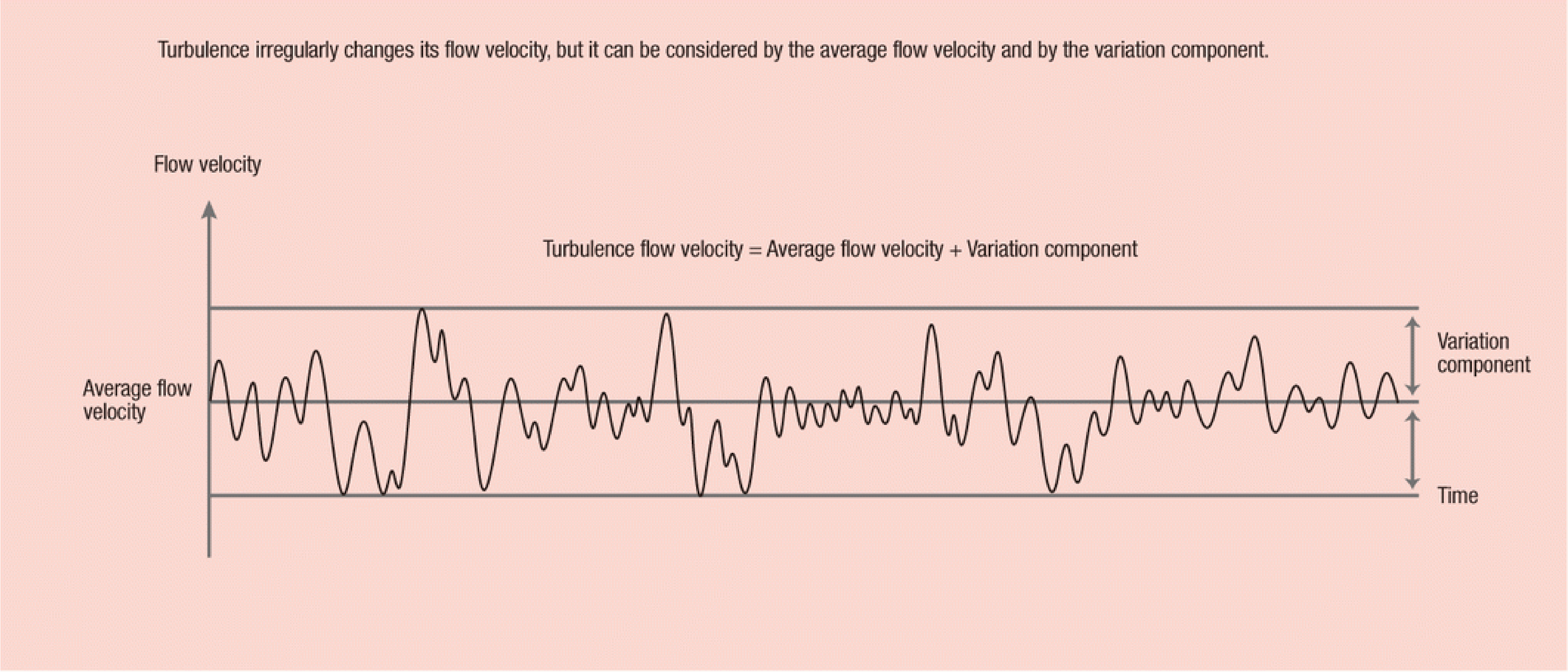
In fluid mechanics theory, by modeling characteristics of turbulence, understanding the true nature of turbulence have seen great progress over the years. Using the theory developed in the field of fluid mechanics theory, a turbulence model with that as base was incorporated into CFD. By bypassing the effort to find all solutions for large and small vortexes, and by calculating only the main properties of any given turbulence, this led to reducing computational complexity. That said, let's look at the most widely used turbulence models, RANS and LES.

TIPS Not using the turbulence model and directly solving the equation of a fluid is called DNS (Direct Numerical Simulation). But as stated earlier, to perform perfect DNS, space must be finely divided. In addition, with dividing of space comes dividing of time, so the computational complexity would be massive.

RANS (Reynolds Averaged Navier-Stokes)

RANS is a turbulence model that converts the flow rate of turbulence into an average rate that is divided into the variation component. The computational complexity required by RANS is relatively low, so this is the most widely used model. However, there are drawbacks such as the difficulty of accurately estimating flow separation.

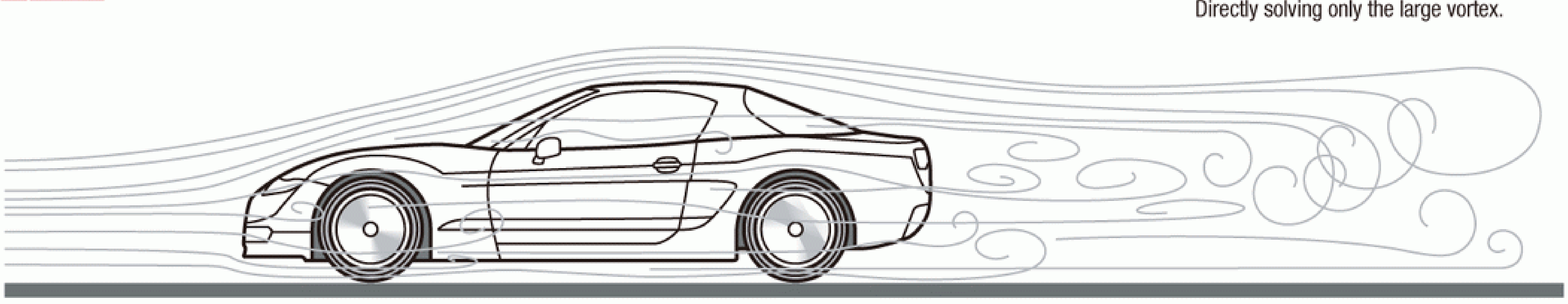
Diagram 5-5-3 RANS



LES (Large Eddy Simulation)

In relation to turbulence, large vortexes are a dominant influence in measuring turbulence and the smaller the vortex, the weaker the overall influence is on the field of the flow. If we avoid solving the small vortex and just directly calculate the large vortex, the small vortex becomes modeled in a process called LES. LES is able to calculate the flow field with a much higher degree of precision than RANS, but will have much more computational complexity involved.

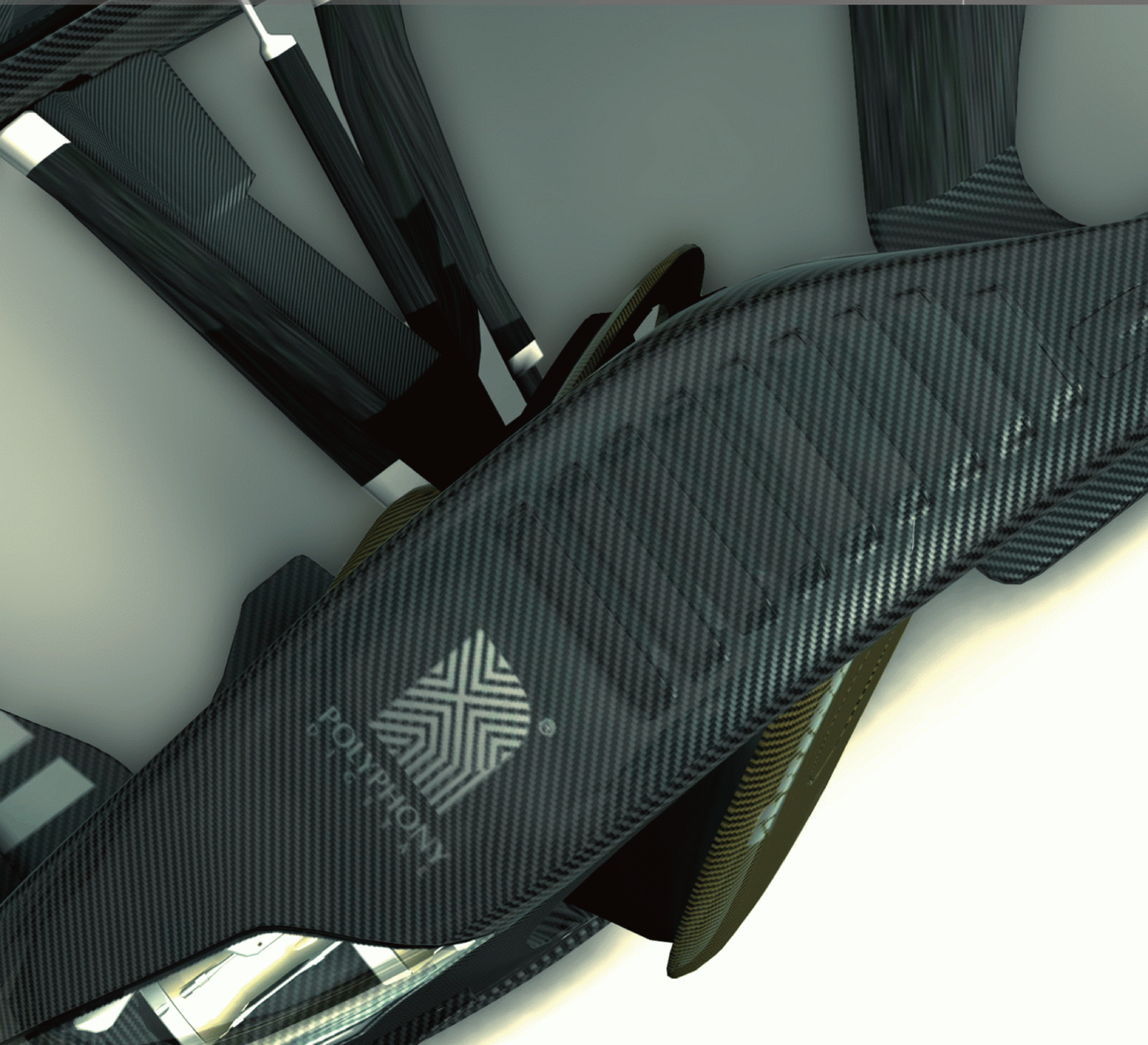
Diagram 5-5-4



Review: Mechanism

2

The Gran Turismo Magazine
Beyond the Apex



Basic Specs

The characteristics and performance of different vehicles varies wildly depending on their intended use. When choosing a vehicle, it's important to understand the basic principles behind each of its specifications.

Dimensions

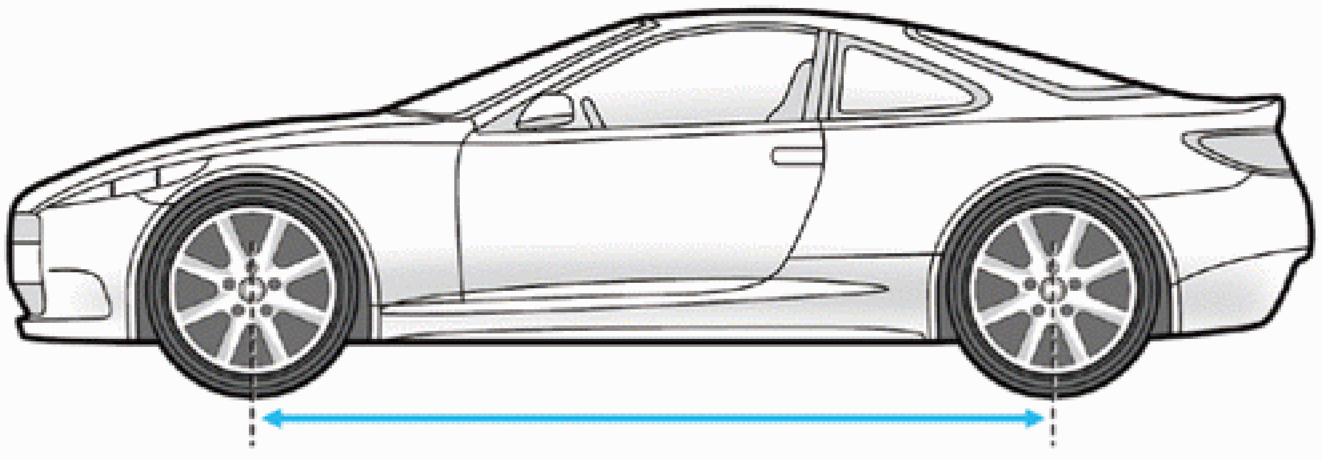
A vehicle's frame and the basic layout of its operating parts are the most basic specifications, and are decided during the initial stages of development, making them the hardest to change later on. These specifications have a crucial effect on the three main functions of driving, turning and braking. Any deficiencies are difficult to compensate for with tuning, and just a slight difference can have a huge effect on performance. Furthermore, the effects gained from tuning are also greatly affected by the car's base potential. To get the most out of your car, you should be familiar with how these basic specifications affect driving performance.

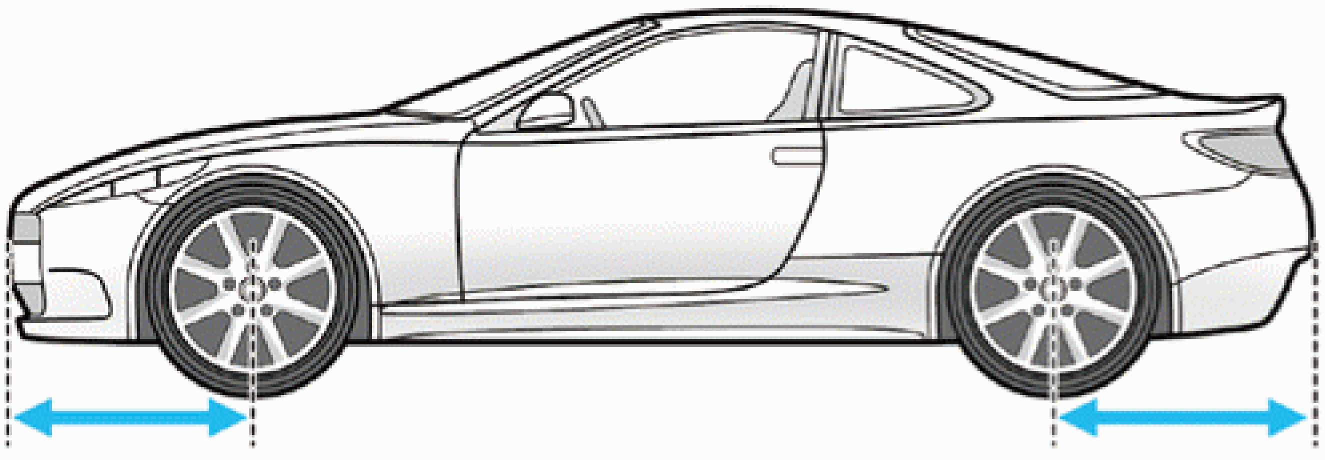
Wheelbase

The wheelbase is the distance from the center of the front wheels to the center of the back wheels when viewing the car from the side. This length has a large impact on the stability of the car. The longer the wheelbase, the less affected the vehicle will be by undulation of the road surface and crosswinds, and it will tend to be more stable in a straight line. On the other hand, although a shorter wheelbase reduces stability, steering responsiveness is improved, and the car will be agile around corners. In terms of comfort, a longer wheelbase is generally considered better.

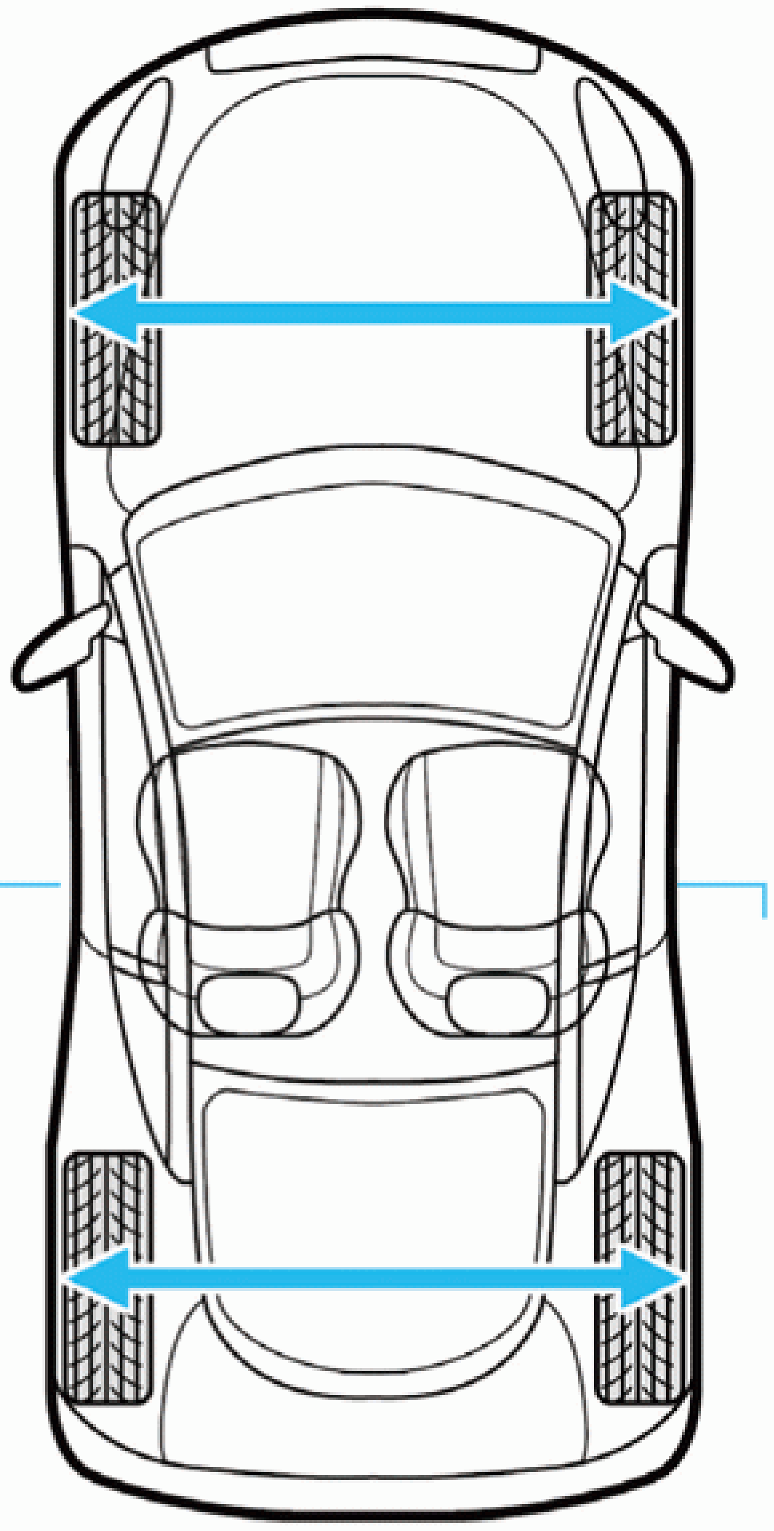
Overhang

The front overhang is the length of the car that extends beyond the center of the front wheels to the foremost end of the front bumper. Rear overhang is the length of the car that extends beyond the center of the rear wheels to the end of the rear bumper. If the parts of the car on this overhang area are heavy, the yaw moment of inertia (resistance to turning) increases, and maneuverability is reduced. Because of this, components of a car with significant weight should be placed within the wheelbase whenever possible. This is especially true for heavy components such as the engine. However, an overhang of some length is important for aerodynamic purposes, so it cannot be avoided altogether.





A Car's Performance is Dependent on Its Dimensions and Weight

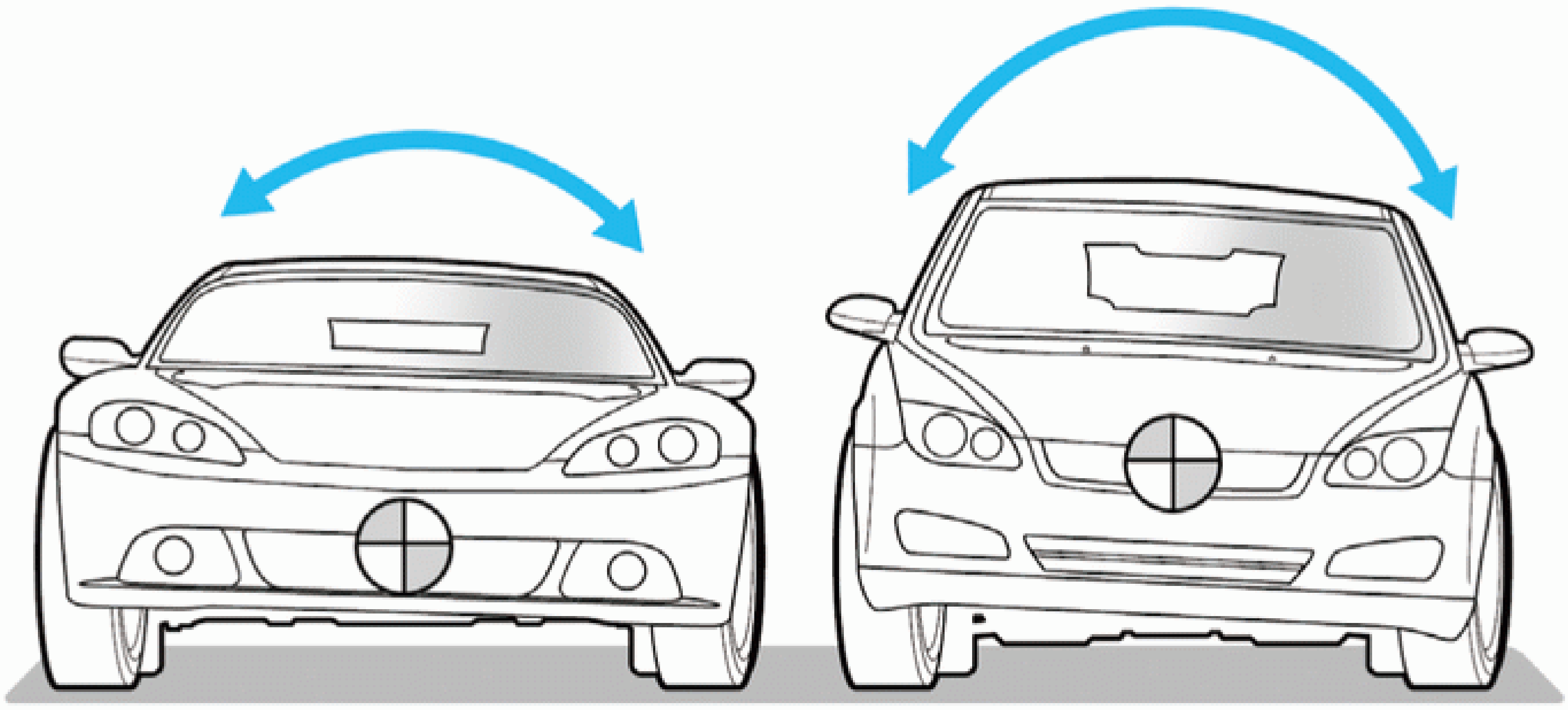


Track Width

"Track width" refers to the distance between the left and right wheels of a car. Increasing track width will lower a vehicle's center of gravity. Generally speaking, increasing track width improves traction when cornering, and increasing the track width of the drive wheels will increase contact with the road surface, and thereby improve the vehicle's ability to transfer its power to the road surface. A smaller track width, on the other hand, will offer quicker handling, but will reduce stability. It's common for racing cars to have different track widths for the front and rear wheels to improve handling.

Height

Height is measured from the road surface to the highest point of a vehicle. Lower height means a lower center of gravity, reducing roll when cornering, and increasing turning speed. However, lower height also means less room for passengers and shortened suspension stroke (the amount of room that suspension springs have in which to expand and contract), and increases the risk of bottoming out the suspension.



Weight

Weight is a crucial factor in determining vehicle performance. The lighter the car, the less demand on the engine, and the more power can be used for movement. Other benefits include reduced brake wear and more efficient cornering. The weight of a car divided by its maximum power output is known as the power-to-weight ratio. The smaller this ratio, the faster acceleration will be, and the sportier the ride. This also has a major effect to fuel economy, and reducing the weight of a car is now an important factor in designing new cars in terms of environmental impact and performance.

Drivetrains and Weight Distribution

Like size and weight, the drivetrain is another basic vehicle specification. Drivetrain specifications are pairs of letters that describe the location of the engine and the drive wheels in terms of "front," "middle" and "rear," with the engine location indicated first and drive wheels second. FF, FR, MR, and RR are some of the more common drivetrain specifications. This information is important because the location of the engine – the heaviest part of the car – and the wheels that it drives will have a huge effect on weight balance and movement.

In cars with good weight balance, the power of the engine will be effectively transmitted to the drive wheels, and will positively impact starting and acceleration. Braking at speed will also be more effective, as the car will pitch forward less.

But the most important benefit of good weight balance is improved cornering. Cars with poor weight balance can be destabilized more easily by centrifugal force, and are at higher risk of spinning out of control.

The ideal weight balance is 50:50 between front, rear, and left and right. In FR cars where the engine is at the front and the drive wheels are at the rear, this distribution is easily achieved. However, FF vehicles (and 4WD vehicles, which are often FF based), where the engine and drive wheels are at the front, will be front-heavy, and RR cars will be rear-heavy. Most FF cars now have their engines mounted transversely ("sideways" when compared to most vehicles) to try and improve weight distribution.

However, hindrances due to weight balance are not impossible to resolve, and it can be improved by tuning and driving to compensate for imbalances to a certain degree. But it is the subtle differences like these that are the reasons why an MR racing car would win against an FR car with good balance.

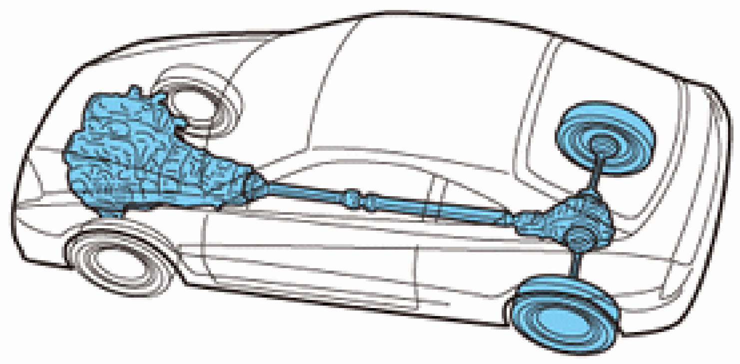
Maneuverability and Basic Structure

Types of Drivetrains

FR

Front Engine, Rear-Wheel Drive

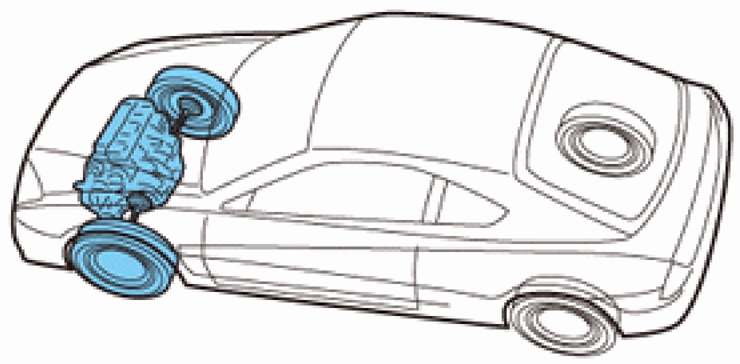
This is a conventional layout, with the engine located at the front, and the drive wheels at the rear. An even weight distribution is easily achieved in vehicles with this layout. In addition to good handling characteristics, it has the advantage of having a good steering feel because the wheels used for steering (front) are separate from the drive wheels (rear). However, it can be difficult to gain traction (and thus drive power) on some surfaces.



FF

Front Engine, Front-Wheel Drive

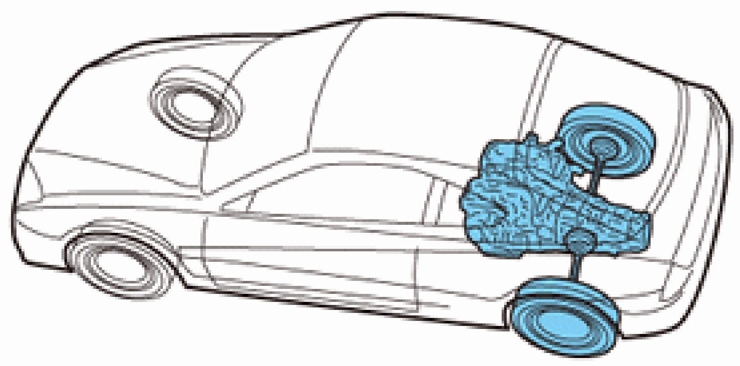
A layout with both the engine and drive wheels at the front. Locating the heavy engine and transmission together in the front means that the cabin can be bigger, but inevitably results in a front-heavy weight balance. Also, as the front wheels manage both drive power and steering, the grip of the front tires is divided between maintaining forward movement and turning when cornering. Because of these reasons, this layout is relatively unsuited for high-powered vehicles.



MR

Mid-Engine, Rear-Wheel Drive

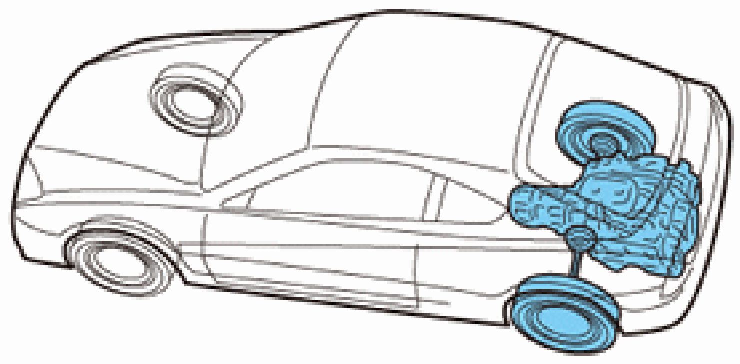
A layout with the engine located in the middle of the car, powering the rear wheels. Mounting the engine near the center of the car makes it closer to the car's center of gravity, which makes sharper cornering possible. It also ensures maximum grip in the front and rear tires during acceleration and deceleration. This layout is a popular choice in sports and racing cars built for speed.



RR

Rear Engine, Rear-Wheel Drive

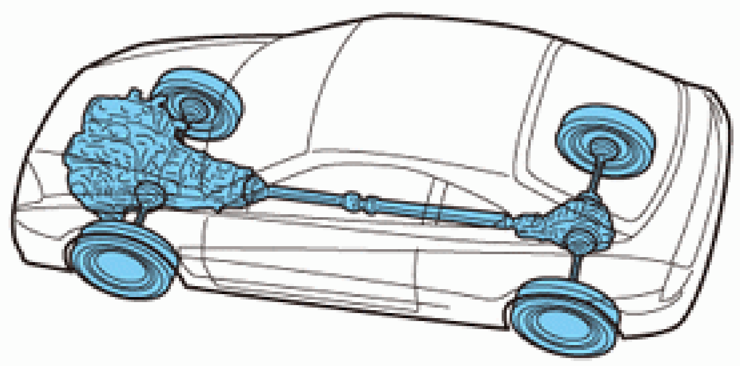
A rear-wheel drive layout with the engine mounted in the rear overhang behind the wheels. This layout focuses the weight in the rear of the vehicle, pushing the rear wheels down onto the road surface, and thereby improving traction and acceleration. However, it reduces load on the front wheels, making it easy to understeer when first entering a corner. Also, as there is so much weight on the rear wheels, if the rear end slips out it does so violently, and requires a high level of driving skill to recover.



4WD

Four-Wheel Drive

A configuration where power is delivered to all four wheels. Despite the increased weight, this layout is the best suited for standing starts and acceleration. However, its extremely high stability can cause it to be difficult to turn. It is possible to make all drive layouts into four-wheel drives, but the layout it is based on will greatly affect its final controllability. Generally, either the front or rear wheels will be considered the "main" drive wheels, and more torque will be delivered to the opposite wheels if the "main" wheels slip.



ENGINE

CHAPTER 02 Mechanism

The Heart of The Automobile

The engine is at the heart of a car. Understanding the engine and how it works is the key to getting 100% out of a vehicle.

Mechanism and Principles

Most cars are equipped with a four-stroke cycle reciprocating engine. Reciprocating engines are made up of cylinders within which pistons move back and forth to create energy. The four strokes of the engine are intake, compression, power and exhaust.

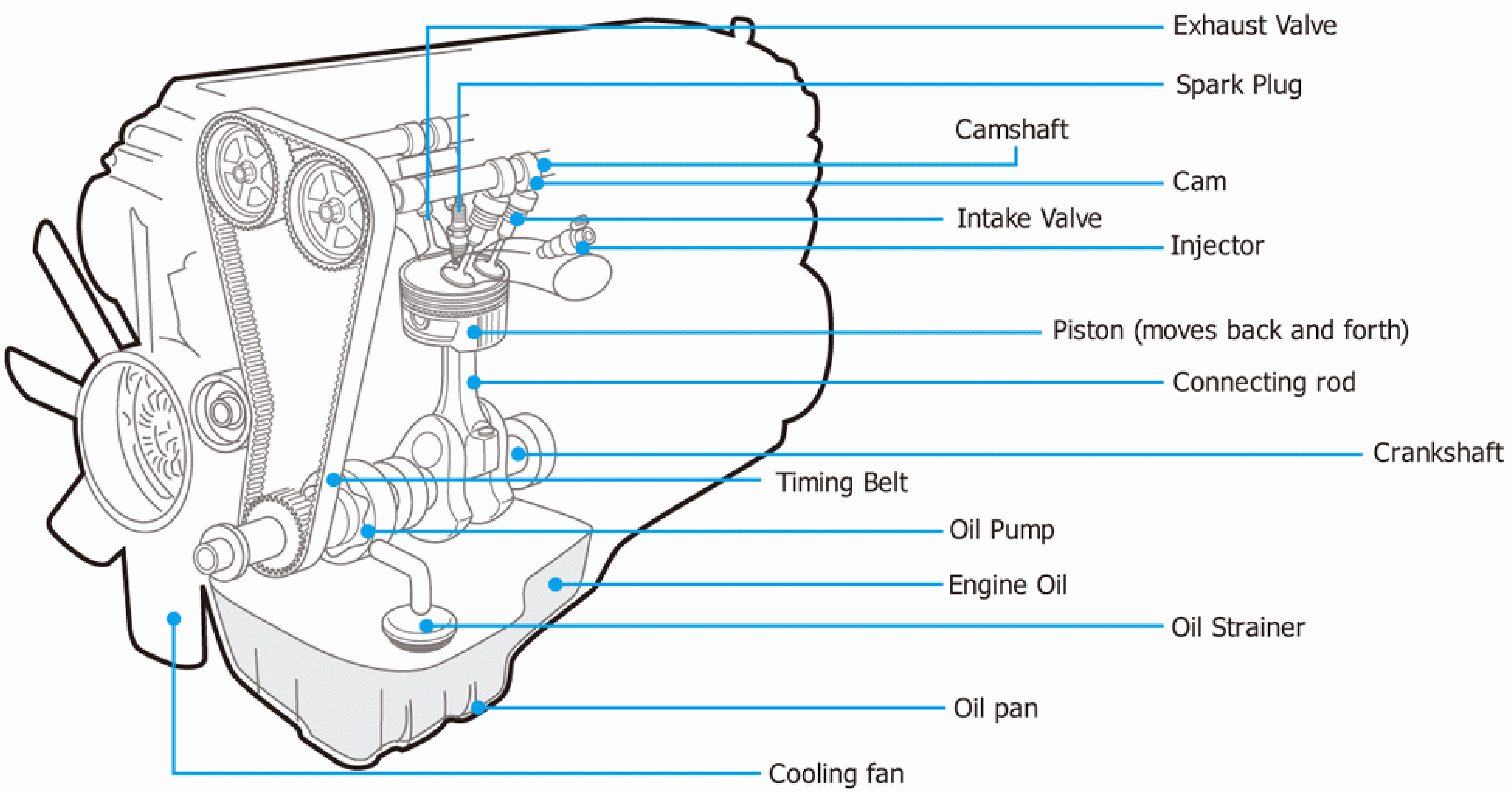
Let's take a closer look at these four strokes of the cycle. In the intake stroke, the intake valve opens just before the piston reaches "top dead center" – the position where the piston is at the top of the cylinder. When the piston starts to go back down, an air-fuel mixture is drawn in through the open valve. When the piston reaches the bottom of the cylinder, the intake cycle is complete, and the compression cycle, during which all the valves close and the rising piston compresses the air and fuel in the cylinder, begins.

Just after the piston has reached the top of the cylinder compressing the air-fuel mixture, the spark plug is ignited, causing the fuel-air mixture to explode. This is the power stroke, at which point the inside of the cylinder can reach temperatures of up to 2000C, and pressures of up to 200 atmospheres. This high temperature, high pressure combustion force pushes the piston

back down, turning the crankshaft, and in effect converting thermal energy into mechanical (rotational) energy.

When the piston reaches the bottom again, the exhaust stroke begins, and the exhaust valves open so that the leftover gases can be discharged. These gases are not discharged by the motion of the piston, but are mostly discharged by their own heat and pressure causing them to fly out through the valves. Once the piston reaches the top again, the intake valves open, and the cycle begins afresh.

A reciprocating engine runs through these four stroke cycles and turns the crankshaft at several hundred times a minute when idling, and several thousands of times per minute at high speeds, to continue creating power for the car.

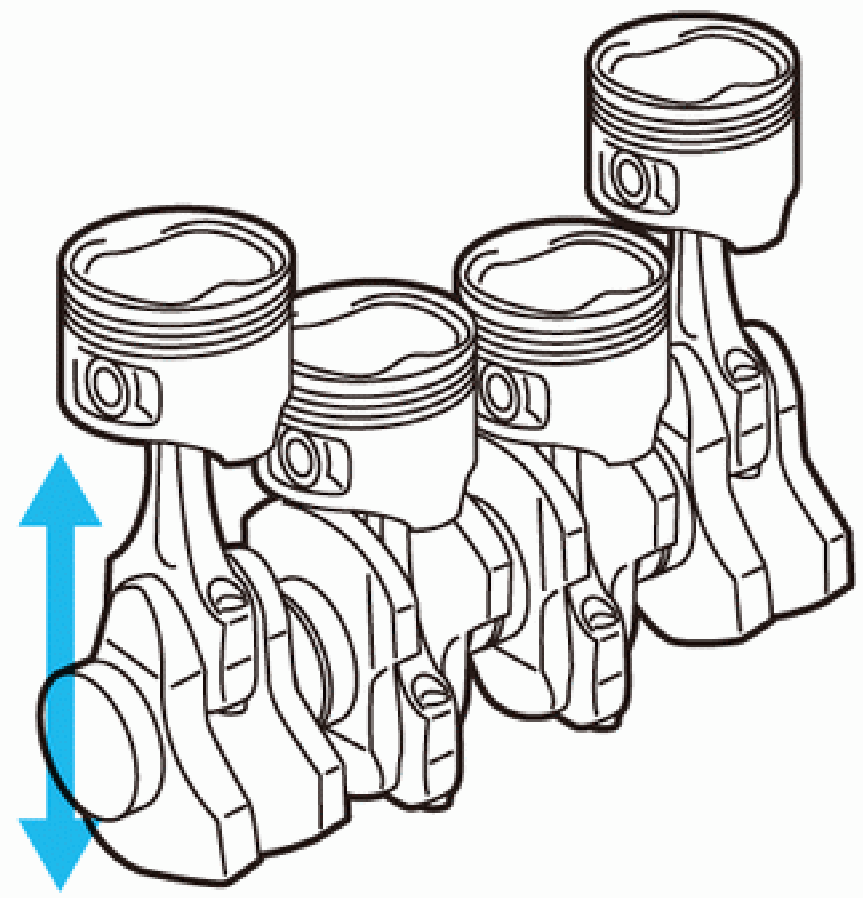


How does an Engine Work?

Types of Cylinder Configurations

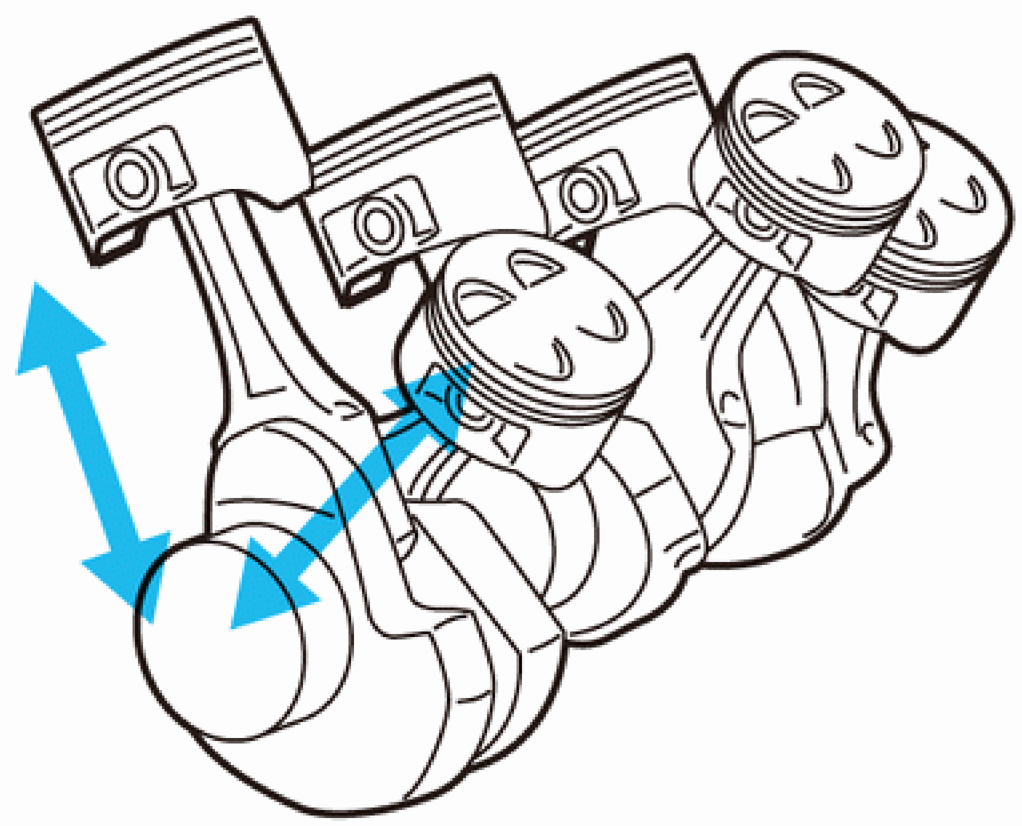
Inline Engine

Multiple cylinders are aligned in a single row. All cylinders share one crankshaft and the cylinder block is made up of a single piece, so construction is simple and the engine can be made to be relatively lightweight. However, the more cylinders there are, the longer the engine will become, which starts to become a hindrance in terms of space required within the vehicle.



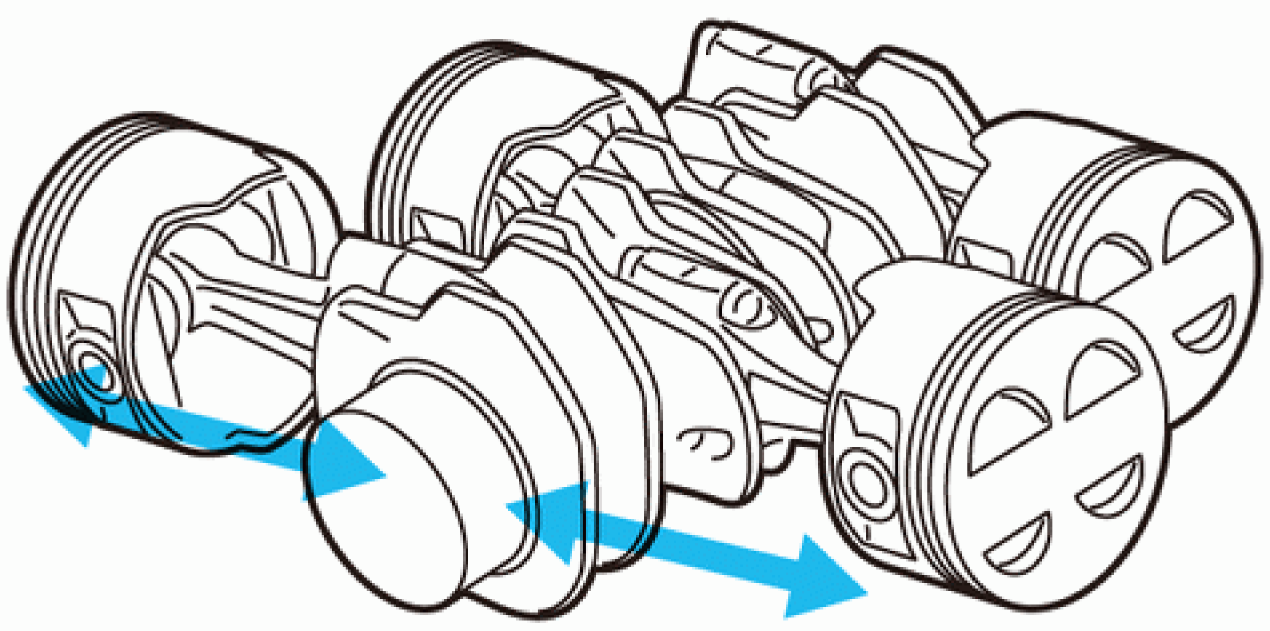
V Engine

Right and left alternating cylinders mounted in a V-shape. The crankshaft can be made shorter, and has the advantage of being compact with even a large numbers of cylinders. Regardless of the number of cylinders, there is little vibration, and the short cylinder block and crankshaft are superior in terms of rigidity.



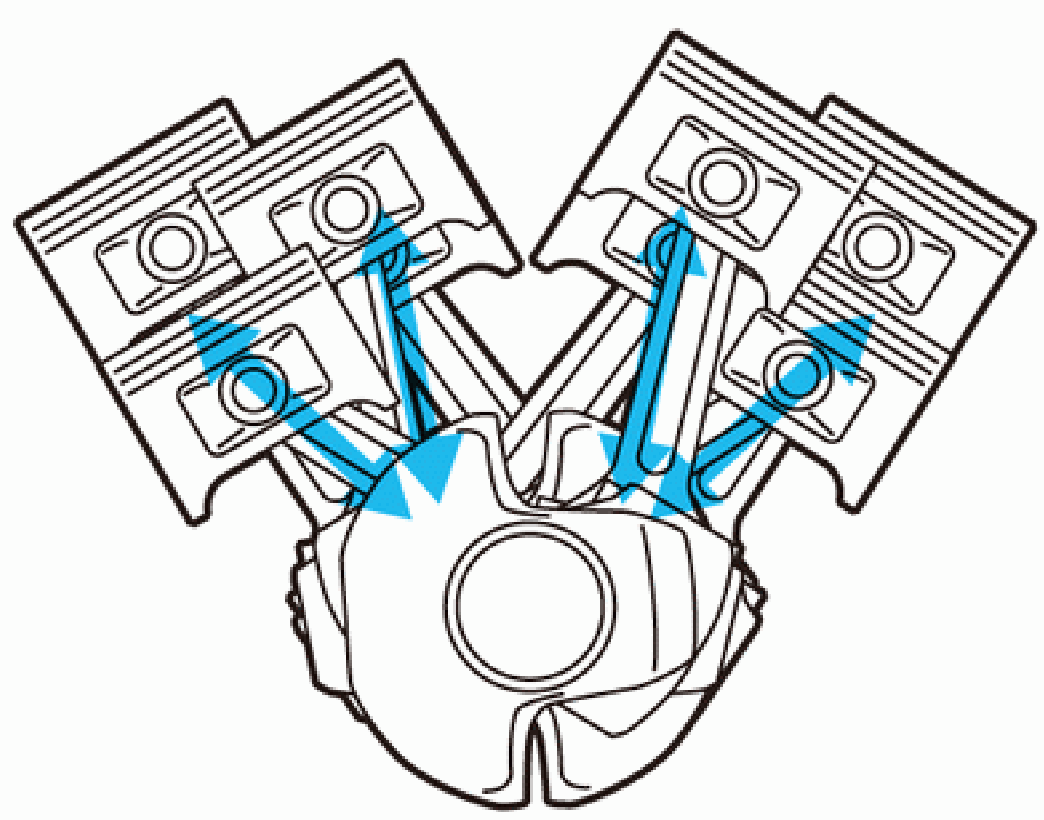
Flat engine

Alternating cylinders arranged horizontally. The right and left cylinders are horizontally opposed with the crankshaft in the middle. These are sometime called "boxer" engines, because the pistons moving left and right resemble the jabs of a boxer. The benefit of this engine is its low center of gravity due to its reduced height.



W Engine

This used to refer to an engine with a single crankshaft with three lines of cylinders fanned out in the shape of a W, but in recent years engines with two narrow angle V engines joined together is also called a W engine. The width of the W engine is greater than that of the V engine, but its shorter crankshaft makes it more advantageous in engines of 12 cylinders or more.



Valve Configurations

In a four-stroke engine there are two types of valves: the intake valves that open during the intake stroke, allowing the air-fuel mix into the engine, and the exhaust valves that open during the exhaust stroke, releasing waste gases. The valves are located in the cylinder head, and play an important role in connecting and blocking off the combustion chamber.

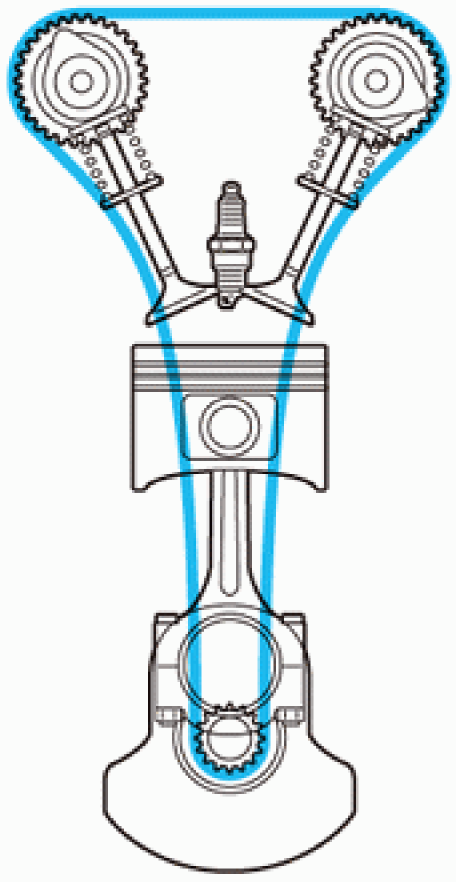
Modern engines typically have the camshaft at the top of the engine, which allows more reliable valve movement. Most modern engines have 4 valves per cylinder with 2 intake valves and 2 exhaust valves, but engines that focus on combustion efficiency at the low RPM range with 2 valves per cylinder, consisting of 1 intake and 1 exhaust valve, will probably be making a comeback in the future.

The latest trend is towards variable valve timing. Initially, this allowed valves to have two timings - one for low revs, and one for high revs - but more recent developments allow valve timing and lift to be varied continuously to match the engines' revs. In the latest variable valve mechanism of the "Valvetronic" BMW engine, power adjustment is accomplished without using the throttle valve, achieving greater efficiency.

Types of Valve Configuration

DOHC

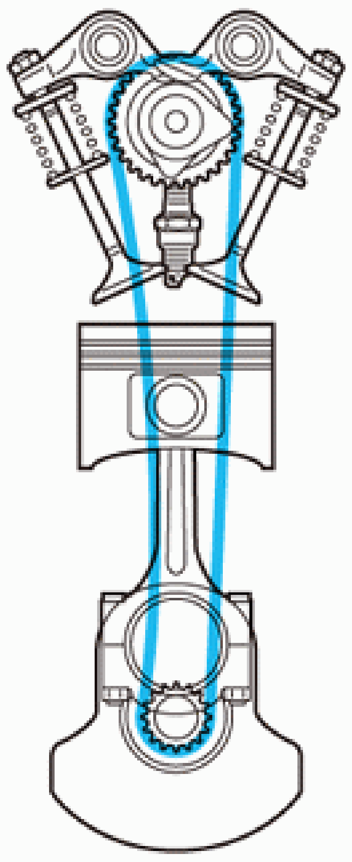
Double Overhead Camshaft



DOHC stands for Double Overhead Camshaft. In a DOHC engine, one camshaft operates the intake valves and one camshaft operates the exhaust valves. Other than ensuring stable operation by sharing the work over two camshafts, it also means that there is less reciprocating mass (inertia) in the valvetrain, and this makes it possible to achieve higher RPMs with the engine. This in turn allows better power output, which is why this layout has been adopted in most of today's high-performance engines.

SOHC

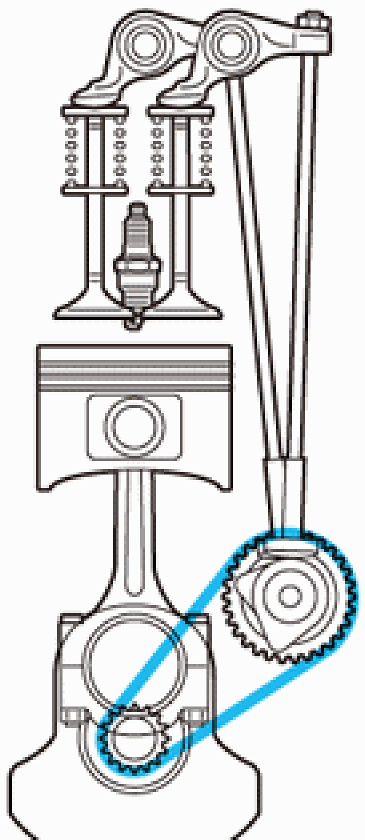
Single Overhead Camshaft



A single overhead camshaft is an engine with a single camshaft operating the exhaust and intake valves. Depending on the type of combustion chamber, the camshaft can either directly operate the valves, or it can operate the valves through rocker arms. Compared to an OHV engine, valve movements are more reliable, and higher revs are possible. Compared to a DOHC engine, valve movements are not as smooth, but high rpm SOHC engines exist, so they are not always inferior.

OHV

Overhead Valve



An overhead valve is, as its name suggests, a system where the valves are mounted on the cylinder head. Unlike an SOHC or DOHC setup, the camshaft is located to the side of the cylinders and the camshaft operates the valves with long arms called "pushrods." This structure is simple, and it is easily maintained. However, valve operations of these types of engines are not as reliable at high RPM, and is not generally suited for high power

Rotary Engines

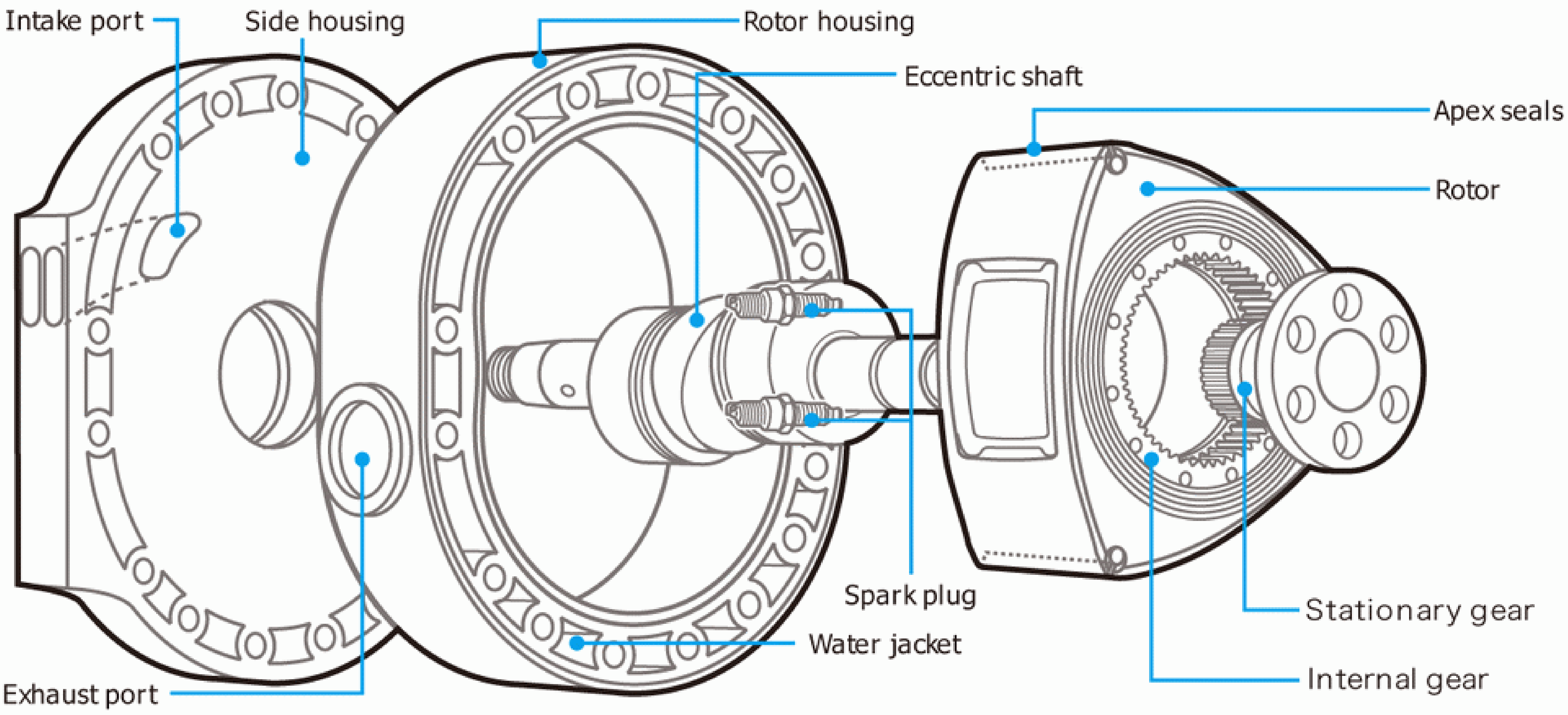
Rotary engines (also known as Wankel engines) produce power in a manner similar to reciprocating engines in that they go through the four stages of intake, compression, power and exhaust. However, these processes are performed in a very different way.

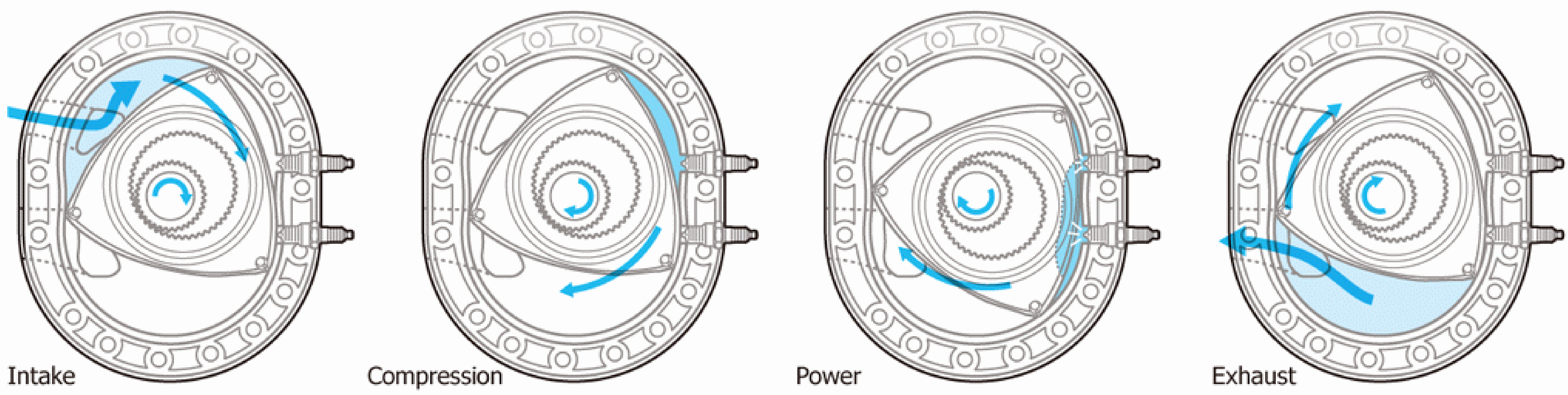
Instead of cylinders, this type of engine has a cocoon-shaped (epitrochoid) rotor housing, within which sits a triangular rotor. This rotor orbits the eccentric shaft within the housing, which expands and contracts the spaces between itself and the housing, and it is in these spaces that intake, compression, power and exhaust cycles are carried out. A rotary engine will usually consist of two or three of these rotors moving within an equal number of rotor housings.

In typical engines, the reciprocating movement of multiple pistons makes smooth power control difficult, and also produces a lot of noise and vibration. However, since rotary engines are based on rotational movement, the operation of the engine is much smoother. Another benefit of this type of engine is its lack of valves, which greatly reduces the number of parts. Rotary engines also used to be significantly lighter, and although advances in reciprocating engine technology have reduced this difference, rotary engines are still the more compact of the two designs.

The timing of the intake and exhaust processes in a rotary engine is dictated by the shape and positioning of the ports (the channels through which the gases move in and out) in the rotor housing wall. Tuning a rotary engine's intake and exhaust is a matter of changing the shape and position of these ports. Also, as rotary engines have no exhaust valve, and exhaust gases are emitted directly through the exhaust port with no interference, they work well with turbochargers.

Compared to a reciprocating engine, a rotary engine is at a disadvantage in terms of fuel consumption. This is due to the relatively large surface area in relation to the combustion chamber capacity, which causes increased heat loss and lower efficiency in converting thermal energy to mechanical energy.





Forced Induction

An increase in the amount of air flowing into an engine will result in an increase in power. The simplest way of achieving this is by increasing engine displacement.

However, it is also possible to achieve a similar effect without altering displacement, through a process known as "forced induction." This involves forcing more air into the engine through compression. Devices that perform this process are separated into two categories: superchargers and turbochargers.

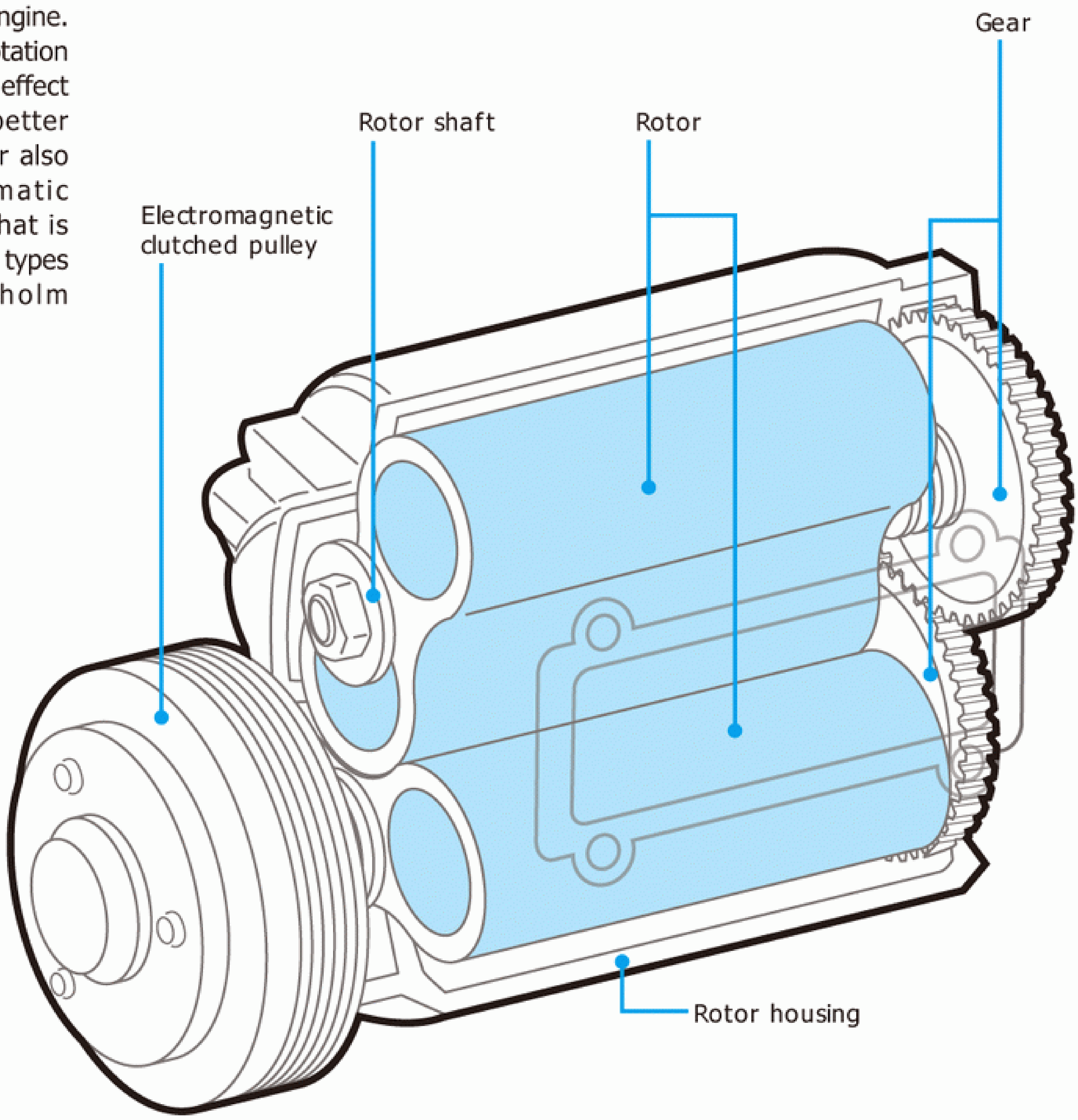
The amount of pressure added when the air is compressed is known as the "boost," and the more boost, the more power can be achieved. One atmospheric pressure is known as one bar, or 1kg/cm2 of air. If the boost is 1 bar, this makes a total of 2 bars of atmospheric pressure (1 bar of natural air pressure plus 1 bar of boost) of air entering the engine, which is double the normal amount.

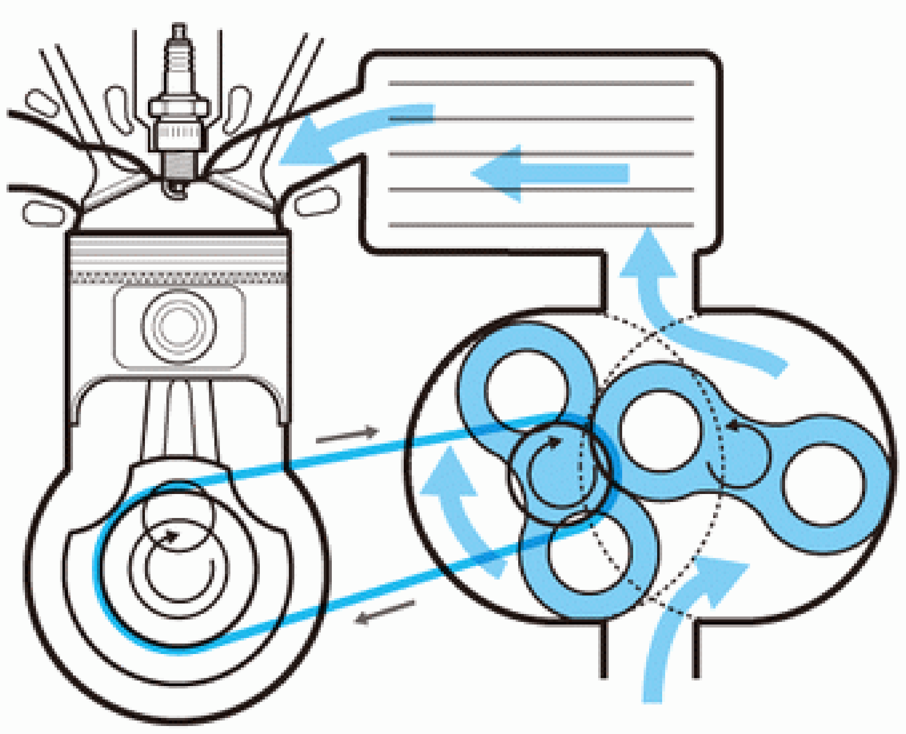
The problem with forced induction is that as pressure increases, combustion energy also increases, which can cause damage to the engine. For this reason, the internal parts of engines with turbochargers and superchargers are usually reinforced, and the compression ratio is lowered to solve the problem of improper combustion.

When air is compressed, its temperature is increased, and its density lowered. This effect is even more pronounced under intensive driving conditions or in hot weather, and prevents the engine from achieving maximum output power. It is said that a

Superchargers

A supercharger is a compressor usually powered by a belt attached to the crankshaft, which compresses air before it is introduced to the engine. Because the compressor is powered by the rotation of the crankshaft, it has a high supercharging effect at low RPM and accelerator response is better compared to a turbocharger. A supercharger also tends to work well in cars with automatic transmission. The illustration here is of what is known as a "roots blower," but several other types of supercharger exist, including Lysholm compressors and scroll-types.





Achieving the Same Effect as Increased Displacement

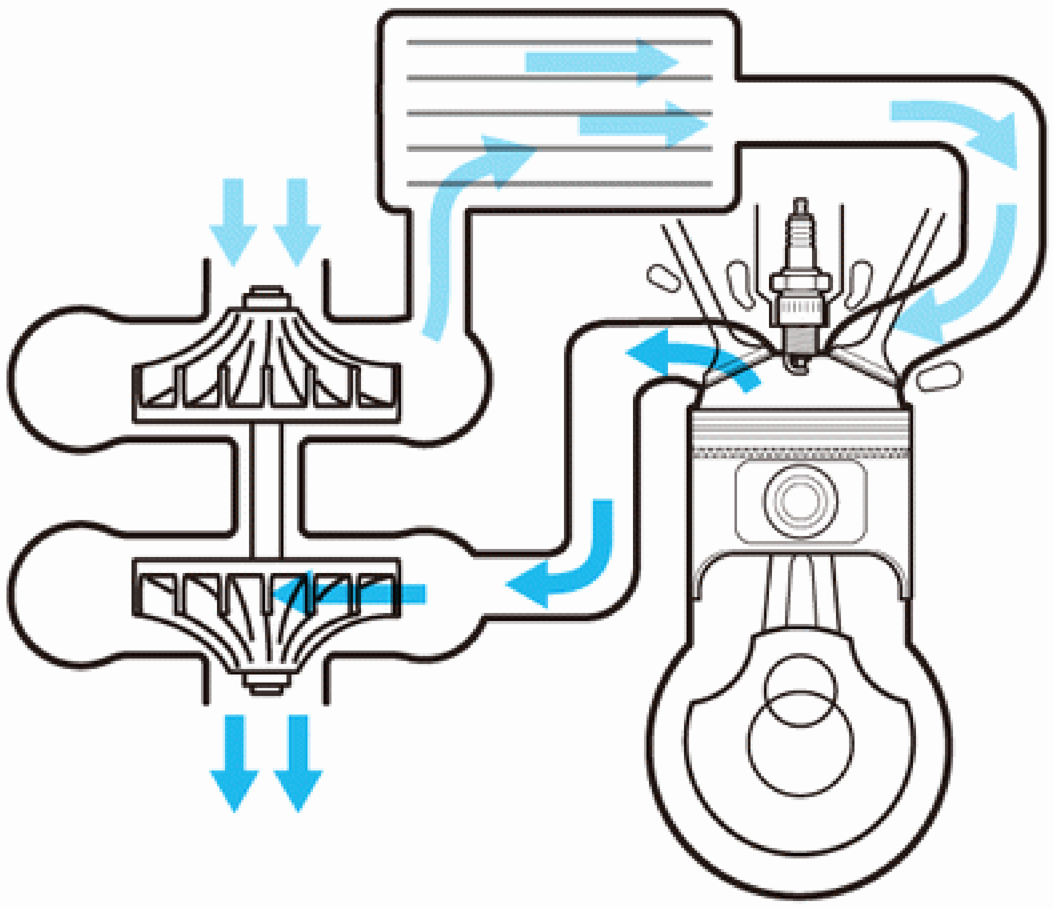
one-degree increase in temperature causes a loss of approximately 1 horsepower, so it is normal to include an intercooler device to cool the compressed air.

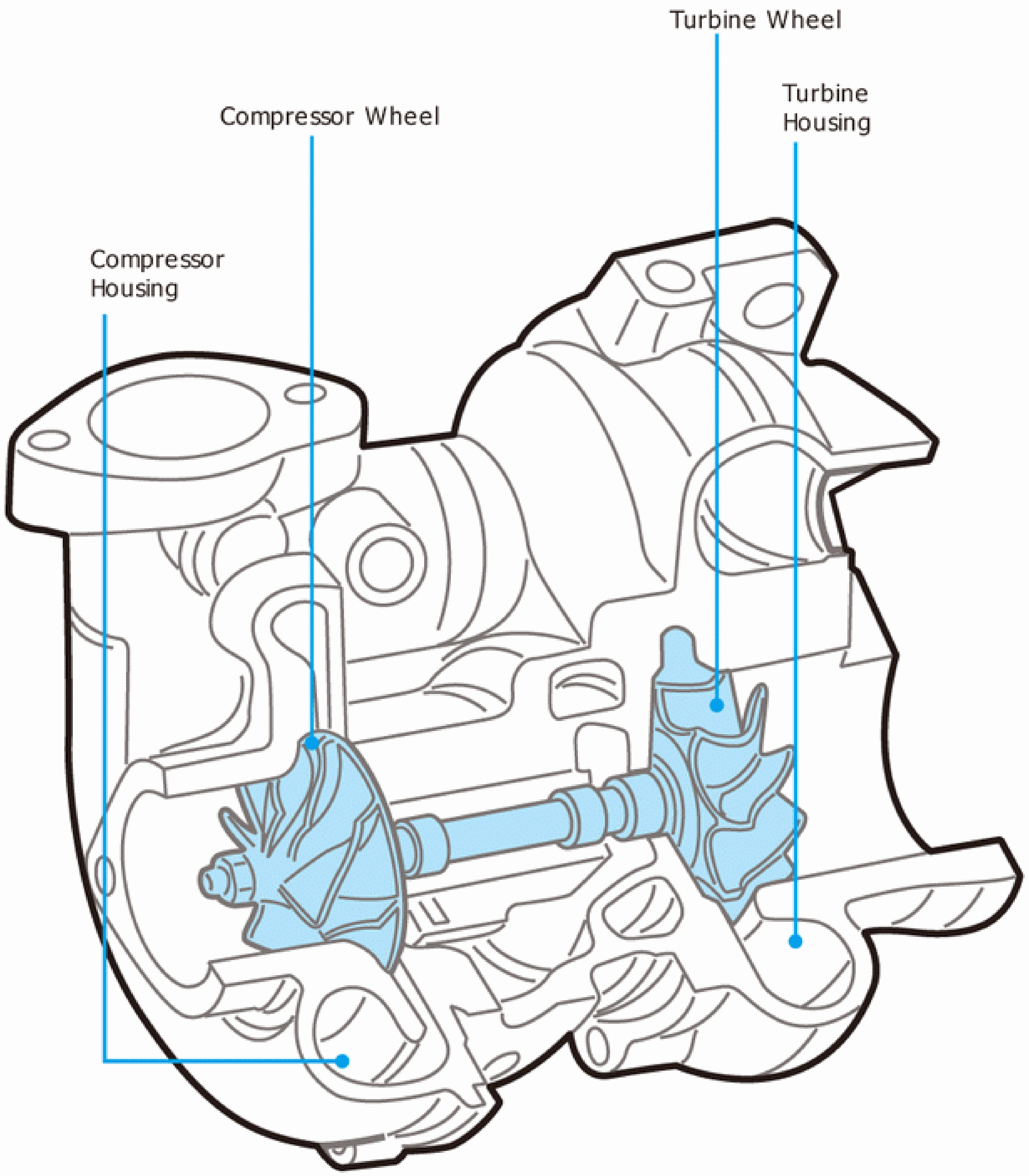
Turbochargers take time to kick in, as their forced induction is powered by exhaust energy and there is a time lag until the boost pressure rises. On the other hand, superchargers powered by the engine crankshaft do not suffer this delay, but they do sap a small amount of power from the engine because the crankshaft drives them.

Engines that harness the merits of both setups by utilizing a supercharger for low revs and a turbocharger for high revs have recently started to attract attention.

Turbochargers

Named "turbo" due to the turbine which powers its compressor. A turbocharger uses the gases released through the exhaust pipe to turn its turbine. Because it uses the energy from the exhaust gases, there is no power loss at high revs as there would be with a supercharger. However, at low RPM's of the engine where there is less exhaust gas produced, the turbine will not turn at operating speed and it takes time for the turbine to spool (speed up) when accelerating. This momentary delay in response is known as "turbo lag." A variety of systems have been devised to compensate for this, and they are still continuing to evolve. In Europe, turbochargers are increasingly being used for smaller engines for improved fuel economy.





Hybrid Systems

The purpose of a hybrid system is to increase fuel economy by using both an engine and an electric motor. Japan has been the leader in hybrid car development, and although these hybrid systems have been known mainly for their environmental benefits, European sports car makers have begun to develop some with the potential to power a new generation of high-performance vehicles.

The weakness of an internal combustion engine is its inefficiency when idling and accelerating from a standstill. On the other hand, an electric motor can generate maximum torque at almost zero revolutions, and because of its high efficiency, can compensate for the poor performance of an engine at low revs. A combustion engine is still more efficient at speed, so the overall efficiency of the hybrid car is achieved by combining the strengths of both systems.

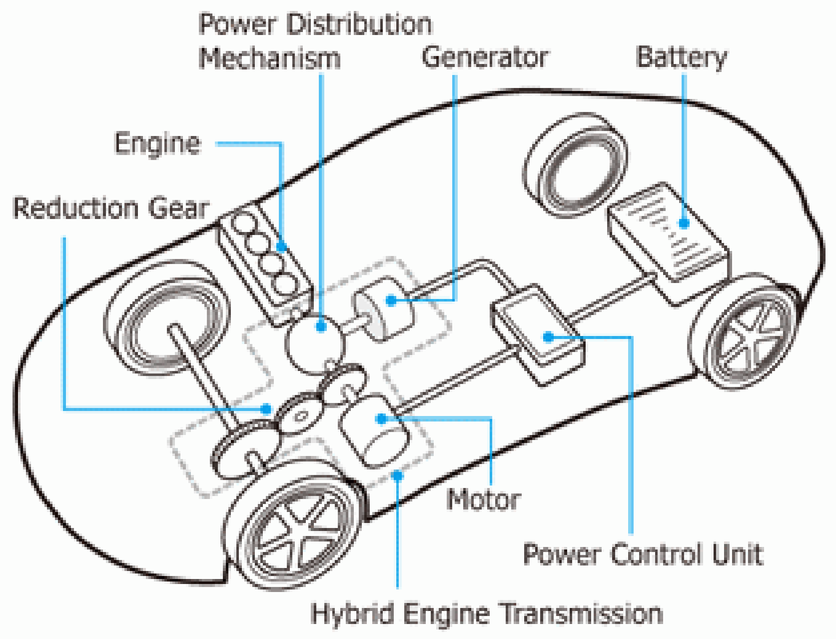
Another advantage of having an electric motor and a battery is that a hybrid system also benefits from the ability to recover energy. When decelerating by taking your foot off the pedal or when braking, the motor acts as a generator driven by the rotation of the wheels, which recharges the battery. This energy can then be reused afterwards to power the motor. In this way, the energy usually wasted as heat when braking can be reused to generate electricity instead.

Another benefit is that the motor can be made to behave like a supercharger for the engine. Many hybrids made by European manufacturers actually place emphasis in this direction, achieving the driving feel of a high displacement engine (with a small displacement engine) by adding electric motors rather than supercharging. Hybrid systems and their merits differ depending on how the motor and the engine are made to work together. There are now several types of hybrid systems in commercial use, but the variety will probably continue to grow. Hybrid engines for supercars are currently under development, and it will be interesting to see what kind of system will come into use in the future.

Driving Using Both Engine and Motor

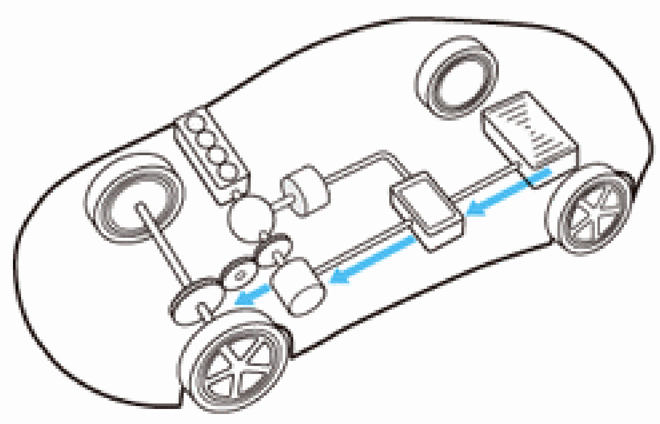
The Toyota Prius

System Overview



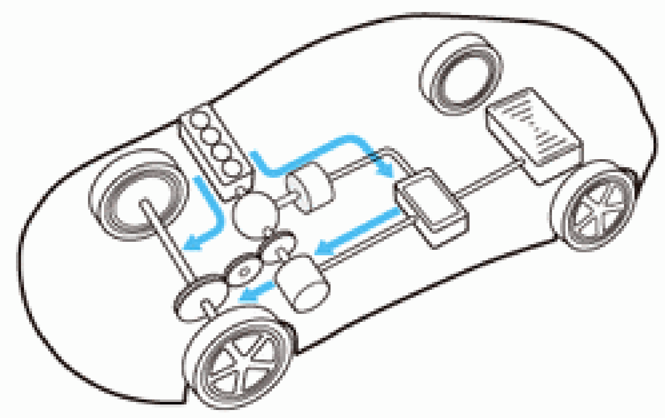
When Accelerating from Standstill or At Low/Medium Speeds

When accelerating from a standstill or driving from low speed to medium speeds, the engine is not efficient and is stopped. Drive power is provided by the motor alone.



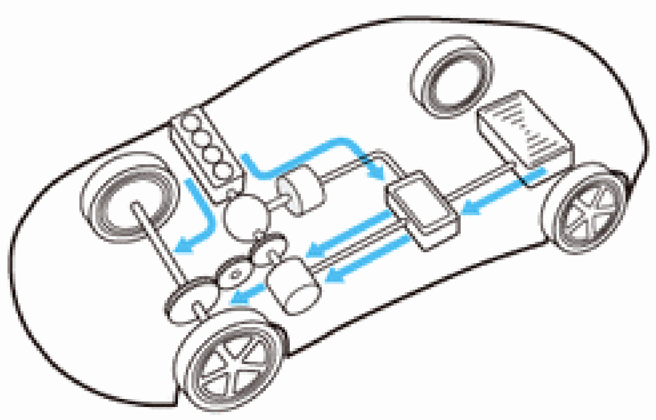
Normal Driving

Engine power is divided into two systems by the power distribution mechanism, one for driving the generator and one for directly driving the wheels.



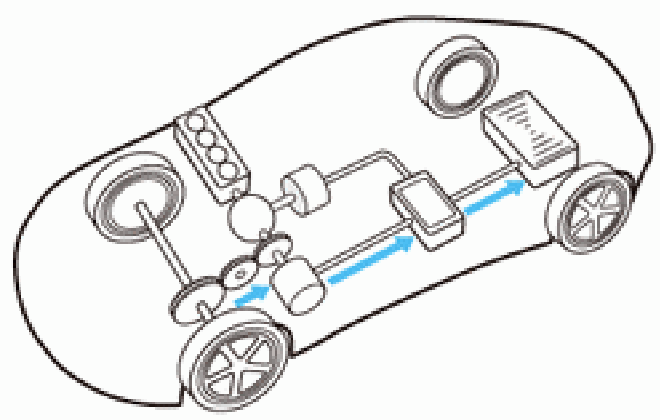
Rapid Acceleration

Boosted by the battery. Drive power from both the engine and the motor combines, resulting in good response and smooth acceleration.



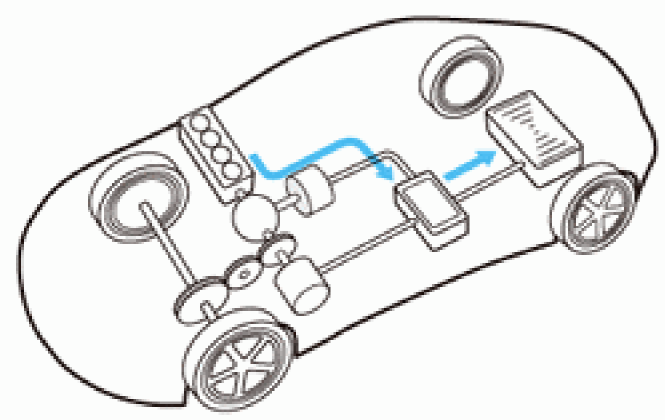
Deceleration & Braking

The wheels drive the motor, which functions as a generator, efficiently transforming the braking energy of the car into electricity, which is used to recharge the battery (also called regenerative braking).



Battery charging

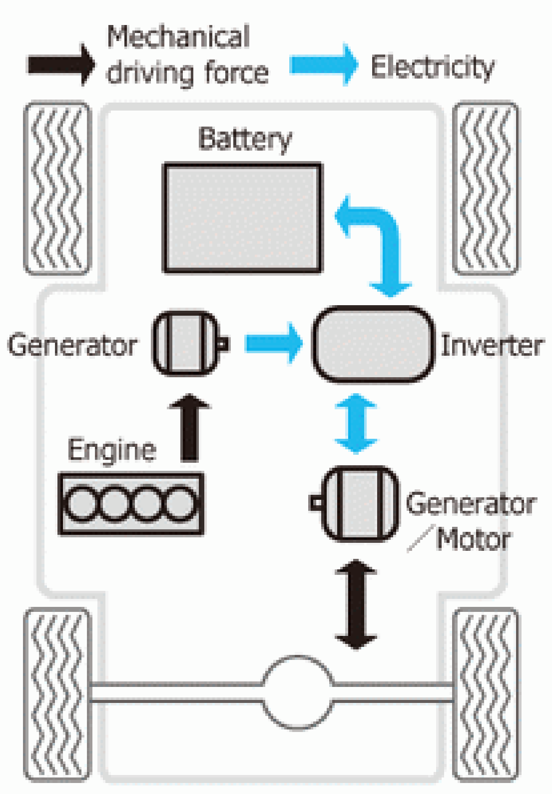
The battery is designed to maintain a constant level of charge. When the battery is low on charge, the engine will start up, drive the generator and recharge the battery.



Types of Hybrid System

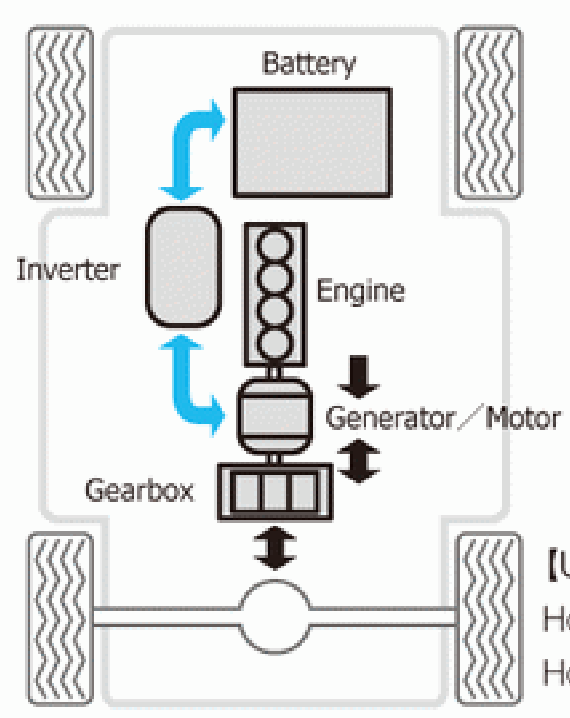
Series Hybrid

The role of the engine is solely to turn the generator, and only the motor propels the car. This system is simple, and the engine can be located wherever desired. This is basically an electric car with a generator.



Parallel Hybrid

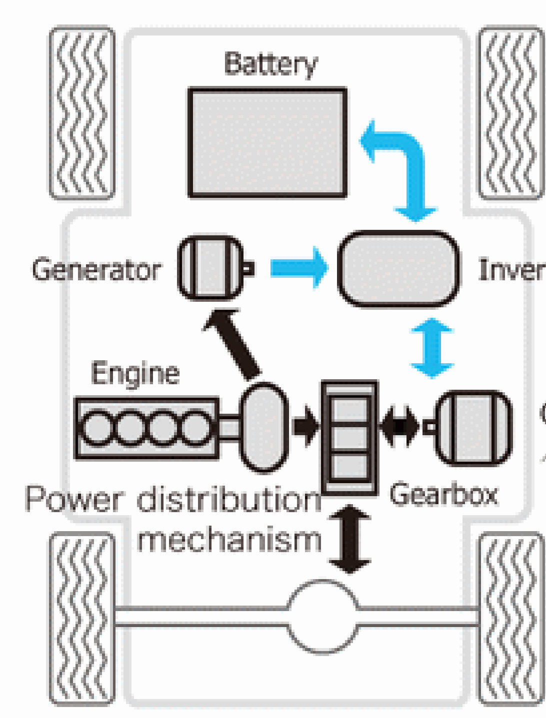
The engine and the motor work in parallel. The motor is usually located between the engine and the transmission, resulting in high productivity. The downsized engine still plays the major role in providing drive force, and the aim of the motor is to assist the engine, in an attempt to combine drive performance and fuel efficiency.



【Use cases】
Honda INSIGHT
Honda CIVIC Hybrid

Series-Parallel Hybrid

Also known as a power-split hybrid. The power distribution mechanism uses a planetary gear to divide power between the generator and the motor. At initial acceleration and at low-speeds the battery provides the power, while during normal driving conditions the engine runs at the efficient RPM range while running the generator and charging the battery.



【Use cases】
LEXUS HS250h
Toyota Prius

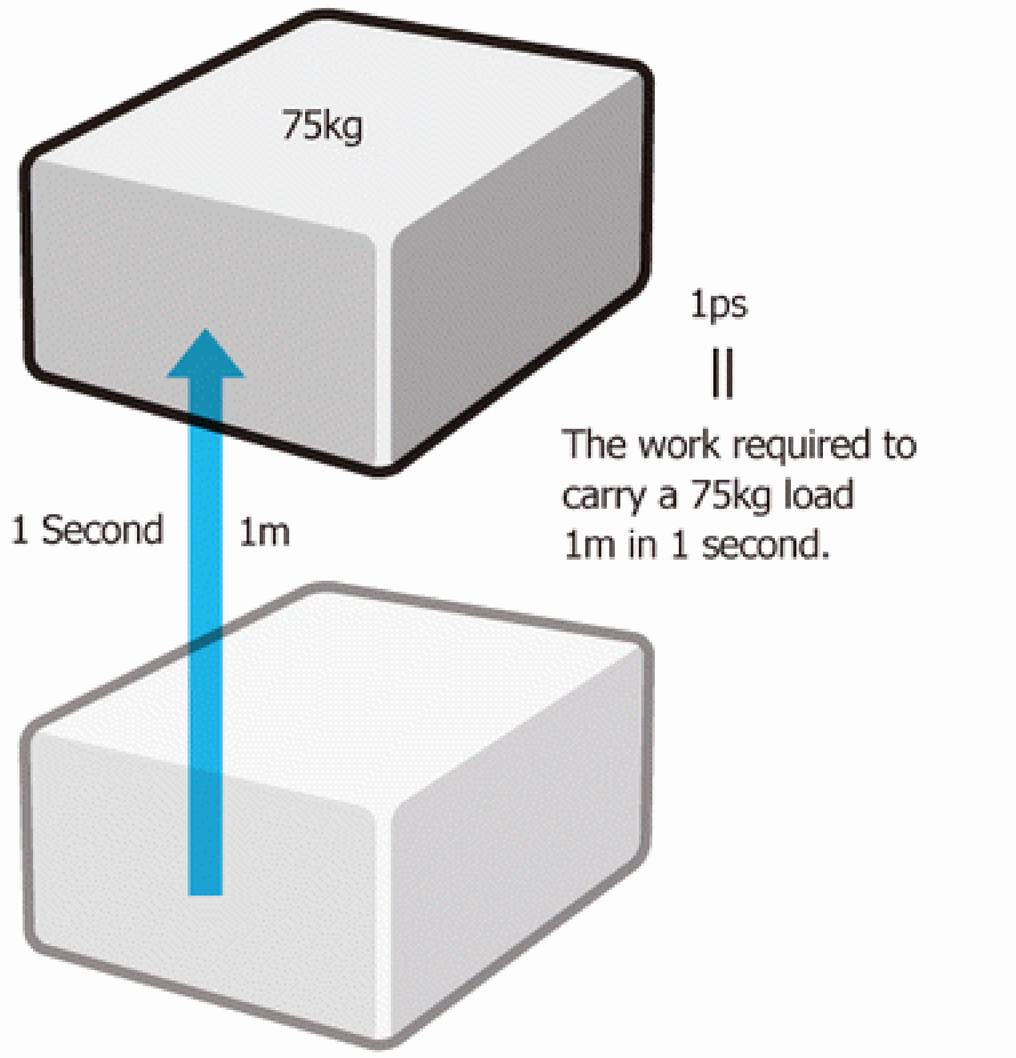
Performance Keywords

When looking at a vehicle's catalog specifications, you'll be presented with a whole host of numbers and specialist terms. It is important to have a good grasp of these in order to really understand a car's characteristics and potential.

There are five basic terms that define an engine's potential. You may think you are familiar with terms such as "horse power" and "torque," but let's take a closer look at them so we can really understand what they mean for a vehicle's performance.

Horsepower

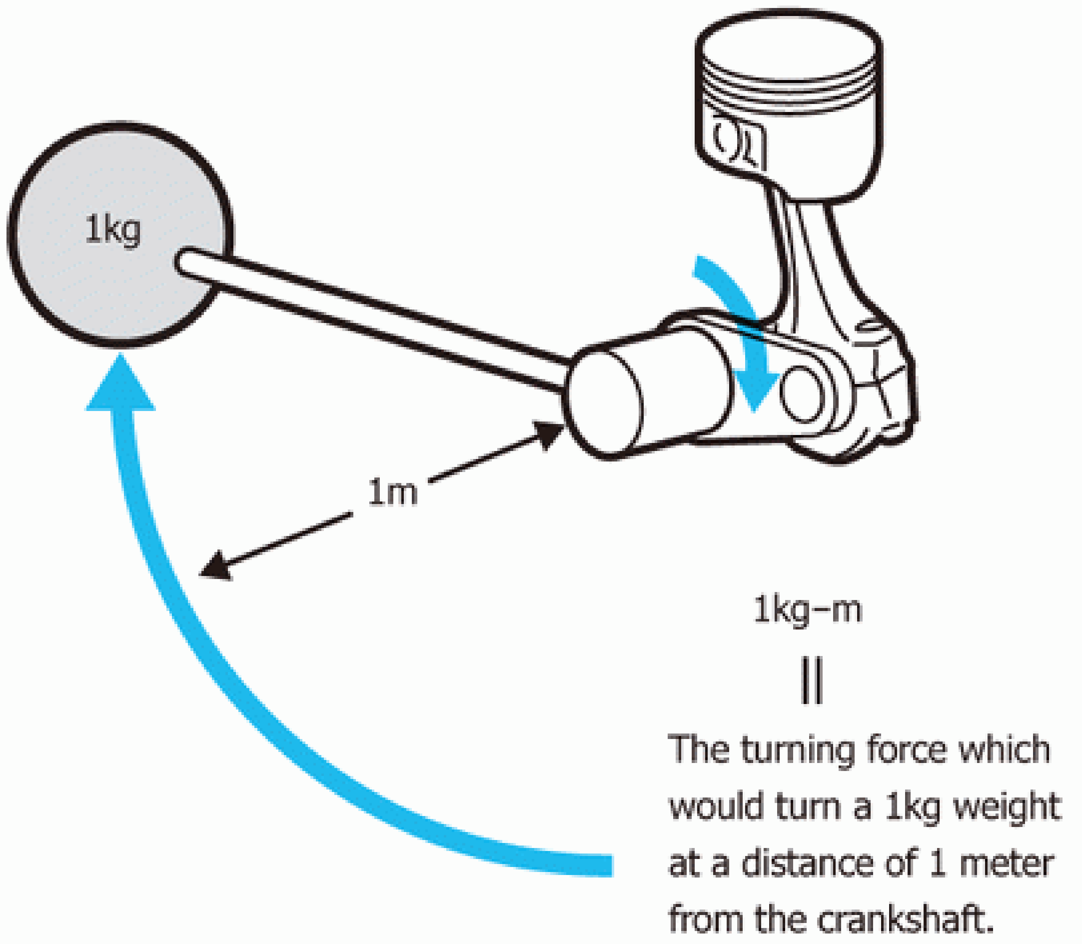
Horsepower represents the upper limit of the engine's ability, and is usually measured in units called "ps" or "HP." One horsepower represents the engine's ability to carry a 75kg load 1 meter in 1 second. In other words, a 100 horsepower engine could carry 1 ton 7.5 meters in 1 second at maximum power. Horsepower is calculated by multiplying torque by engine revolutions, so a low-displacement engine can still provide a large amount of output power if high enough revs can be achieved. Internationally, horsepower is also sometimes listed in kW. (1PS=0.735kW)



Torque

Torque is a measure of turning force. For example, using 1kg of force to turn a nut with a 1-meter-long spanner would be exerting a turning force or torque of 1kg-m. In terms of engines, torque describes the strength of the force acting to turn the crankshaft.

The higher the torque, the stronger the power maintaining the engine revs, and the easier the driver will find it to control the engine.



Displacement/Number of Cylinders

Displacement describes the volume of air-fuel mixture drawn into an engine. In a reciprocating engine, this is calculated by multiplying the volume of the cylinders where the piston reciprocates by the number of cylinders.

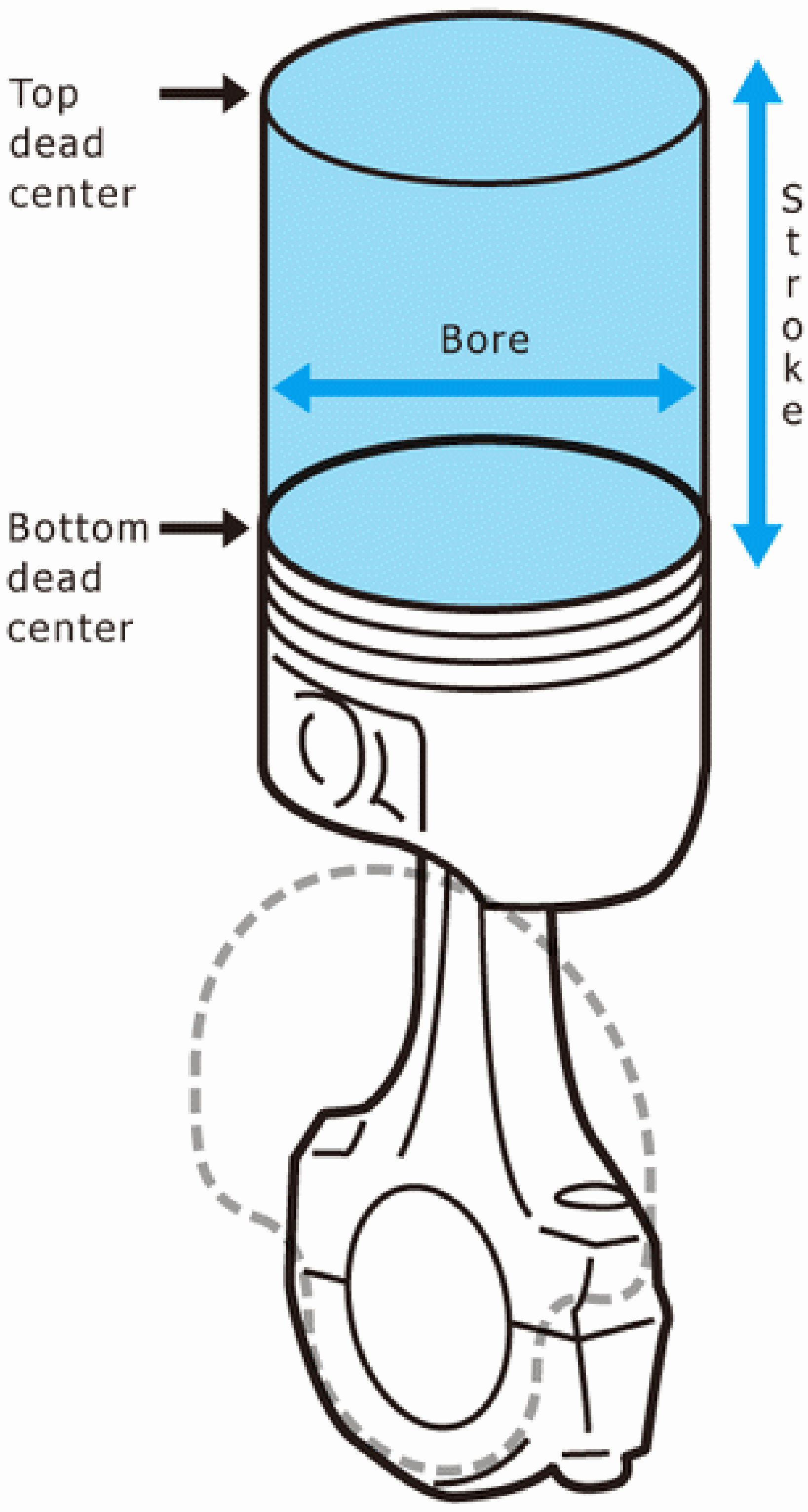
The more displacement, the greater the output power, but the larger the volume of a single cylinder, the less smoothly it will turn the engine. That is why the number of cylinders is increased to keep the volume per cylinder low. Also, increasing the number of cylinders also increases the number of combustion cycles per 1 rotation of the crankshaft, and the revolution of the engine becomes smoother.

Generally speaking, a cylinder's displacement should be between 350cc and 600cc. However, engines with a large numbers of cylinders are more expensive, so cylinder size is generally dictated by the size and class of the vehicle.

Bore/Stroke Ratio

The bore/stroke ratio is the relationship between the diameter of the cylinder and the length of the piston's movement within the cylinder. Engines with a ratio of less than 1:1 are known as "short-stroke" engines, while those with a ratio of more than 1:1 are "long-stroke." A ratio of exactly 1:1 is known as "square." The size of the bore/stroke ratio affects how the engine behaves. Generally speaking, a long-stroke engine can produce torque at low to medium revs, but power at high revs is harder to achieve, while the opposite is a true for a short-stroke engine.

It is also useful to know that when the piston is at the very top of the cylinder, this is called "top dead center." and when at the bottom of the cylinder, the condition is called "bottom dead center.."



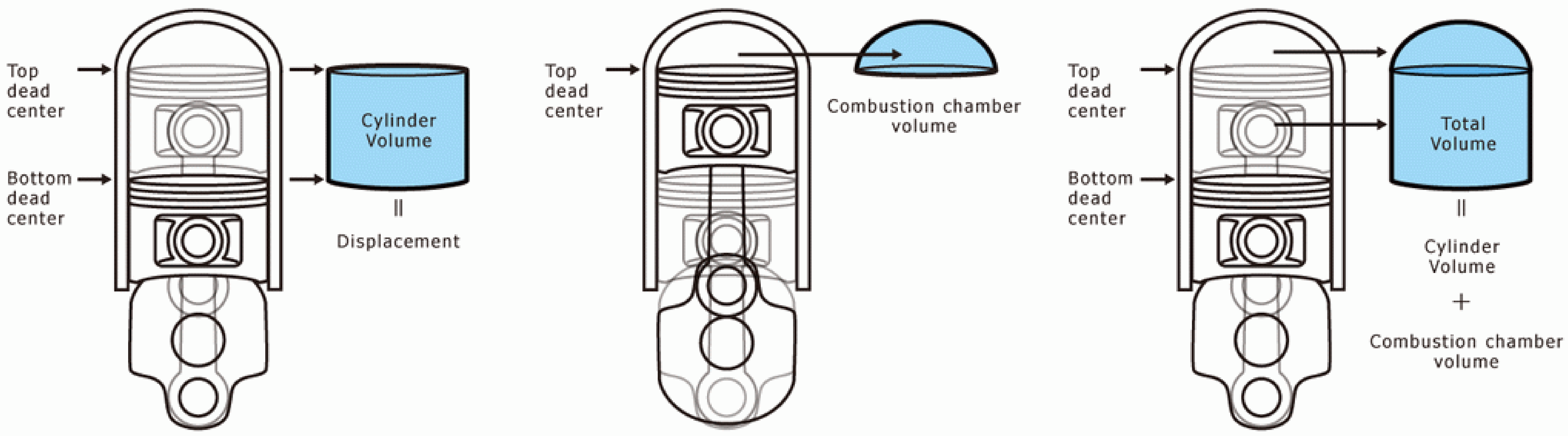
Compression ratio

The compression ratio describes how much the air-fuel mixture drawn into the engine is compressed. Engine power is greatly influenced by compression ratio.

The compression ratio is calculated by dividing the volume of the cylinder when fully open ("total cylinder volume") by its volume when fully closed ("combustion chamber volume"). Total cylinder volume is the displacement plus the combustion chamber volume.

For example, in a 2,000cc, 4-cylinder engine, displacement per cylinder is 500cc. If the combustion chamber volume is 50cc, the total cylinder volume is 550cc. 550cc divided by the combustion chamber volume (50cc) gives a compression ratio of 11.

Typically, naturally aspirated engines have a compression ratio of between 9 and 11. Compression ratios of over 10 produce high output for the amount of displacement. Engines with forced induction devices generally have compression ratios of between 7 and 9.



DRIVETRAIN

CHAPTER 02 Mechanism

The Drivetrain - Turning Power into Speed

Gearing and traction are necessary to turn power into speed.
The parts of the drivetrain have a massive impact on driving performance.

Transmission

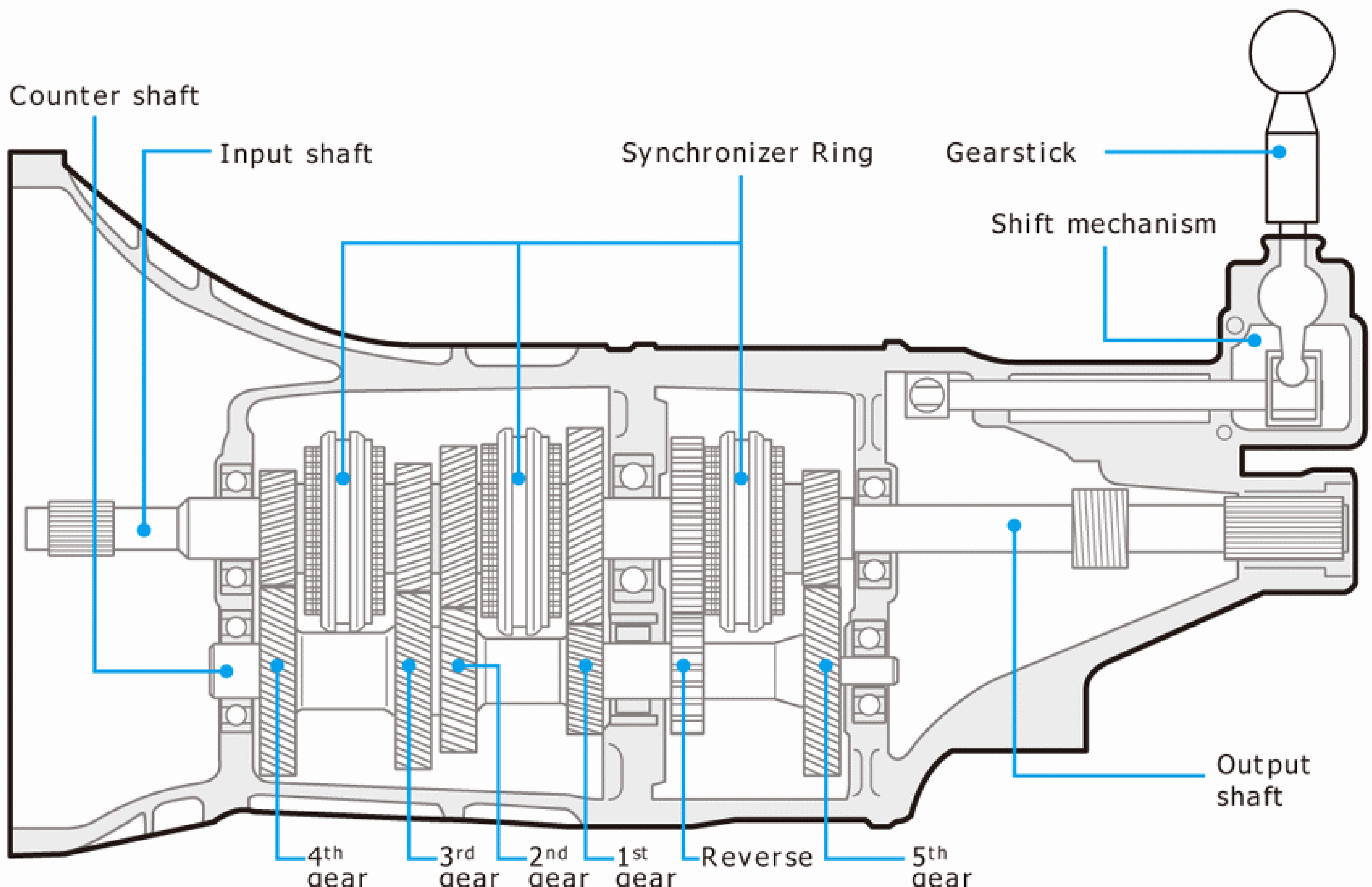
An engine revolves at anywhere between several hundred and several thousand times a minute. This would be too fast to turn the wheels directly, so an intermediate mechanism is needed. This is where the transmission comes in. The transmission uses different gears to transmit the appropriate amount of power and speed to the wheels for any given situation.

Let's look at how gears work. If a small gear is driving a larger gear, the larger gear will rotate slowly, but its torque will be increased. Conversely, if a large gear is driving a smaller gear, the small gear will turn faster, but with less torque.

The transmission can make use of these principles to fit the appropriate gear to the appropriate situation. A car needs most power when accelerating from a standstill, and conversely, only needs a small amount of power to maintain a steady speed. Thus, when accelerating from zero, a large gear (with slow rotation but high power) is used to transmit enough power to set the car in motion.

A large gear will create a lot of torque, but will rotate slowly. This means that in first gear, even revving to the limit will only produce speeds of several tens of kilometers per hour. This is why several gears are used, gradually getting smaller as the driver shifts up, and producing more speed and less torque. The ability to move freely between these gears allows the driver to use the right gear for the right situation.

On an actual car, in addition to the gears of the transmission which are connected directly to the engine, the overall gear ratio is determined by combining with another "final gear" that is between the transmission and the drive wheels. The gear ratio can greatly affect the driving characteristics of a car, and especially in circuit racing, the selection of the proper gears suited for the course will be a major key in improving your lap time.



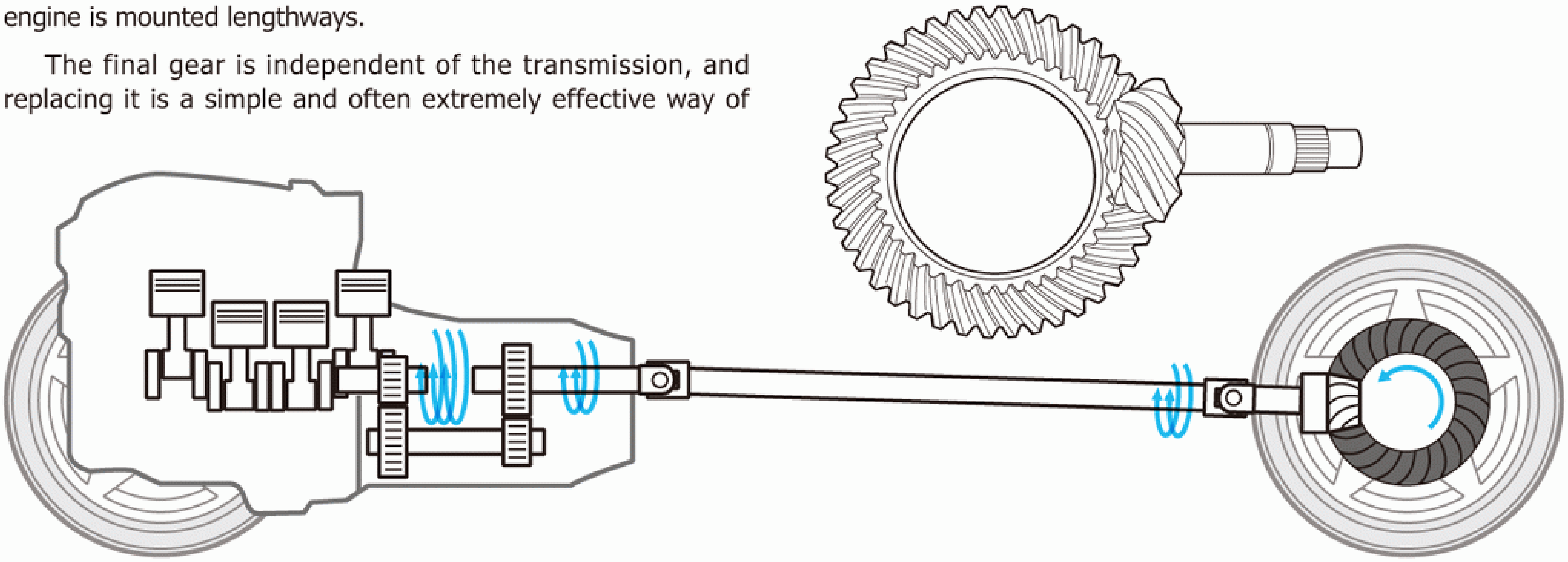
[Structural diagram for Manual Transmission]

Efficiently Harnessing Drive Power

The Final Gear

The gear that mediates the final transmission of power from the engine to the drive wheels is known as the "final gear." It is the last step in the chain that brings engine revolutions down to an appropriate speed to power the wheels, and also changes the direction of the power by 90 degrees in cars where the engine is mounted lengthways.

The final gear is independent of the transmission, and replacing it is a simple and often extremely effective way of adjusting how a car behaves. In sports cars, the gear ratio of the final gear is usually large to improve acceleration performance, but if the focus is on fuel economy, a smaller ratio can be used to reduce overall revs.



Types of Two-Pedal Transmission

AT

▶ Automatic Transmission

A common transmission that uses a torque converter (a type of fluid coupling) to automatically change gear based on speed and engine RPM. The system uses planetary gears controlled by hydraulic pressure. Has the advantage of smooth transition between gears, but the hydraulic slippage and loss due to the mechanism causes poor fuel economy.

CVT

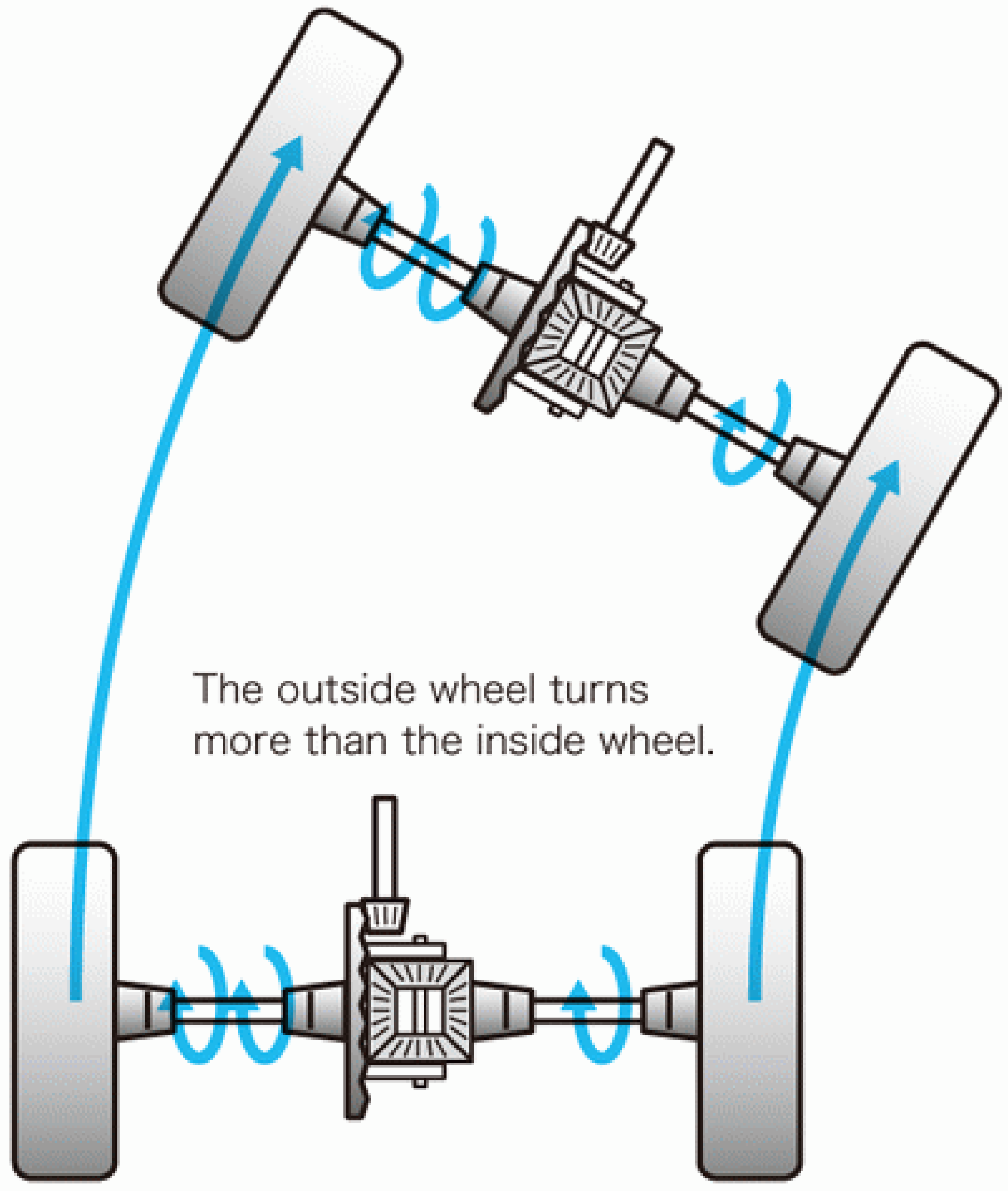
▶ Continuously Variable Transmission

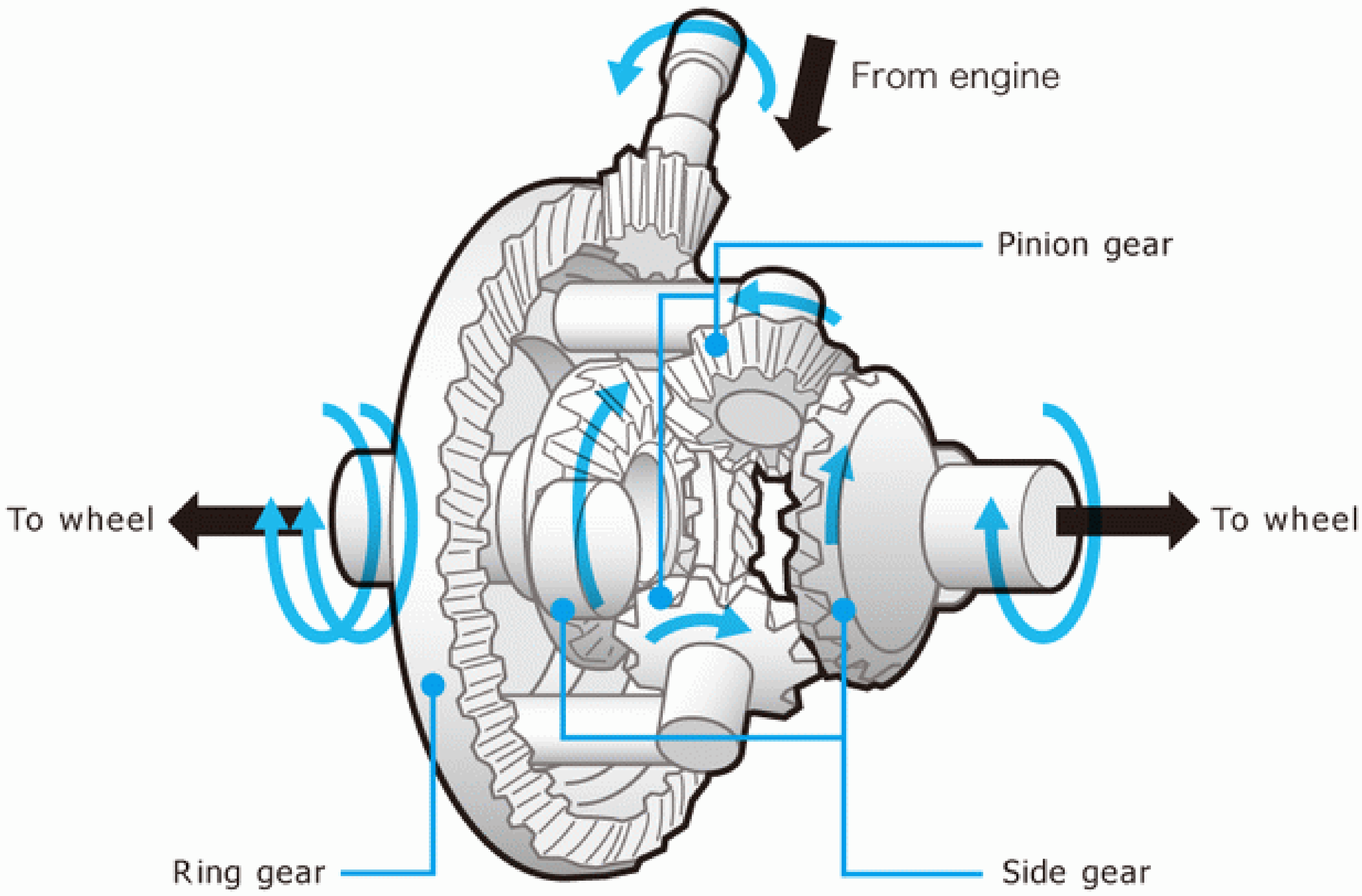
A continuously variable transmission does not change through gears one-by-one like a normal transmission. Instead, it uses two pulleys or disks connected by a metal belt or chain, to seamlessly and continuously vary the gear ratio. It is extremely smooth producing no shock from shifting, and allows the engine to run at peak efficiency under almost any conditions.

DCT

▶ Dual Clutch Transmission

A dual-clutch transmission is basically a system in which the operations of a manual transmission has been automated by the use of two clutches. Odd and even gears are separated onto two shafts, and by instantly switching between them with the clutch, it shows shifting performance that exceeds that of manual transmissions. In the AT, the rotational limit of the planetary gear places a restriction on the maximum RPM of the engine, but the DCT is compatible with high RPM engines. This is a transmission system that will continue to grow hereafter, being suited for both sports cars and eco cars. (see also "DSG" on page 117).





Differential

A differential is absolutely essential in vehicles with drive wheels on both the left and right sides. If we only ever drove in straight lines, differentials would not be necessary, but as soon as a car turns a corner, the need for one becomes very clear.

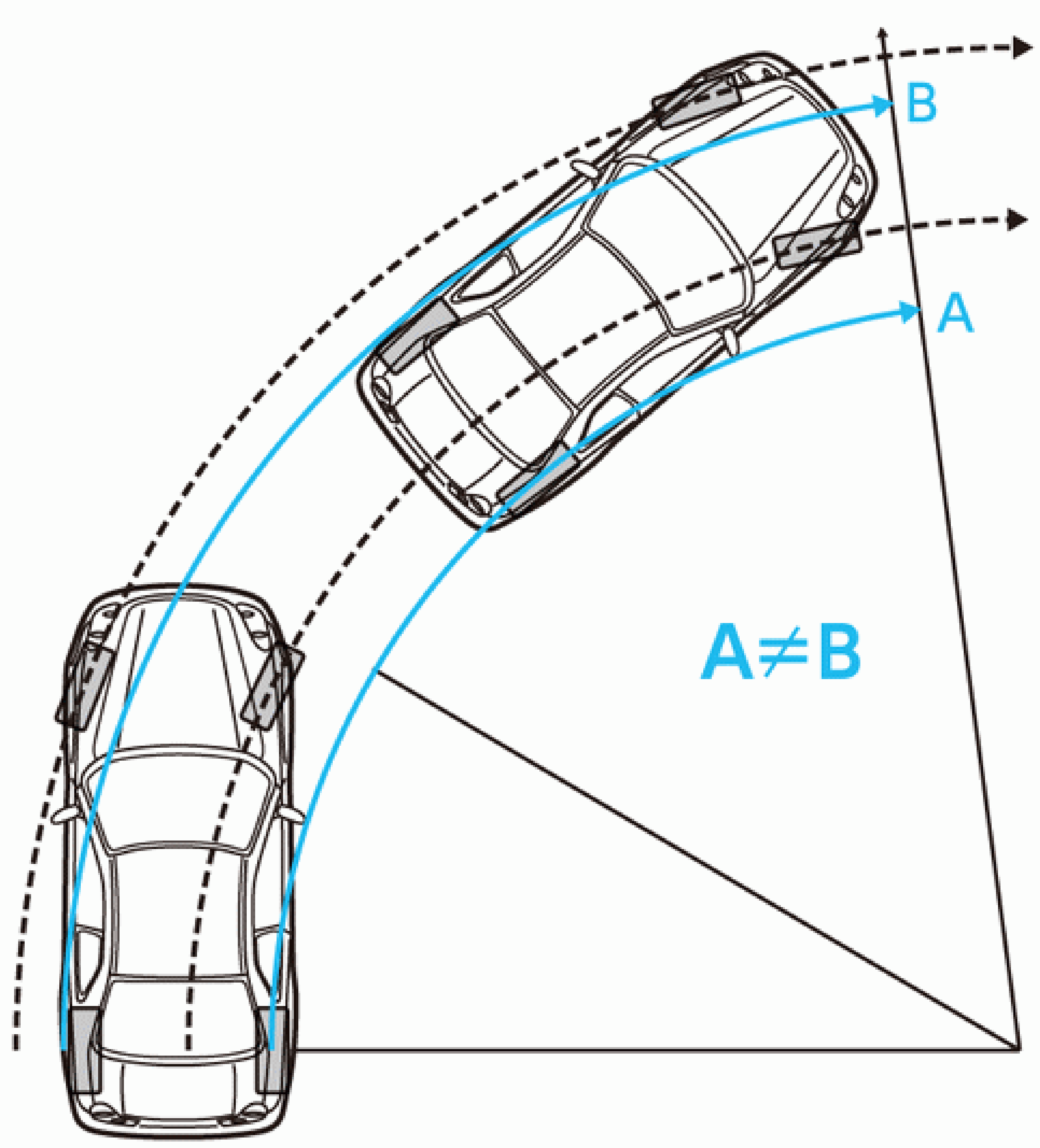
When cornering, the wheels on the outside of the corner have to travel further than the wheels on the inside. If the inside and outside drive wheels cannot be driven at different speeds when this happens, the inner wheel will resist and skid, and the car will find it difficult to turn. The differential is a type of gear integrated with the final gear, set between the drive wheels in order to solve this problem.

Take a look at the diagram to the top-right. Engine power is transmitted through the final gear to the ring gear. The ring gear has two pinion gears fixed to it, which turn the two adjacent side gears, and these gears transfer the power to the left and right wheels.

When the car is moving in a straight line, the rotation of the final gear operates the ring gear, turning the pinion gears, and is transmitting power evenly to both of the side gears. Here, both the left and right wheels turn at the same speed.

However, when cornering, the wheel on the inside of the corner generates resistance, and this is transmitted to the corresponding side gear. When this happens, the pinion gears that were revolving evenly with the side gears without turning will begin to turn to allow a difference in rotation speed to develop between the left and right wheels.

This means that slightly less power will be delivered to the wheel encountering resistance on the inside of the turn, and slightly more to the wheel travelling further on the outside, and each wheel will turn at the correct speed to negotiate the corner.



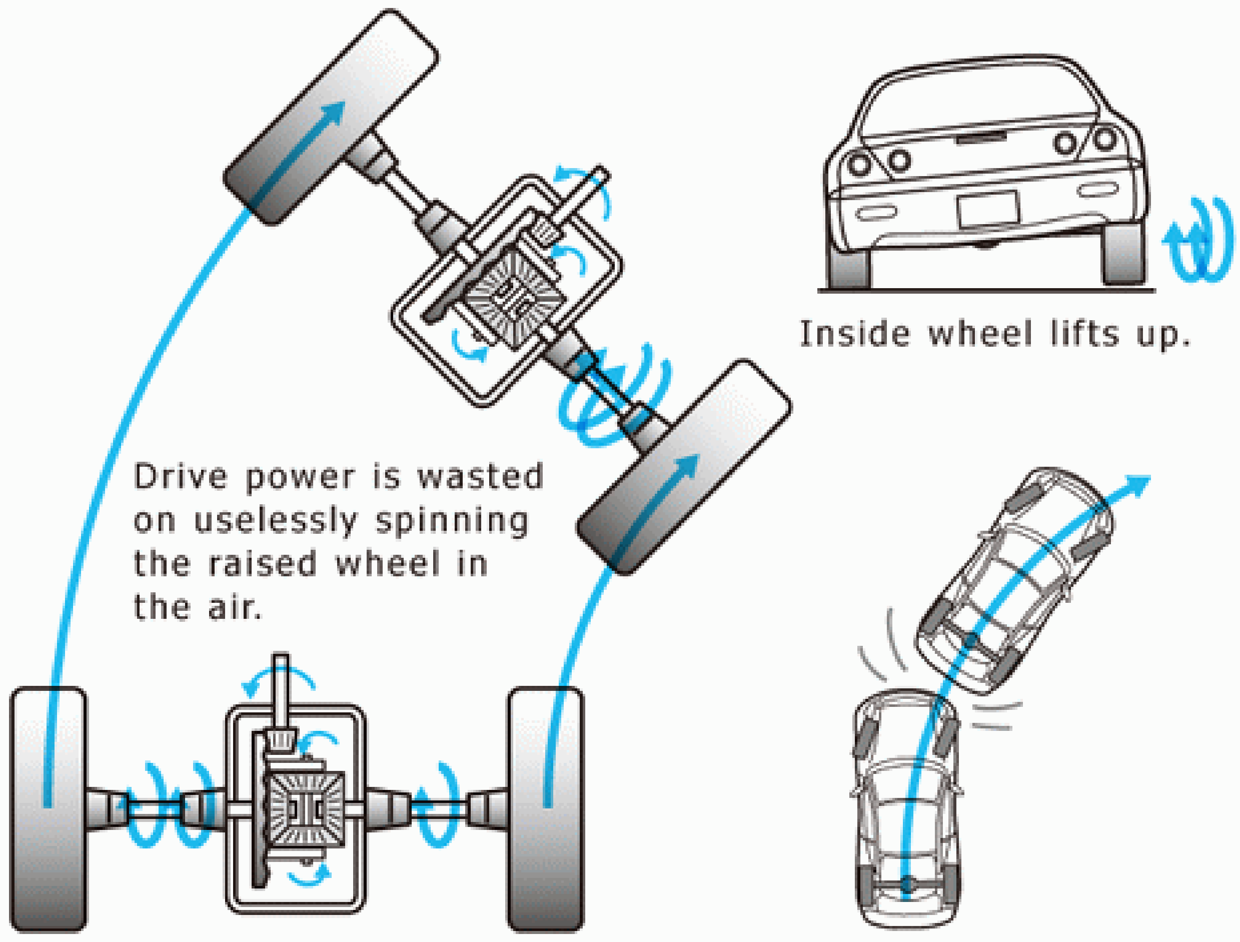
Smooth, Solid Cornering

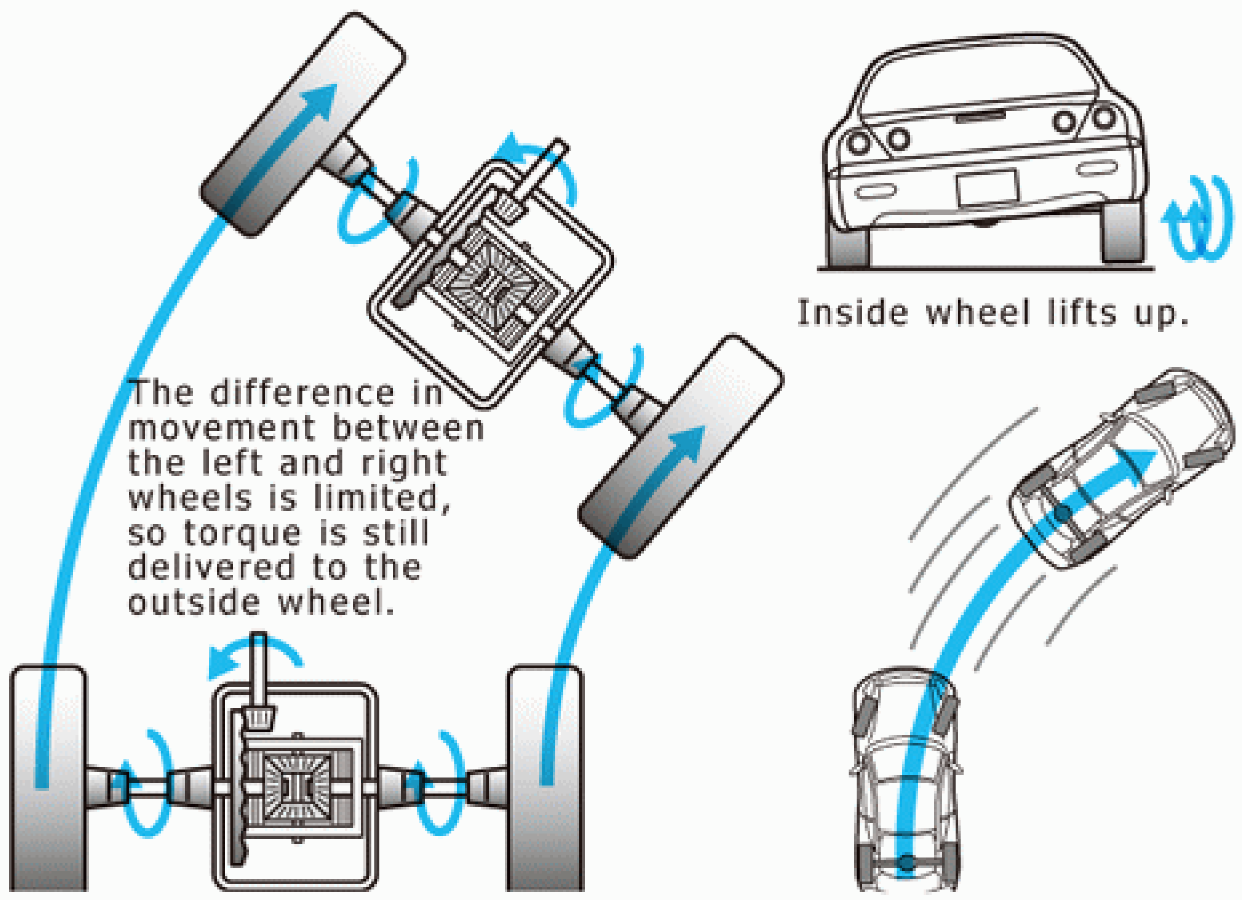
Limited-Slip Differential

We just went over the role of a differential in a corner, but they have one disadvantage. If one drive wheel loses contact completely with the road surface, the other drive wheel will not receive any drive power, and the wheel that is not in contact with the ground will spin wildly. This is because the differential is trying to correct the difference in rotation by transferring all the drive force to this one wheel. This phenomenon can also be seen in cars stuck in ice or snow, where the complete loss of traction on a single drive wheel again causes that wheel alone to spin uselessly.

A limited-slip differential (LSD) is a system that is designed to suppress the function of a differential, when there is more than a certain amount of difference in rotation speed between the right and left drive wheels. The idea of an LSD is to ensure that the correct amount of drive power is distributed between the drive wheels by using a device to limit the difference in turning speed between the two side gears. There are several ways of achieving this, including multi-clutch systems, electrically controlled systems, and systems that rely on friction acting in viscous fluids.

In sports cars, LSDs are used not so much for escaping mud and snowy potholes, they are used to ensure effective use of drive power and improve handling.





Types of LSD

Torque-Sensitive Type

A system that employs specially designed gears. When a difference in torque arises between the left and right wheels, resistance increases between these gears, limiting the amount of difference that can occur. As these systems can place strict limits on drive-wheel speed difference, they are effective in demanding driving situations such as circuit driving, and their response time is also very short. There are several types of torque-sensitive LSD, including multi-plate, Torsen and helical.

Speed-Sensitive Type

These systems generally restrict the differential using a highly viscous silicon oil rather than gears. The most common system of this type is the viscous-type, which uses the shearing resistance of the oil, but there are also so-called "orifice-type" systems that use the resistance of oil moving through small orifices. These systems cannot restrict movement as well as the torque-sensitive types, and their response is not as good, but they are easier to control on low-traction surfaces.

Active-Control Type

Electronically controlled systems that use a computer to gather and collate information from sensors and control the difference in drive-wheel rotation. Many competition racecars, particularly rally cars in the WRC use these systems, and some commercial vehicles have also adopted them. Limitation of the differential's operation is controlled by friction plate pressure, using a hydraulic or electromagnetic clutch.

B O D Y

CHAPTER 02 Mechanism

The Framework that Supports it All

A car's body shape and construction can affect its performance just as much as its engine and transmission. This is the foundation that determines the good or bad in controllability.

Body Performance Requirements

Along with the engine and suspension, the body makes up the basic framework that dictates how a car will behave. The most desirable qualities in the body of a car are rigidity, strength and, once those two have been established, a lightweight construction. The best way to think of rigidity and strength is in terms of "resilience against deformation" and "resilience against breakage" respectively.

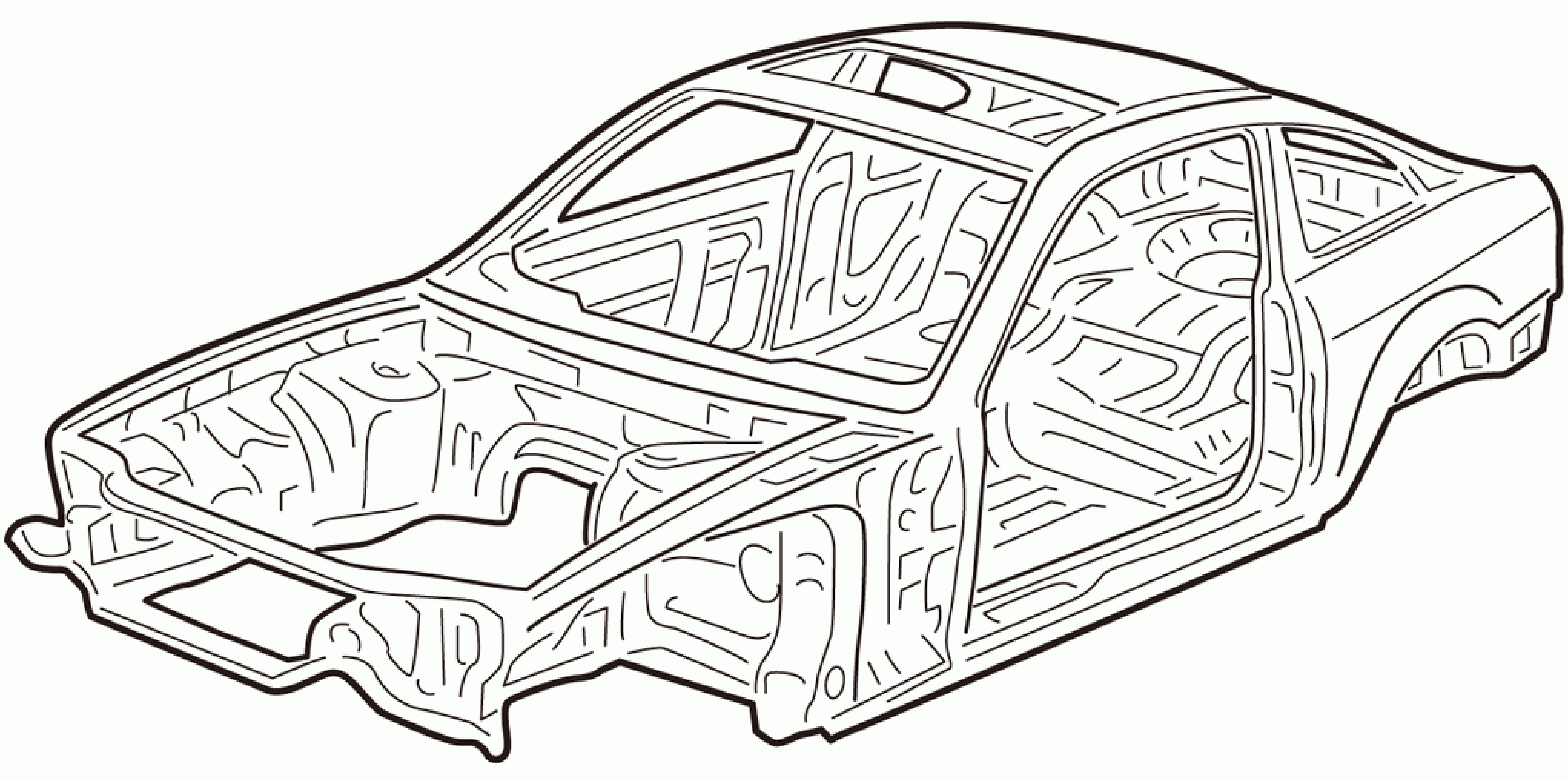
Rigidity has a particularly strong influence on driving performance. For example, when load increases or shifts while driving on a bumpy road or cornering, a rigid body will not bend or change shape as a result.

Even if the body shape does change, it should return to its original shape immediately so that the suspension can operate normally and the tires can continue to grip the road. The more rigid a car's body, the easier it is to transmit power to the road surface, the more predictable the car's behavior will be, and the easier the car will be to drive. Conversely, if the body deforms easily, it will be more difficult to transfer power to the road surface, and maneuverability will suffer greatly.

The forces acting on the body of a car are not constant. There are those that have a slow and gradual effect, and those that impact suddenly and violently. Cars are often described in their publicity material as having good rigidity when turning or under torsion, but this usually means only when these forces are applied slowly. A truly rigid body should be able to sustain sudden impact from any of the forces that may act upon it.

Strength can be thought of as a car's toughness. If a car with low strength takes an impact, it will sustain heavier damage. However, it is not enough just to minimize damage - a car with high strength must be built in such a way that the shock of an impact is not transferred to the passengers.

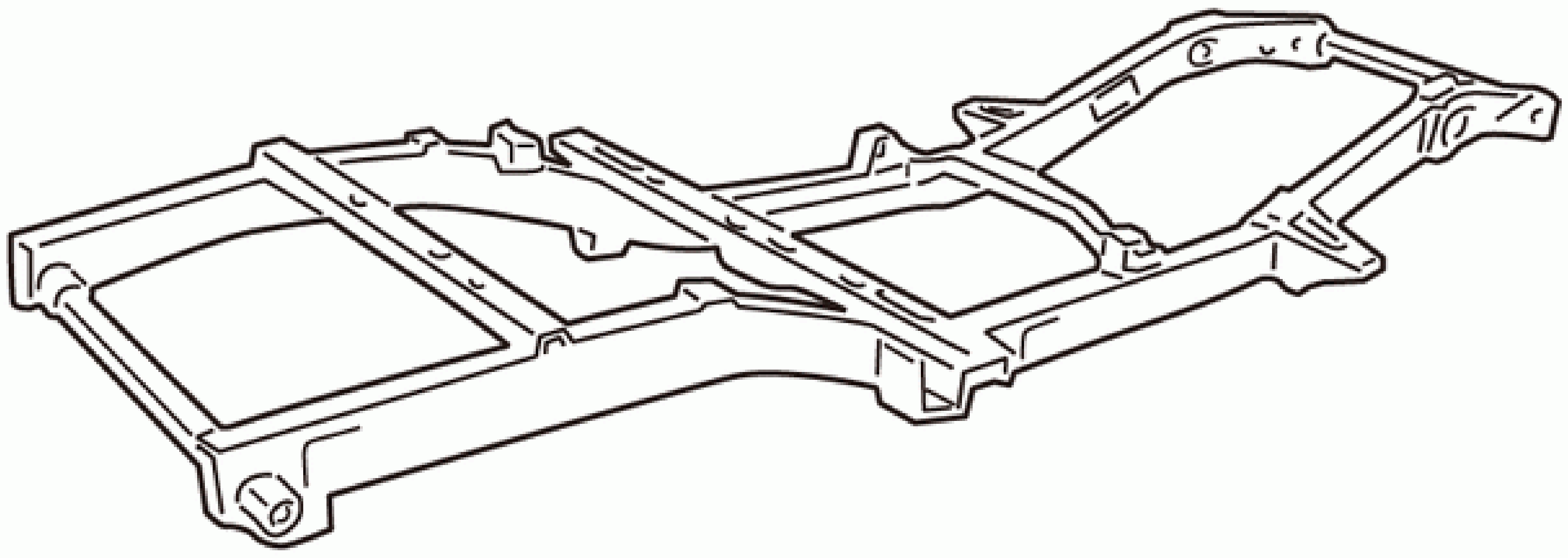
Ideally, a car's body should have a good balance of high rigidity and strength. The easiest way to increase both of these qualities is through reinforcement, but then an increase in weight becomes unavoidable. This is the major reason why convertible cars without roofs actually become heavier than closed top cars, as their floors are reinforced.

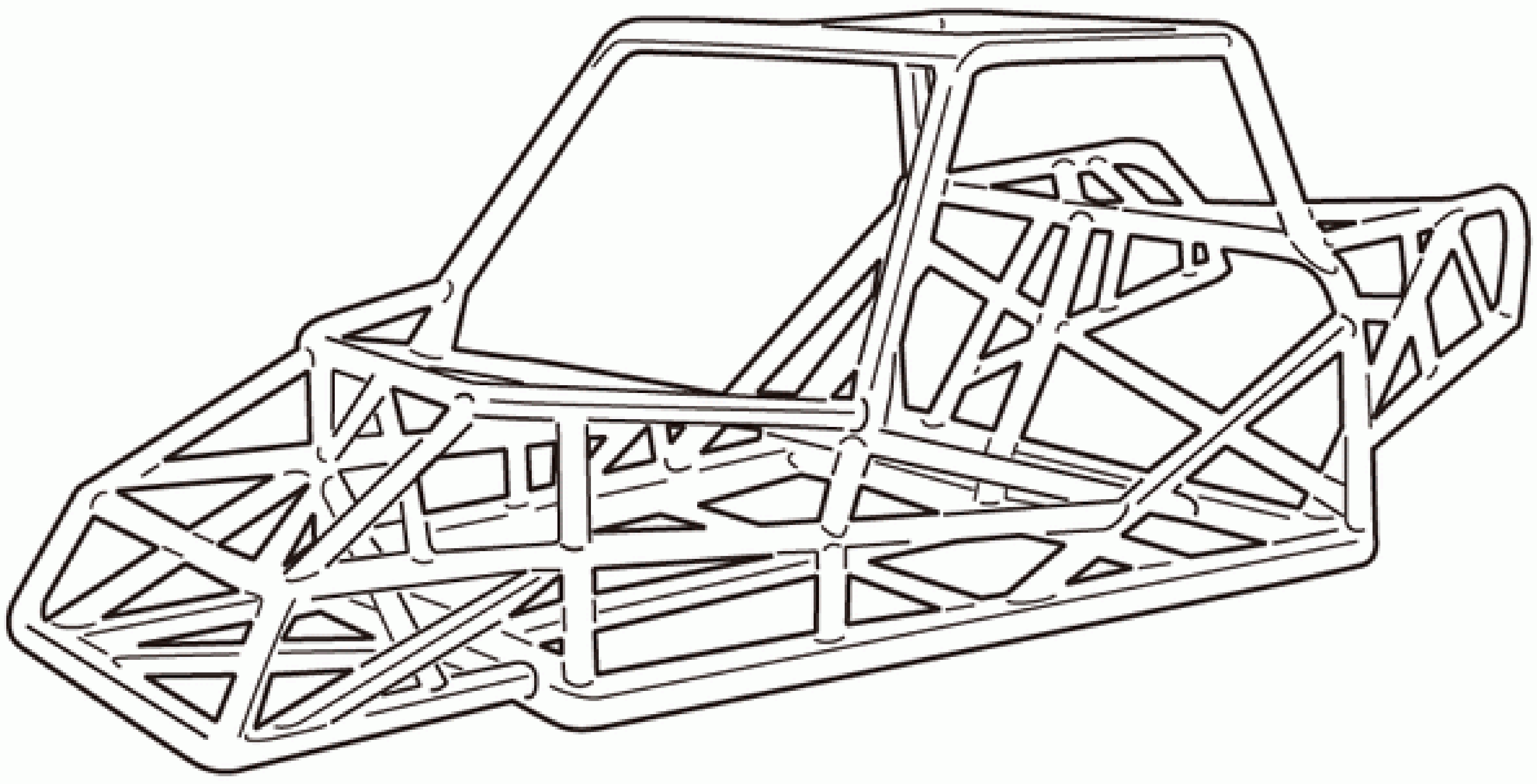


Strength and Rigidity

Body-on-Frame

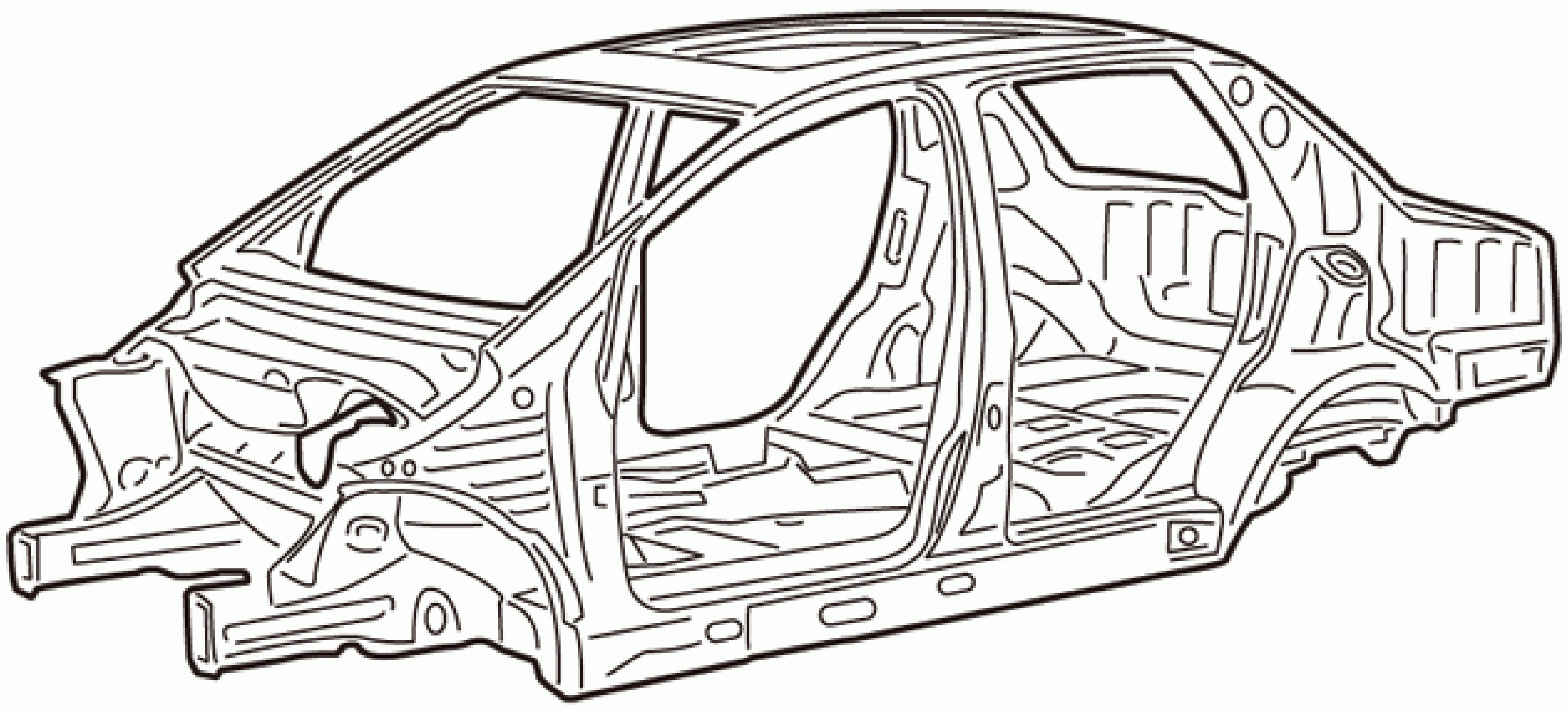
In separate frame or body-on-frame types, the engine, transmission, suspension etc. are fixed to a frame, and then a separately manufactured body is attached. There are various frame designs, including ladder, backbone, perimeter and platform, but ladder frames are the cheapest and also the easiest to strengthen, and are therefore the most common, particularly in off-road vehicles. Another type of body-on-frame design is created by welding lots of small pipes together to make a frame to which panels can then be attached. This is known as a multi-tubular frame, and cannot be disassembled once built. However, it is easier to achieve high rigidity and a lightweight body with this type of frame, and modification and repairs are simple, so this construction is often adopted for racing cars or low-volume production sports cars.





Monocoque Body

This is the most common body type in modern vehicles where the frame and body are combined. The strength of the body is created by through the entire assortment of parts like the component body panels, and is lightweight and rigid. It also has the advantage that the floor height can be lowered, and it is excellent at absorbing energy in an impact. The fact that the engine and suspension are directly attached to the body initially caused problems with ride quality and noise, but advances in suspension and engine-mounting technology have made these problems a thing of the past.



BRAKES

CHAPTER 02 Mechanism

Brakes – Thermal Exchangers that Reduce Speed

A car's brakes turn drive energy into heat energy in order to decelerate. Not only must they have stopping power, these essential components must also be able to dissipate heat effectively.

Construction and Principles

A car's brakes turn kinetic energy into heat energy to achieve deceleration. The brakes are also responsible for ensuring a car doesn't move when parked.

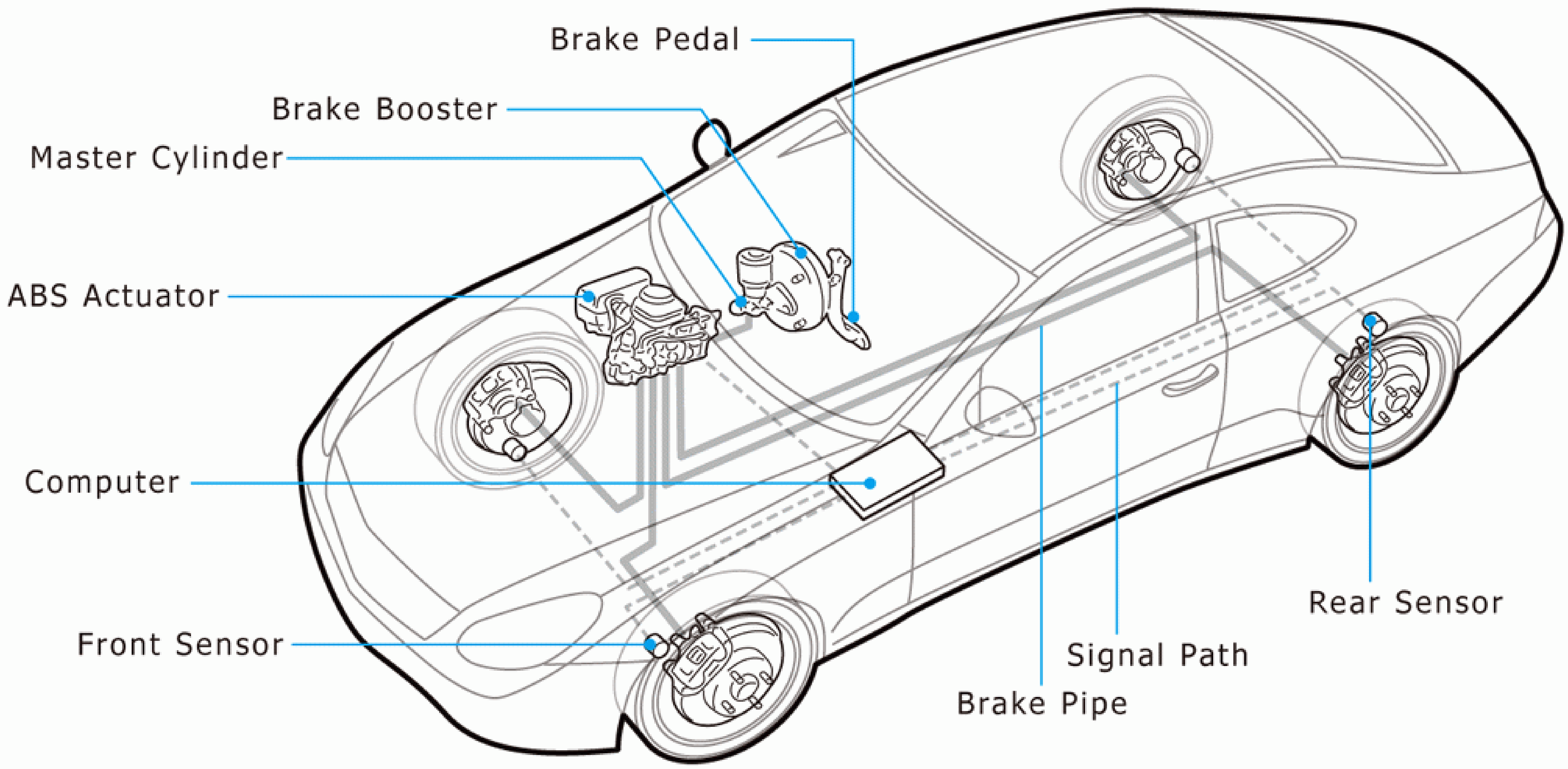
The basic components of a brake system involve a control device, which takes the input from the driver, a hydraulic system that relays the control operation, and the actual braking device. Recently, this process has been improved with the introduction of control mechanisms that multiply driver input to increase braking power, and ABS systems that stop the wheels from locking up.

The brake pedal and the brakes are connected via a hydraulic line. Since the Pascal principle applies to a hydraulic line, the brake pedal is connected to a large cylinder. The pressure built up at this cylinder is boosted and sent to the brake pad or brake shoes. The pads and shoes are made of high friction materials, and by pressing these against the brake disc or brake drum, kinetic energy is converted into thermal energy, thereby slowing the car down.

The fluid used in the hydraulic line is not oil, and is a specialized fluid made for brakes. Brake fluids must not boil when exposed to the heat of the brakes, and there are various types of brake fluids with various boiling temperatures available.

As motorway driving has become more common, the front brakes of most road cars have moved from drum to disk brakes. In a disk brake system, braking force is applied on both sides of the brake disks by the brake pads that are supported by the caliper.

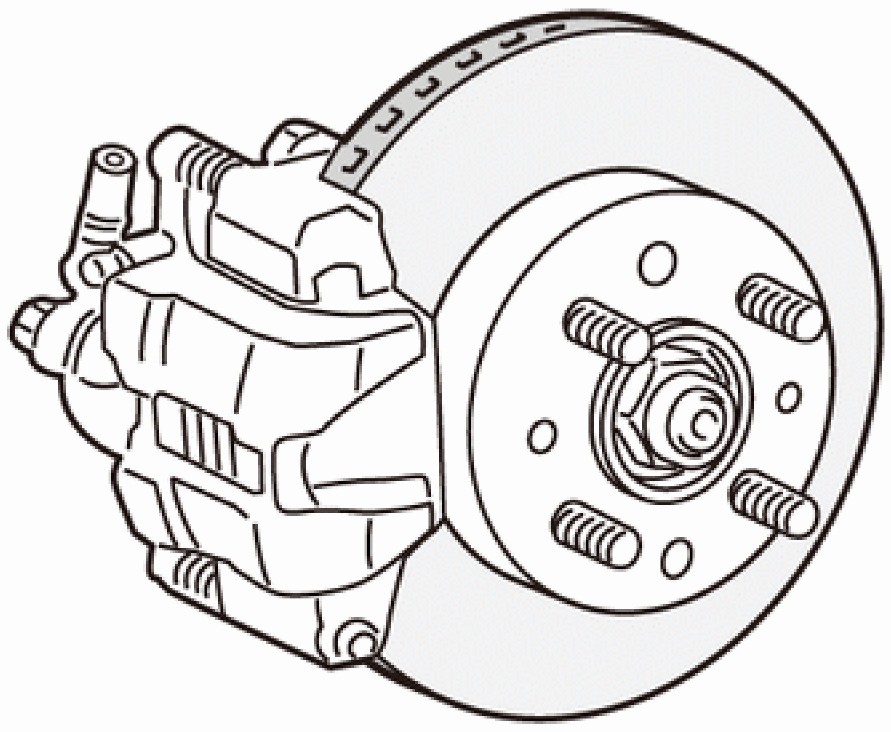
Disk brakes have advanced along with other car technologies, and ventilated disks with improved cooling properties have been developed. Caliper technology has also improved, with traditional floating calipers being replaced by large, high performance opposed-piston calipers.

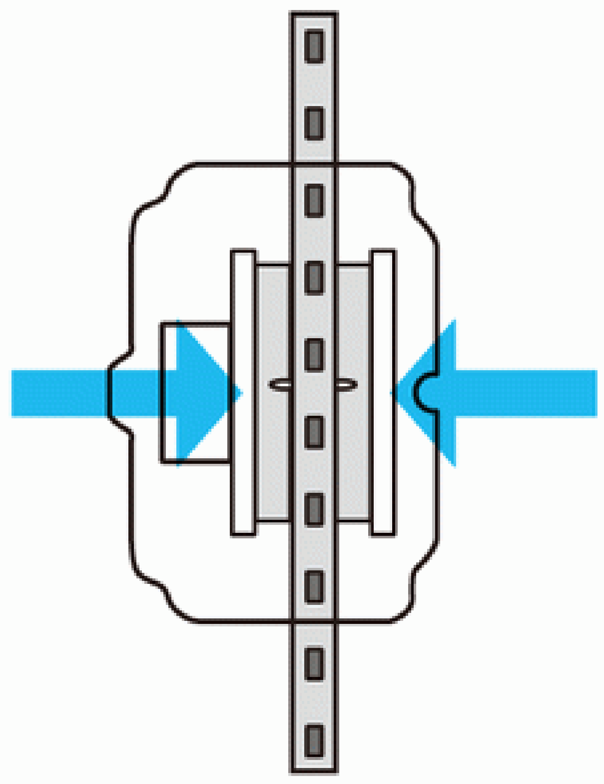


What Makes a Car Stop?

Disk Brakes

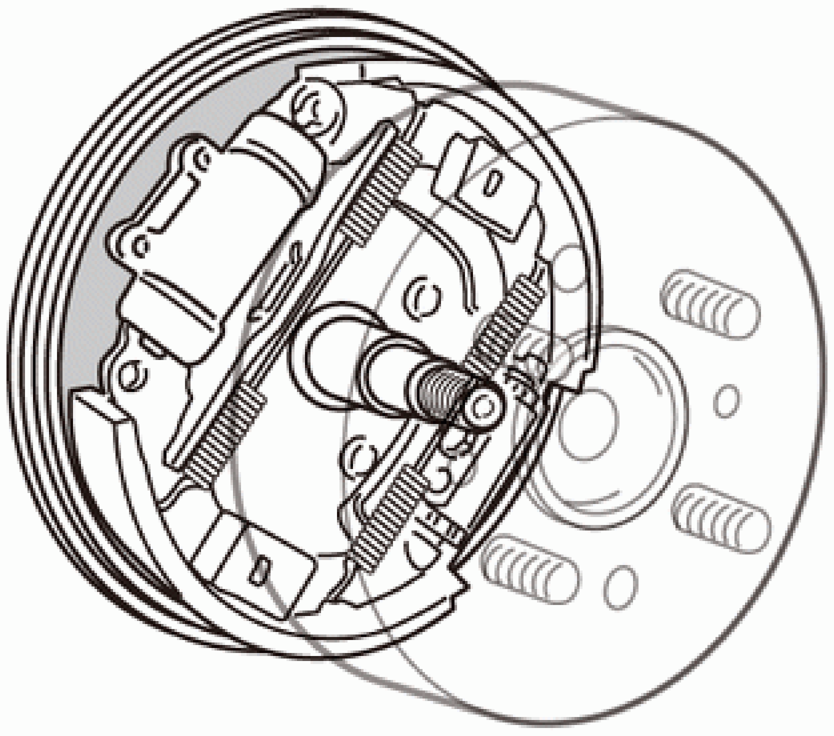
Friction is applied to both sides of a metal disk that turns with the wheels. Their major advantage is that because most of the components including the disk itself are exposed to the elements, ventilation and heat dispersion are excellent, making them less prone to overheating. Another benefit of disk brakes is that if they get wet, the water will naturally disperse as the wheel turns, and there will be no significant friction loss. It is easier to perform sensitive control of the brakes through the brake pedal with disc brakes, but the brakes do not multiply its own braking power as in a drum brake, and holding ability when parked is less than that of a drum brake.

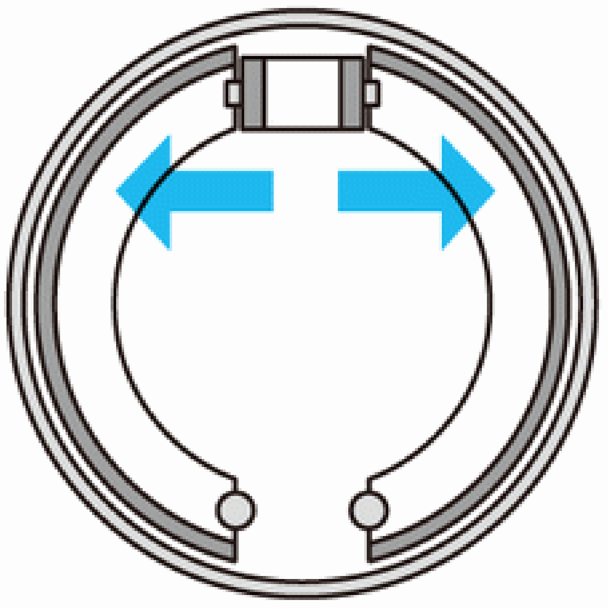




Drum Brakes

Braking is performed by pushing brake shoes against the inside of a cylindrical drum that turns with the wheels. Heat dispersion is poor, and overheating occurs much more easily than in disk brakes. Also, if water enters the drum, it takes time to recover friction. However when braking, the rotation of the drum automatically drags the shoes against the friction surface, causing the shoes to bite more, and producing additional braking force. In passenger cars, it is normal for drum brakes to be fitted to the rear wheels, which take less of the braking burden. In larger vehicles, drum brakes are often mounted inside disk brakes on the rear wheels to act as a parking brake.





Braking Problems Caused by Excessive Heat

Fade

Fading is a reduction in braking force caused by overuse of the brakes. The pads or lining overheat and release gas, which acts as a sort of lubricant and reduces friction.

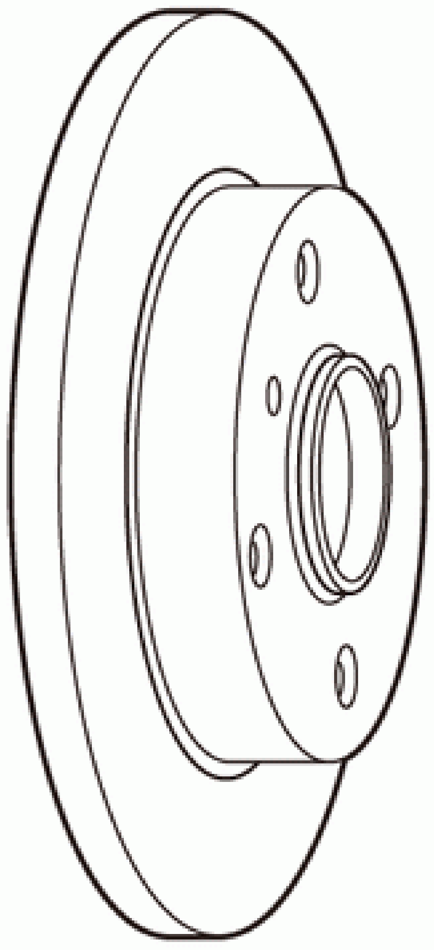
Vapor Lock

This is a condition in which the brake fluid has absorbed the heat from overheating pads or brake lining and has boiled, creating air bubbles in the brake line. When the brake pedal is pushed, the pressure isn’t passed effectively through the fluid and, in the worst-case scenario; the brakes will fail to work completely.

Types of Brake Disk

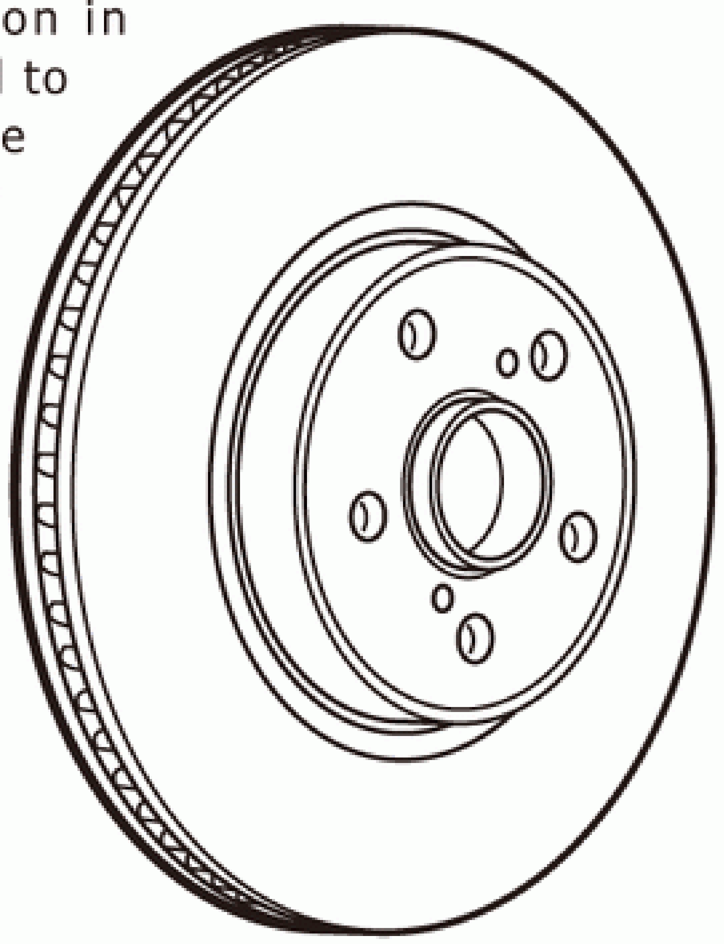
Solid Disks

This is the most basic type, consisting of a simple metal disk. Heat dispersion is inferior to that of ventilated disks, but low manufacturing costs mean that solid disks are often used in the front brakes of light cars, and also on the rear brakes of four-wheel drive vehicles, where the braking loads are relatively small. All disks, including ventilated disks need to be strong against frictional heat and good at dispersing heat, which is why the majority are made from cast iron.



Ventilated Disks

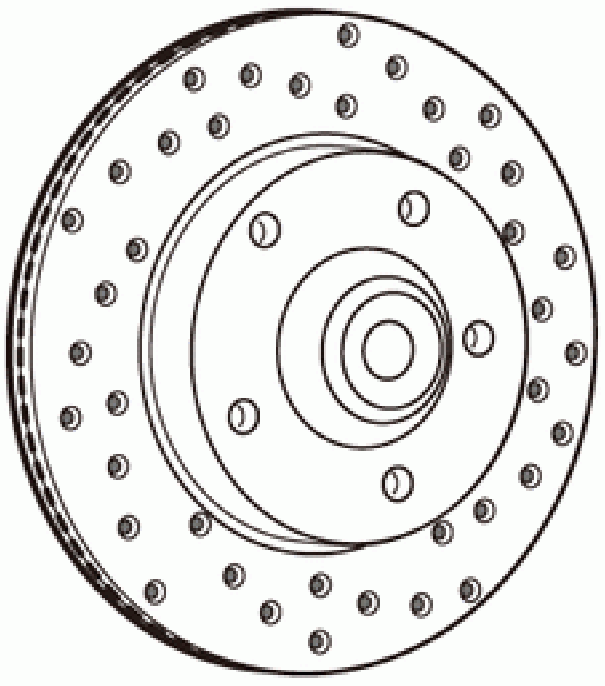
Two disks are layered together, and there are holes between them to provide ventilation. These were initially developed for racing cars, but are also now common in passenger cars. Compared to solid disks, the surface temperature is reduced by around 30%, increasing resistance to fade, and lengthening brake pad life. The downside is that their double thickness makes them a little heavier.



Advanced Ventilated Disk Types

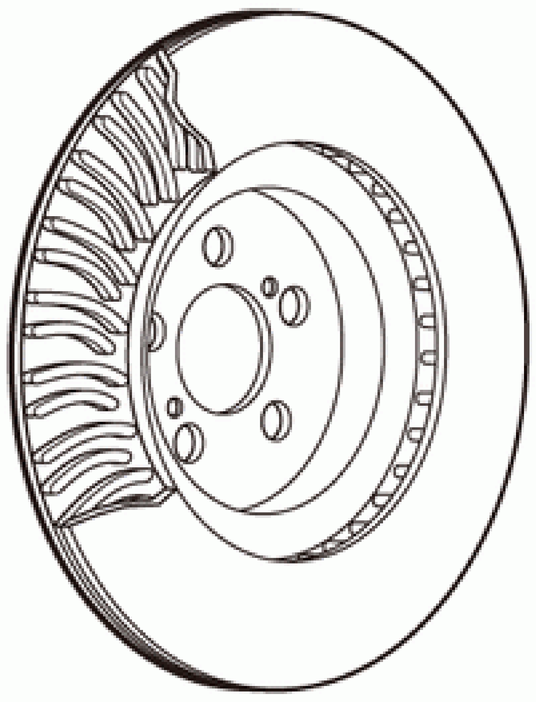
Cross Drilled Disks

Similar to a ventilated disk, but with additional holes drilled on the disc surface to increase heat dispersion and cooling. These are frequently used in racing cars and high performance sports cars. The holes are also effective at removing the dust created when braking. Another type of disk called a “slotted disk” has channels machined into its surface to achieve the same effect.



Spiral Fin Disks

Two disks are layered together, with heat-dissipating fins arranged in a spiral shape between them. These fins are designed using numerical analysis of the airflow in the disk, to provide maximum airflow through the disk. As a result, heat is dispersed extremely efficiently as the wheels turn. These disks are used in high-performance sports cars and heavier high-powered saloons.

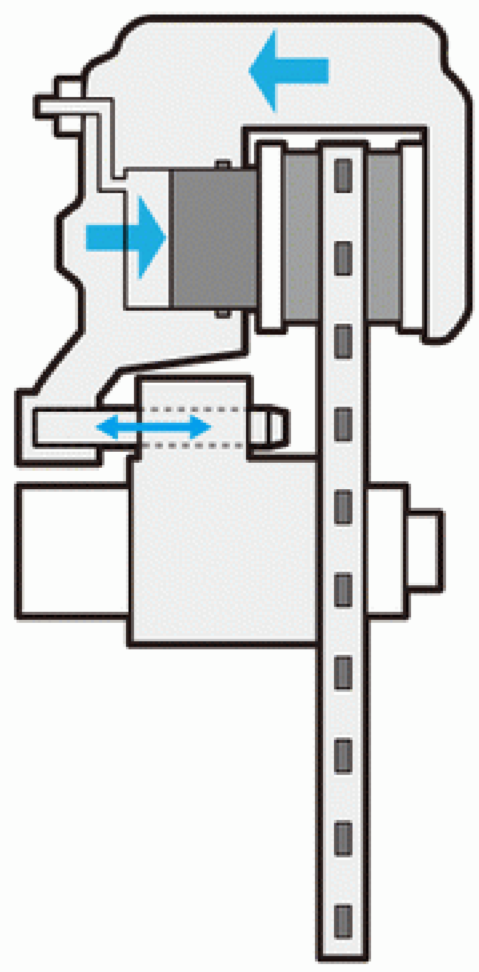


Disks and Calipers

Types of Caliper

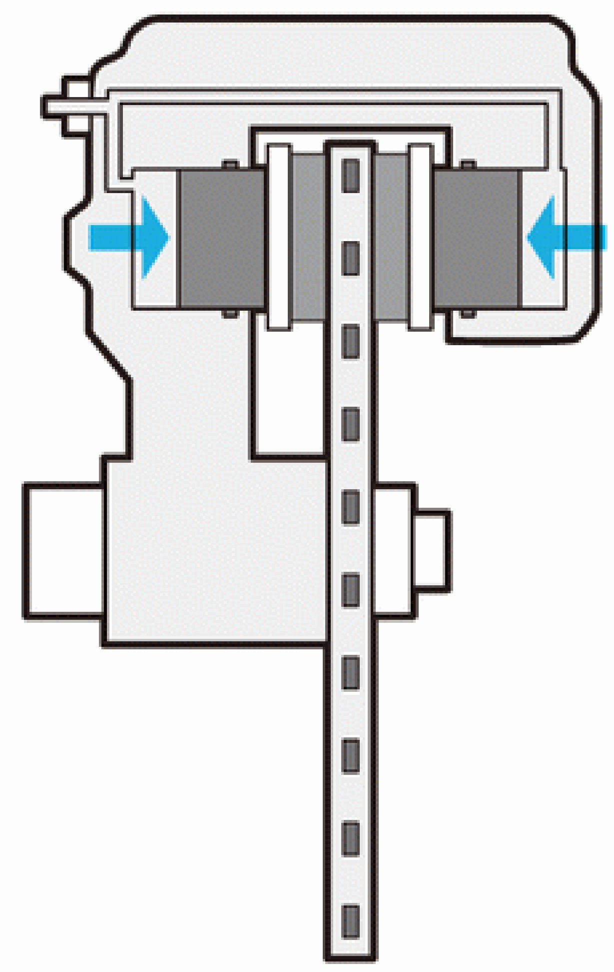
Floating

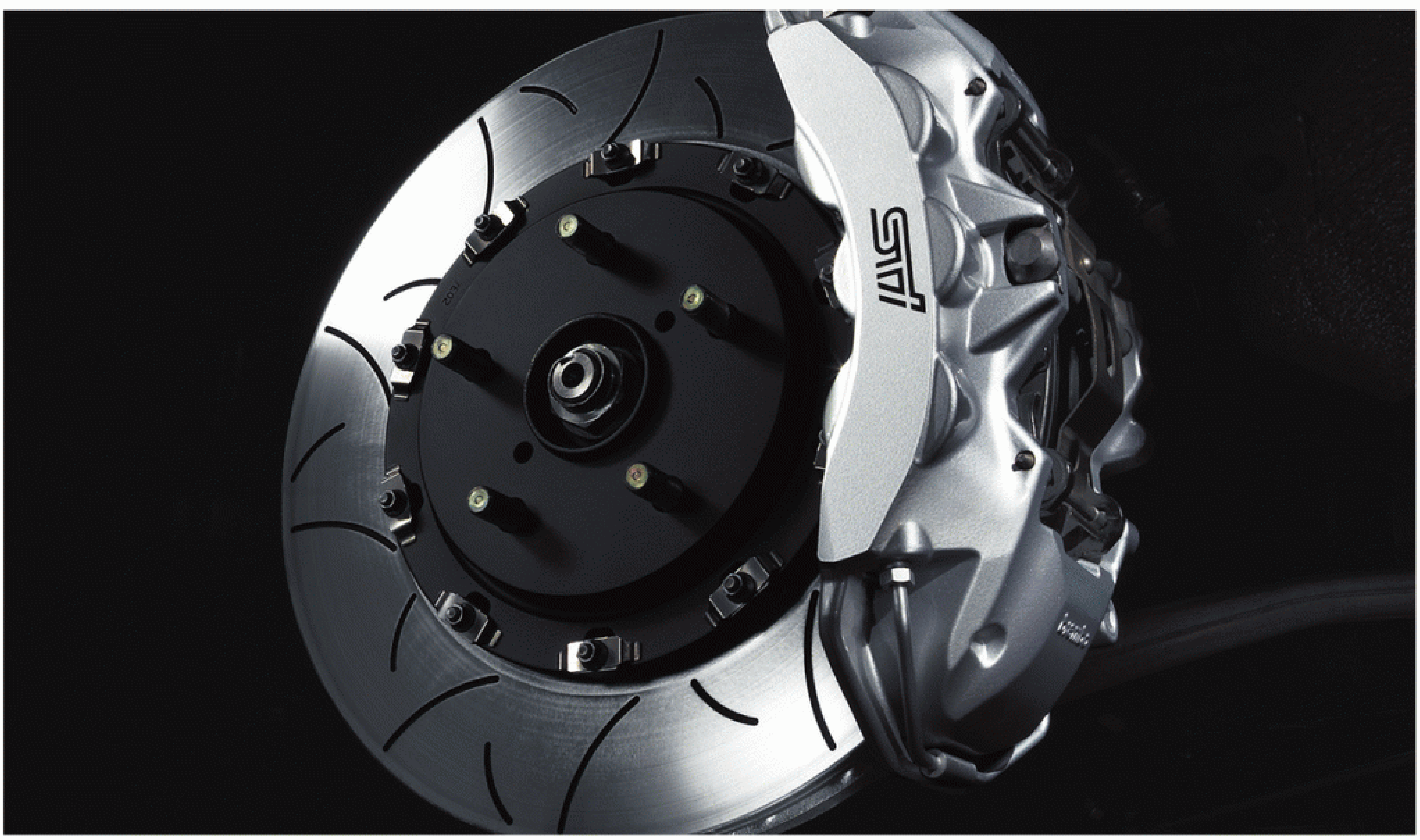
A floating caliper has a piston mounted on one side, which pushes the brake pad against the disk when the brake pedal is pressed. The opposing force presses the brake pad on the other side against the disk's other side. Contact of the pads to the disk is constantly adjusted, and there is no time lag between the actions of the two pads, ensuring an identical braking feel every time. The caliper itself is small and light, and can still provide braking power even if the disc warps from extreme heat. Although they begin to lose effectiveness in sustained racing situations, they present no problems at all for regular driving.



Opposing Piston

This is a setup in which brake pistons are located on both sides of the disc, to squeeze the brake pads against the disc from both sides. Because this setup makes the calipers larger and heavier, there's little choice but to make the caliper body out of aluminum to reduce weight, which in turn makes it difficult to maintain proper rigidity for the caliper unless it is properly designed. It is very effective in racing on a circuit, but to fully utilize their full potential the brake discs also need to be floating mount discs; otherwise with normal brake discs the heat will distort the disc, putting the it at an angle so that the brake pads cannot properly engage the disc surface. With larger brakes becoming popular, multiple piston brakes with 4 pot and 6 pot calipers having a wider brake pad surface area have also been applied to commercial cars as well. A visibly large, opposed piston caliper peeking out from behind the alloy wheels is a strong indication of the car's high performance.





Dampers for Controlling Body Movement

Compression and extension may seem like a simple process, but without a proper suspension system, you wont be able to drive a car straight, let alone control one.

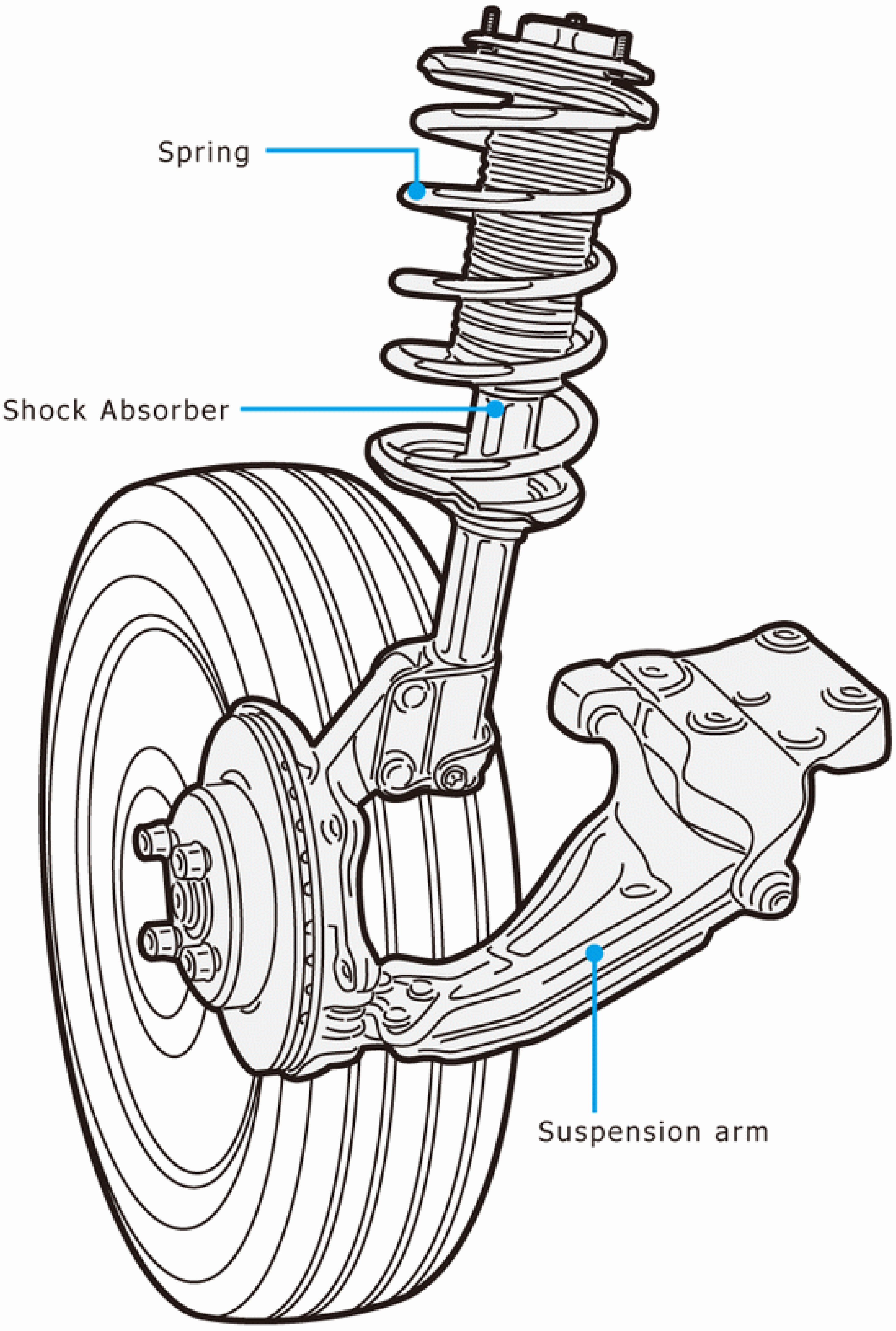
Construction and Principles

The suspension is the mechanism positioned between the body and the wheels to absorb the shocks that the wheels receive as they support the body of the car. It also has an important influence on handling, and as such, is an important mechanism in a car's construction.

Suspension can generally be categorized into "dependant" suspension systems where the movement of one wheel affects the wheel on the opposite side, or "independent" suspension where left and right side wheels move independently without affecting each other. Examples of dependant suspension include beam or live axle, linked, or torsion beam suspension, and independent suspension include those such as strut type and double wishbone suspension.

The suspension itself is made up of springs, shock absorbers and linkages. The springs absorb the shock from the road surface, and the dampers suppress the vibration of the springs to provide ride comfort and stability. The links restrict the movement of the tires, so that the tires will maintain optimal contact with the road surface. The suspension system has an important role of pushing the tires against the road surface through the springs, and to regulate their positioning.

The illustration shows a strut-type suspension. After it was first used in Japan in the Toyota Corolla, it went on to become an extremely common suspension type in production cars. In a strut type suspension the casing of the strut damper acts as and replaces the upper arm of a double wishbone suspension. This reduces the number of necessary components and allows for a larger engine room.

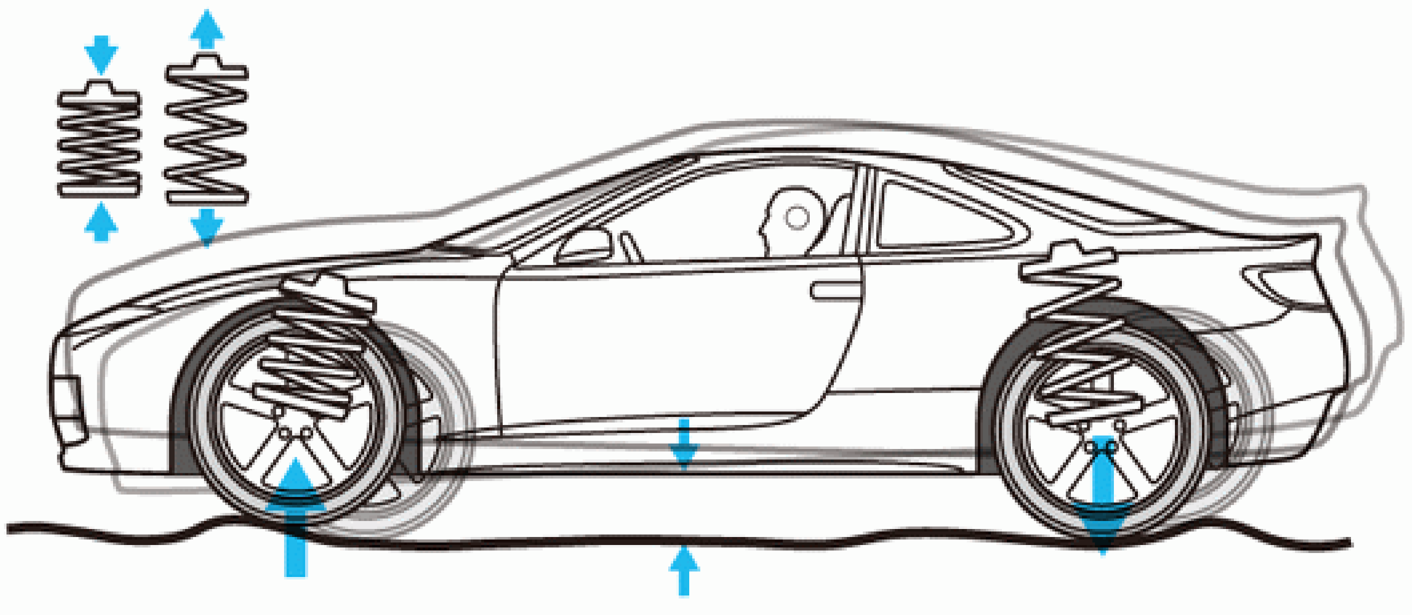


[Example of Strut-Type Suspension]

Full control over running, turning & stopping

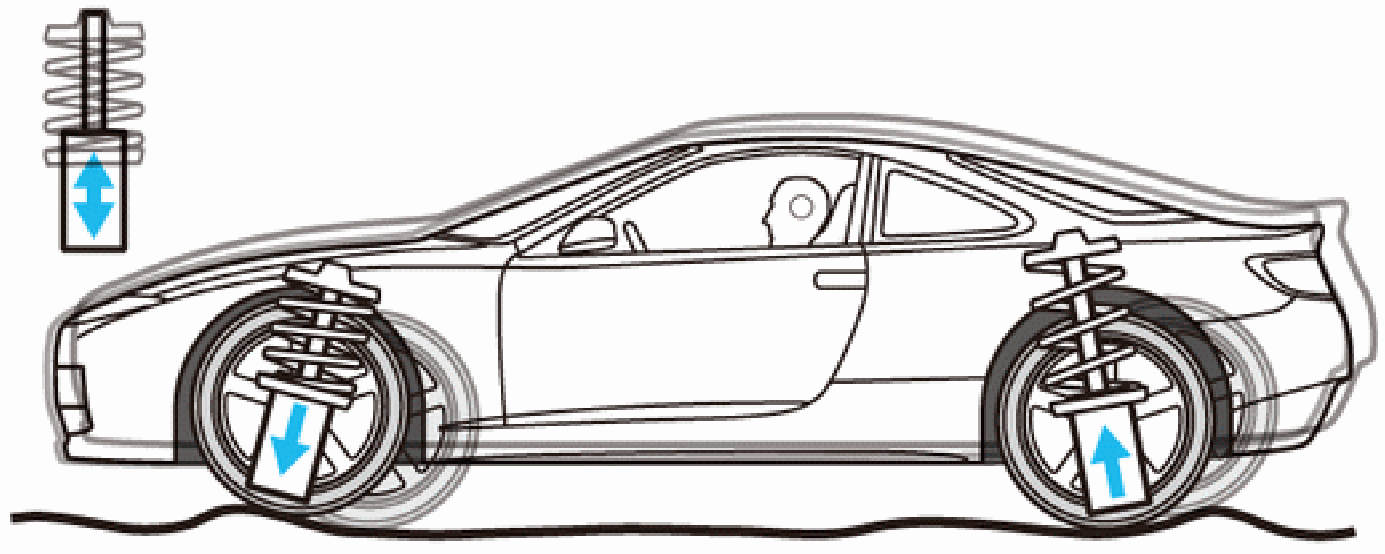
Springs

Springs absorb the impact taken by the car during driving, and as well as lessening the shock, they also ensure that the car stays at a constant height. In addition to ensuring controllability, the springs are also an important factor in handling and stability. It is no exaggeration to say that the setting of the springs alone can greatly affect a car's performance. Metal coils are most commonly used, but some cars also have air-powered pneumatic suspension.



Shock Absorbers

A coiled spring can absorb impact when weight acts on it, but once it has done so, it will not stop bouncing vertically. The shock absorbers is what dampens its movement (also called dampers) The most common type of shock absorber uses resistance created by a piston moving through oil and gas. The slower back-and-forth movement serves to absorb the violent vertical movement of the spring. Shock absorbers affect controllability and stability in the same way as springs do.



Suspension Arms

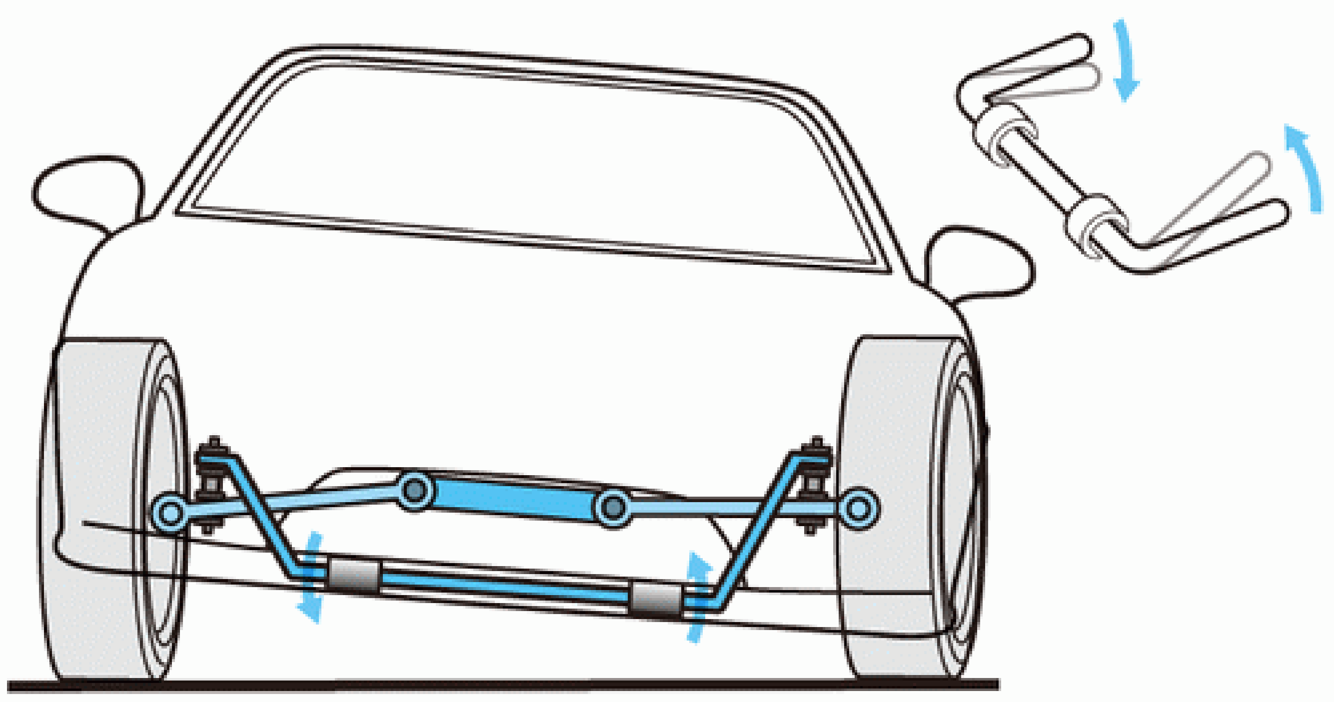
The suspension arms are the parts that control wheel movement. They are attached to the body and axle with bushings in between. There are various types, such as the A-arm and I-arm. They are usually made from pressed steel, but some sports models use aluminum components to reduce weight. In the case of suspension arms that are in sets of two as in a double-wishbone suspension, the top arm is called an upper arm and the bottom arm is called a lower arm.

Suspension Bushings

Suspension bushings are shock-absorbing materials placed at the joints of metal links and arms of the suspension, or other mounting locations of the body. If the bushings are too soft, they will deform under large loads such as during cornering. This will create an unwanted movement of the suspension, and be detrimental to controllability and stability of the car. For this reason the suspension bushings are normally made of rubber material with very good shock absorption characteristics, but on competition racing cars, spherical metal joints called a pillow ball is often used instead so that the suspension will move with the highest precision possible. The suspension bushings are very important components that ensure the proper performance of the springs and the shock absorbers.

Sway bars / Stabilizers

A sway bar or stabilizer is a stabilizing device that helps to suppress roll in vehicles using the twisting of a torsion bar spring. It is also sometimes called an anti roll bar. It is connected to both ends of the lower suspension arms, and only reacts to uneven movement of the left and right suspension. For example when cornering, the car's body on the outer side of the turn will sink down, while the body on the inner side of the turn will be lifted up. The sway bar will work to equalize this motion of the left and right sides, so that the car will not roll as much, stabilizing the stance of the car. This effect of sway bars can be used to set a car against understeer or oversteer.



Types of Suspension

Although all suspensions perform the same basic roles of maintaining vehicle height and absorbing the bumps and load changes of driving, each type has its own particular characteristic. The characteristics of the suspension will affect driving performance such as cornering, the controllability of a car (which also affects safety), and even things like ride comfort.

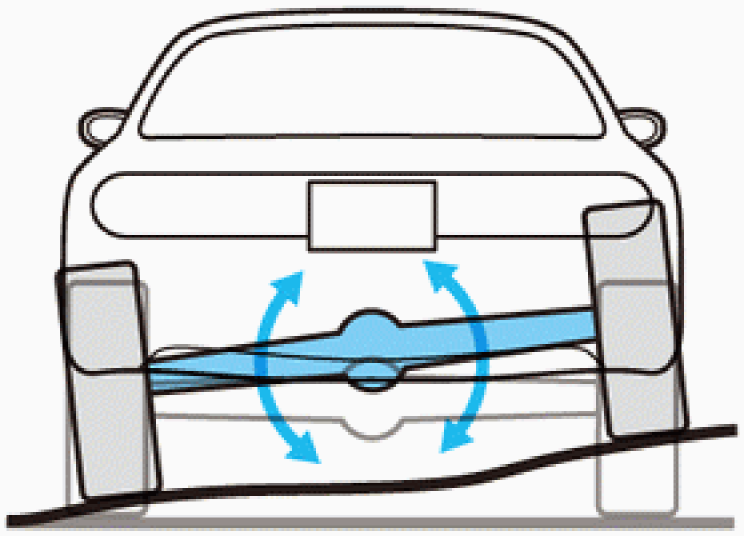
Suspension is always improving, and new types are springing up all the time. A complicated system does not necessarily mean a better system, but the need to deal with bumps and undulations instantaneously and to keep the wheels in constant contact with the road surface has led to the introduction of ever more intricate solutions.

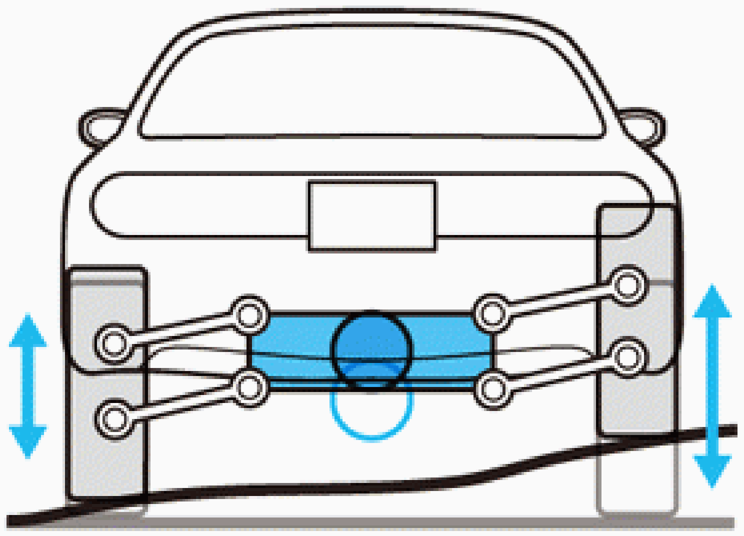
Rigid axle

In a rigid axle suspension, the left and right wheels are connected by a single axle. As a result, movement on one side also affects the other, making it easier to lose contact with the road. The axle beams and axle housing are heavy, increasing the unsprung mass of the car. However, as it is cheap to manufacture and also strong, rigid axle suspension is often used for the rear suspension of inexpensive rear-wheel drive cars.

Independent Suspension

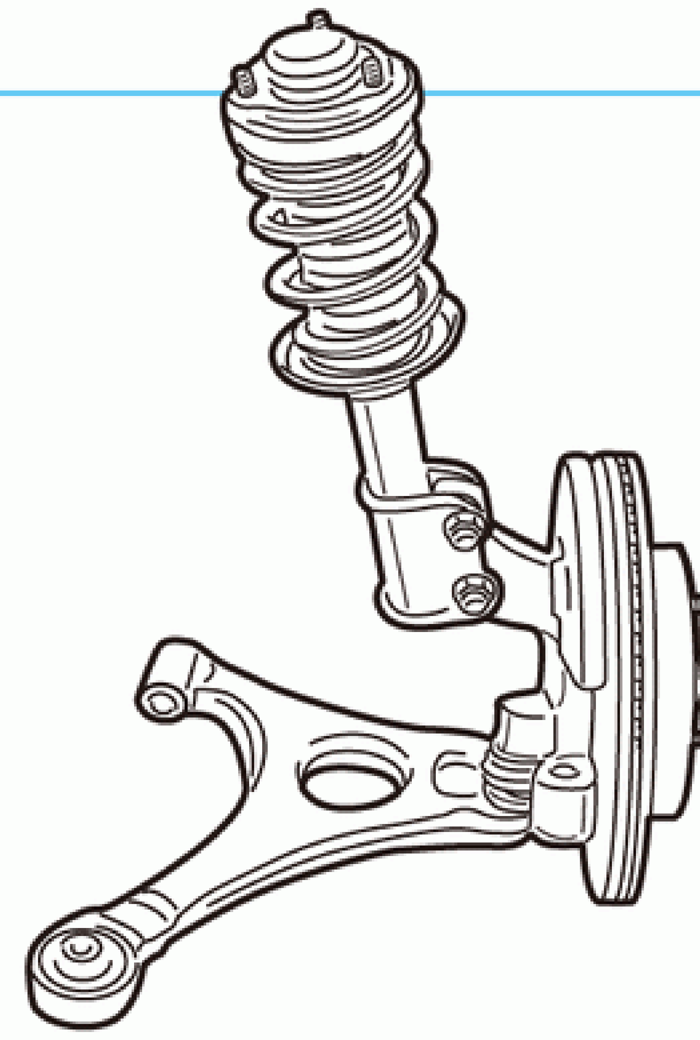
Independent suspension allows the left and right wheels to move up and down individually, making it excellent at dealing with undulations and bumps in the road. In the case of a rear-wheel drive car, this also helps transmit power efficiently to the left and right wheels. The system is light, stable and offers a comfortable ride.





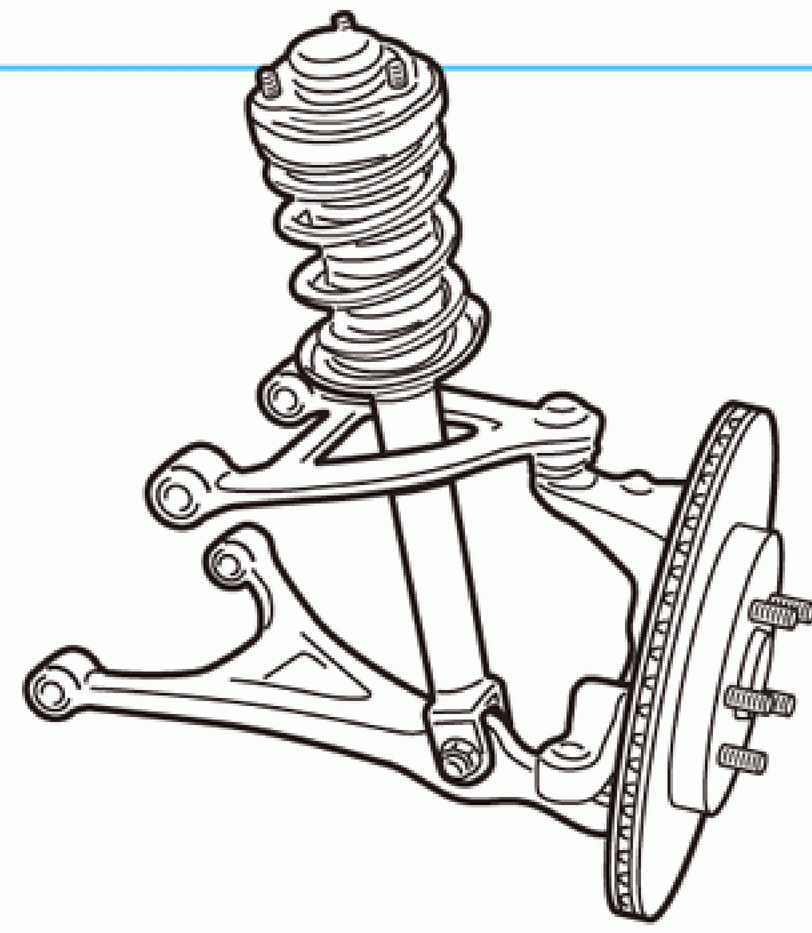
Independent Suspension – The System of Choice for Most Sports Cars

MacPherson Strut



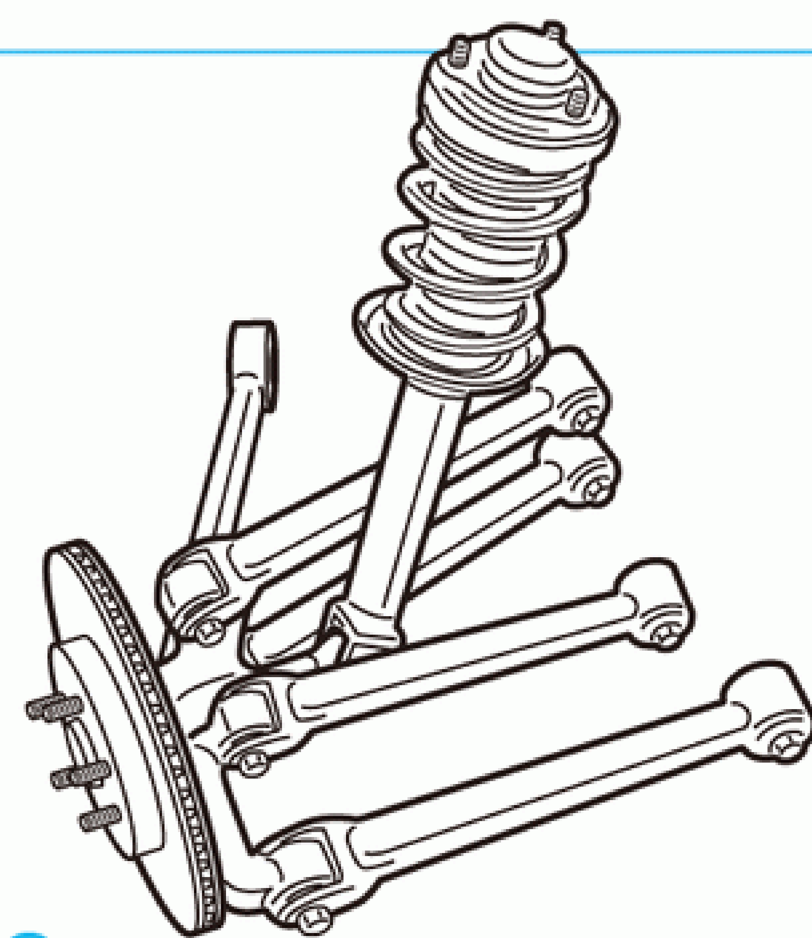
A simple suspension system consisting of a spring, shock absorber and lower control arm. The "Strut" refers to the damper itself, which also serves as a support in this type of suspension. The upper part supports the body via a mounting rubber, and the lower part of the shock absorber is supported by the lower arm. Fewer parts means it is lightweight, and it has good stroke length, meaning that vibration can be absorbed over a broad range. The system was designed by Earle S. MacPherson, for whom it was named.

Double Wishbone



A design that supports the wheels on an upper and lower arm joined together. The arms are usually in the shape of a V, and resemble the wishbones of a bird. Depending on the shape of the arms and the car's layout, it can control changes in alignment and position of the car when accelerating relatively easily. It is also very rigid, making it a popular choice for sports cars that priorities controllability and stability. However, it has a complicated construction using a lot of parts, and takes up a lot of space.

Multi-Link



This is an advanced form of the double wishbone system that uses between three and five arms to maintain the position of the axle rather than two. The arms are all separate, giving it a lot of freedom as far as positioning is concerned, which also allows it to be set up very specifically. The increased number of arms allows it to deal with movement in many directions, and keeps the wheels in close contact with the road surface at all times. This suspension type is often used for the rear suspension of high-performance FF cars to maintain stability at high speeds, and in high-output rear-wheel drive cars to maintain traction.

The Characteristics of Different Suspension Types

Wheel Alignment

Take a look at a piece of furniture with wheels attached to it. If you look straight down from above, you should notice that the axle of the wheel is at a slight angle in relation to the axle connecting it to the piece of furniture. This slight misalignment is what causes the wheel to move in a straight line when pushed, rather than wobbling.

Now imagine taking a car tire and rolling it along the ground. If you stand the tire up straight and roll it, it will move in a straight line, but if you lean it even slightly, it will turn in that direction as it rolls.

From this, we can see that when wheels are mounted on a car, if the they are set to the right angle it will be possible to move the wheels in a way suited to the operational conditions of the car. This is the basis behind wheel alignment (or suspension geometry).

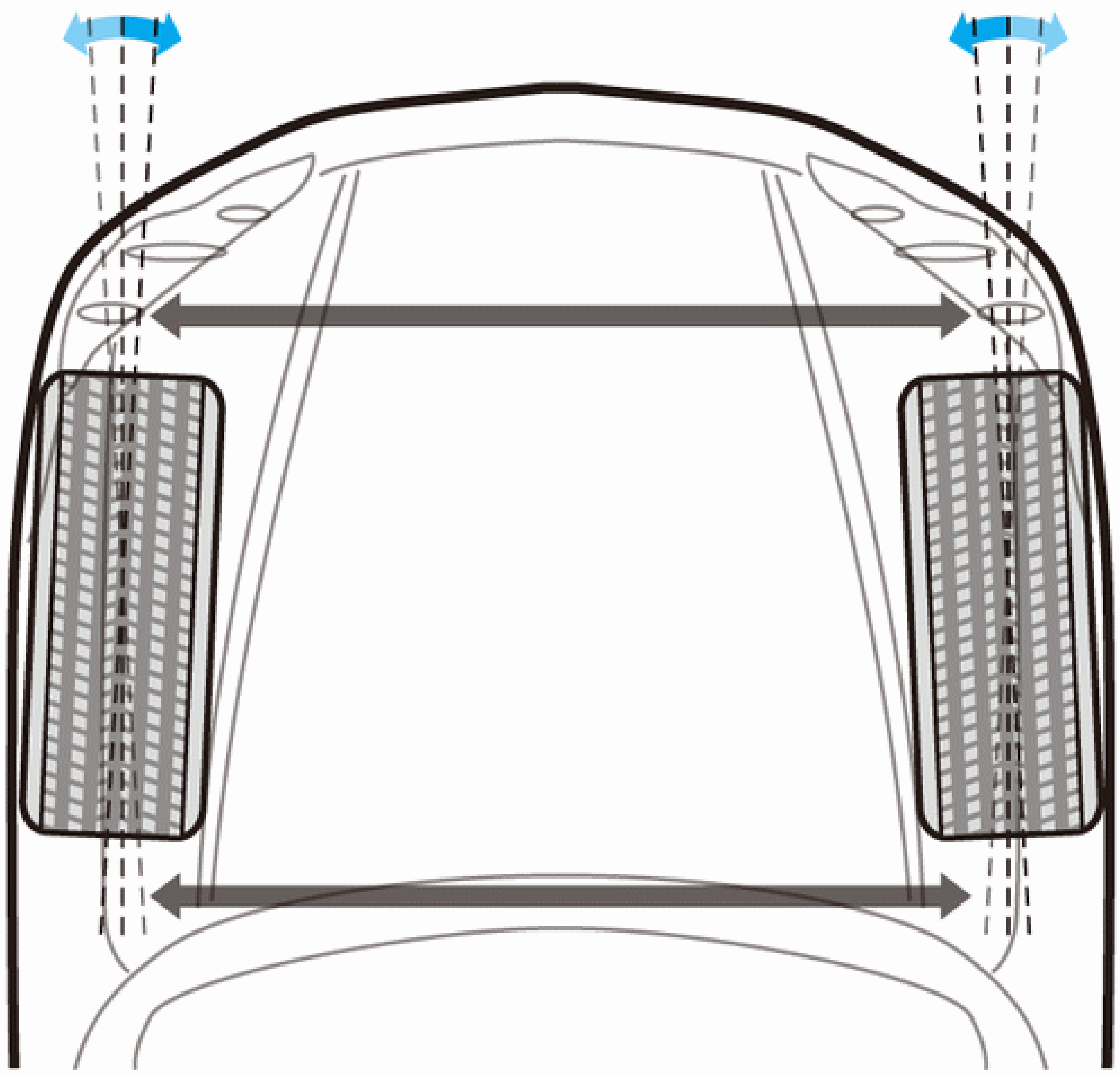
Driving, turning and stopping all rely on the fact that the wheels are aligned properly. This "positioning" of the wheels can maximize the performance of the tires, and can set the characteristics of a car.

The page opposite illustrates the four basic angles of wheel alignment: the toe angle is the angle of the wheels when looking down from above, the caster angle of the suspension viewed from the side, the camber angle of the wheels when looking at them from the front, and the kingpin angle - the angle of the suspension in relation to the wheel viewed from the front. These settings are adjusted in increments as small as 0.1 degrees/0.1 mm, so the margin for error is tiny, and if a mistake is made, the car may not travel in a straight line, or the handling may be adversely affected. You'll want to remember the different effects these settings can have.

Wheel Angle Affects Road Contact and Handling

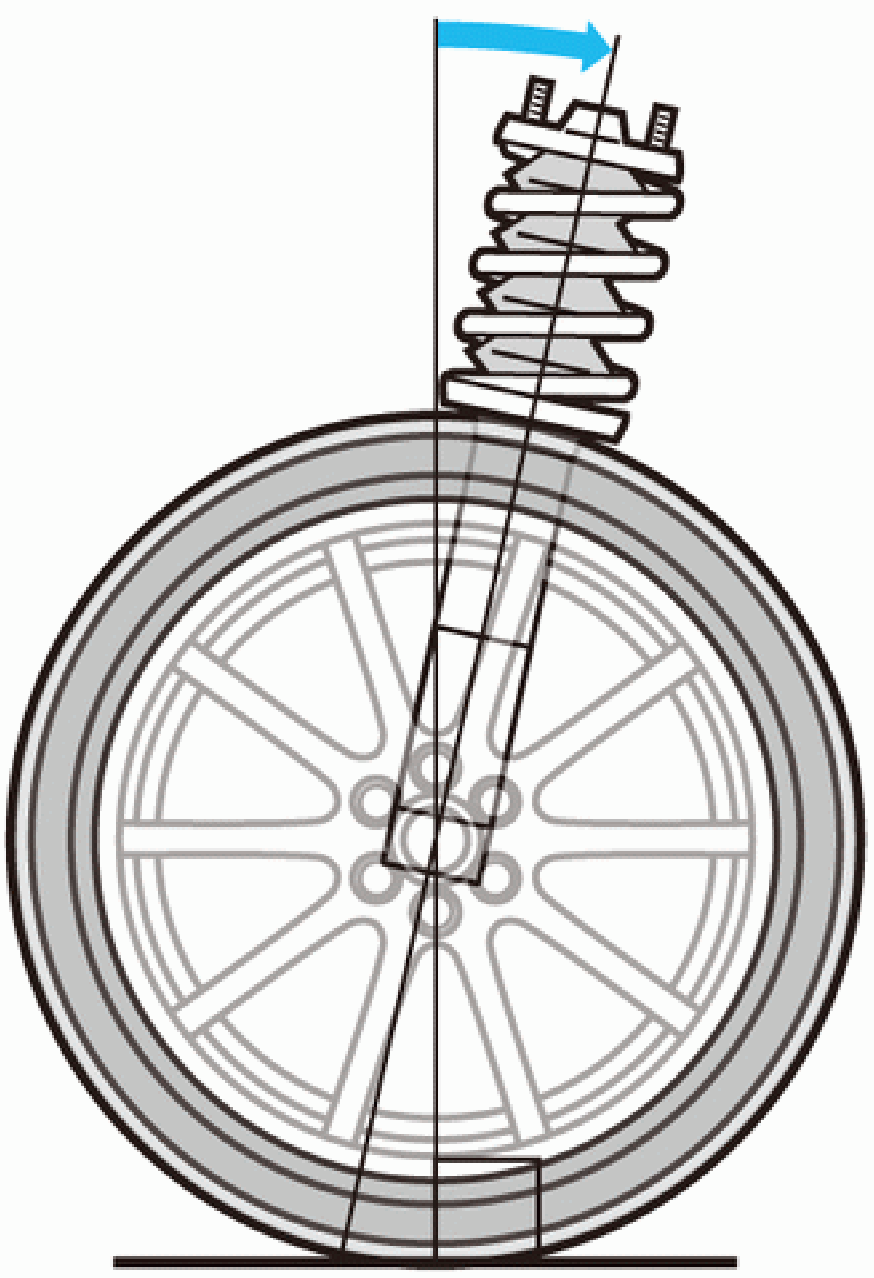
Toe angle

This is the angle of the right and left wheels when looking at the car from above. If the front of the wheels point outwards, this is called "toe out," and if they point inwards, it is "toe in." This angle has a large impact on the car's forward movement, and if set at an excessive angle, will cause uneven wear on the tires.



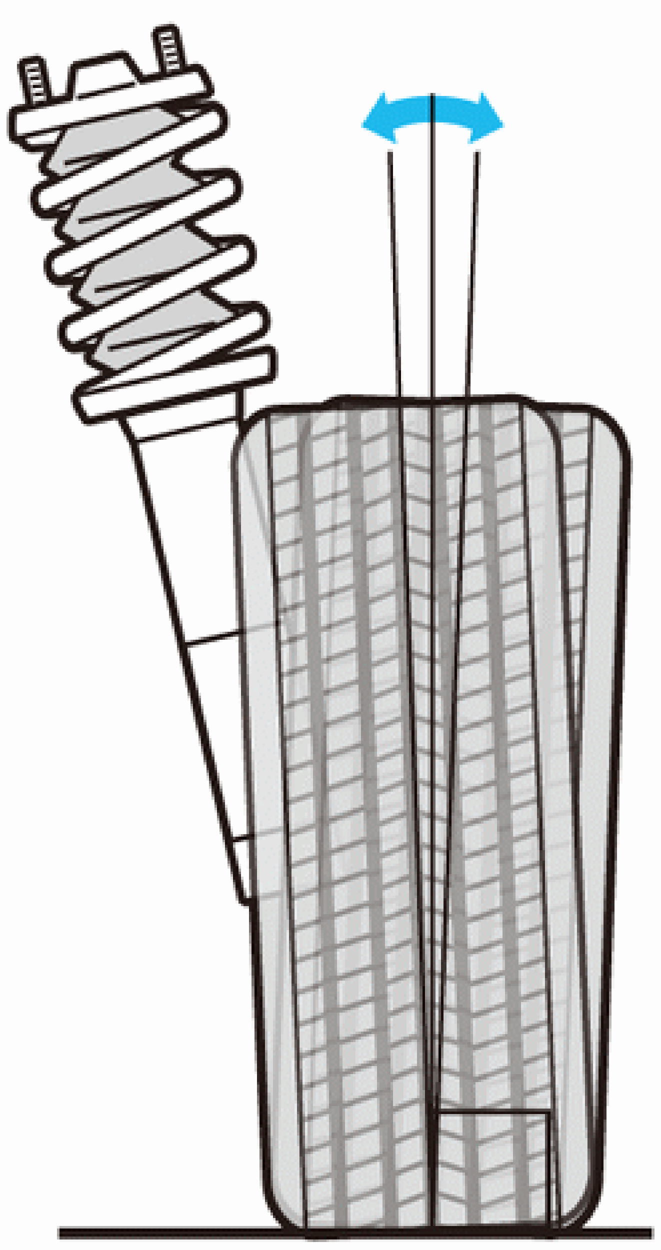
Caster Angle

This is the angle of the front suspension relative to the front tires when looked at from the side. The angle suppresses how much the wheel shakes from side to side, and it also affects self-alignment torque (the force that tries to return the wheels to a straight position when the steering wheel is turned). If the caster angles of the right and left wheels are different, the car will pull in the direction of the shallower angle, or the steering will pull to one side when braking.



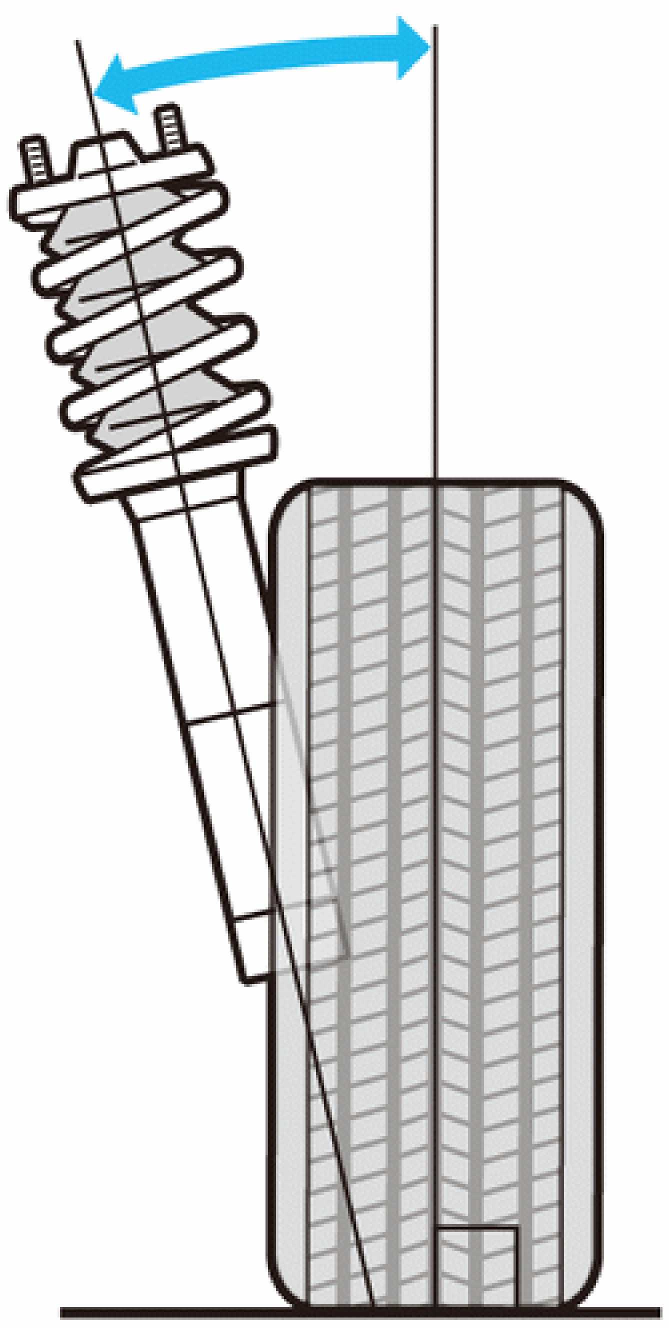
Camber Angle

This is the angle of the wheels relative to the road when looking at the car straight on. If the top of the wheels point inwards, this is a "negative camber." If they point outwards, the camber is positive. In most cars, the camber is set to be slightly positive to counteract the effects of heavy loads.



Kingpin Inclination

This is the angle of the wheel attachment axis when viewed from the front. Normally, it is adjusted to suppress road surface features from pulling the wheel out of the driver's hand, but it can also affect straight-line travel, steering return (self-alignment torque) and steering force.



The Link Between Car and Road

Once it has passed through the drivetrain and the suspension, the power of the engine will finally be transferred to the road via the wheels. No matter how good the car, its performance will only ever be as good as its tires.

High-Performance Sub

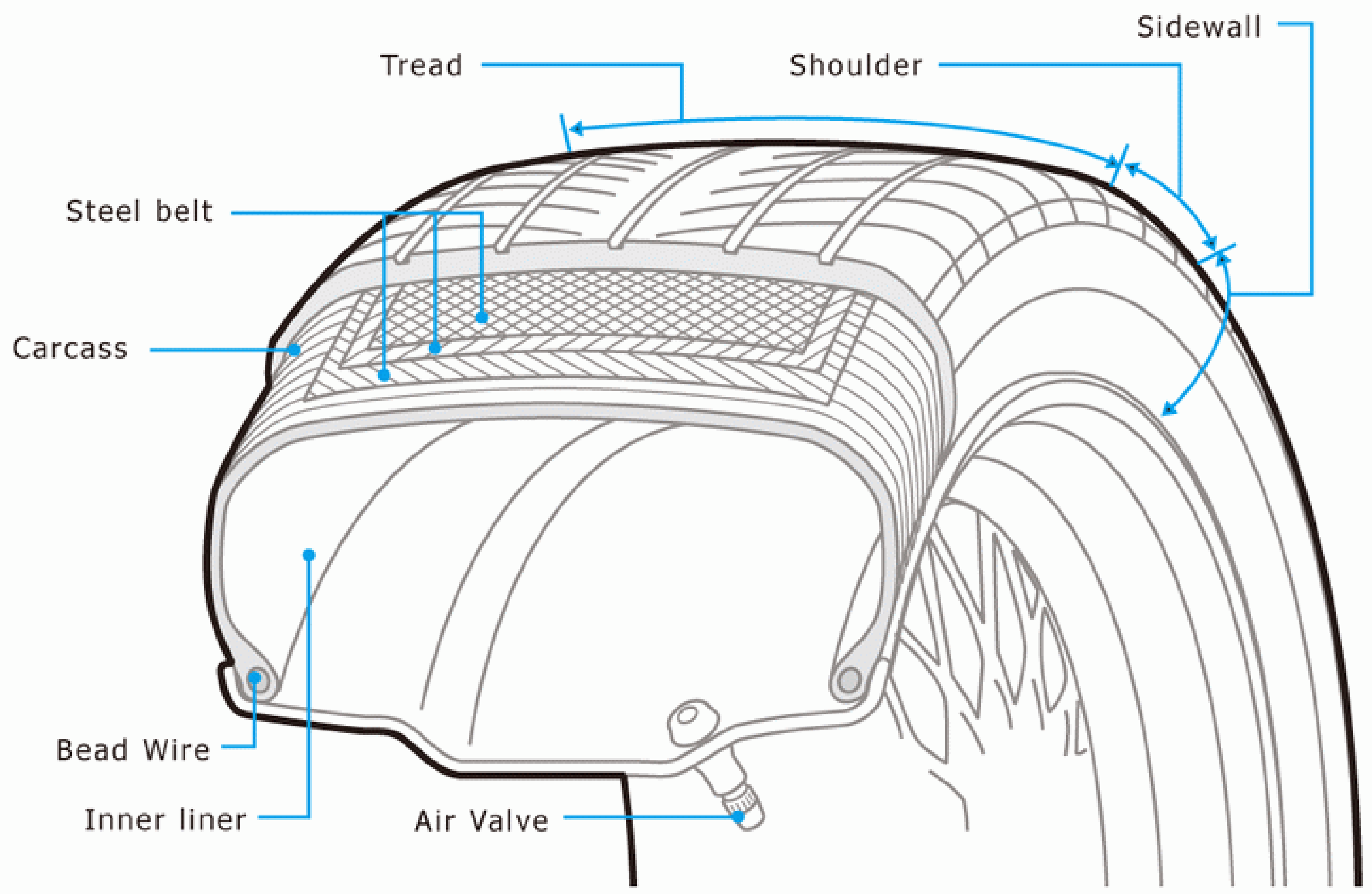
Tire characteristics can be roughly divided into four categories: load support, shock absorption, acceleration and braking and maintaining heading in a straight line and during cornering. Once a good balance of these four basic functions has been established, the tires are fine-tuned to suit specific needs.

Sports cars favor tires that can accelerate, decelerate, and maintain heading well, to ensure good driving, cornering and braking performance. These tires will be made from high-grip rubber that sticks to the road surface, and will be very rigid to prevent them from changing shape under load. This increases steering response when cornering, and allows corners to be taken at higher speeds.

Of course, high-grip tires also have their disadvantages. Although they have a high capacity of grip when cornering, recovery when that capacity is exceeded is difficult, and a high level of driving skill to match is required. It will increase the amount of stress caused to the suspension and body, and roll during cornering is increased due to the extremely high grip. The tires are so high performance that they can offset the balance of the car, and that means that the car itself has to be high performance enough to use those tires in the first place. You should also remember that because there is a lot of friction between the tire and the road, they wear out more quickly, will detract from passenger comfort, and will be noisier.

Grip on wet roads is largely dictated by the pattern of grooves carved into the tire surface. These grooves are designed to effectively rid the tire of water picked up from the road surface, but these grooves reduce rigidity, so striking the right balance is difficult, especially with sports tires.

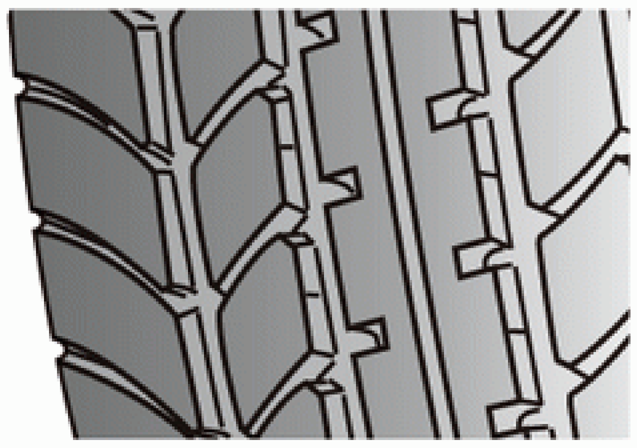
A car cannot exceed the limitations of its tires, and for this reason, it is essential for a driver to fully understand tire performance and characteristics to select a tire that matches their needs.



Grip and Rigidity – the Key to Speed

Tread compound

This is the rubber used on the tire surface that makes contact with the road. The soft rubber used for high-performance tires keeps a strong grip on the road, but wears out quickly, while tires for standard cars where durability is a priority, a harder compound is used, but these will only maintain grip to a certain level. Tires are normally hard and will not exhibit their full grip potential until they are heated to a certain level, however if they are overheated, their grip will be reduced.

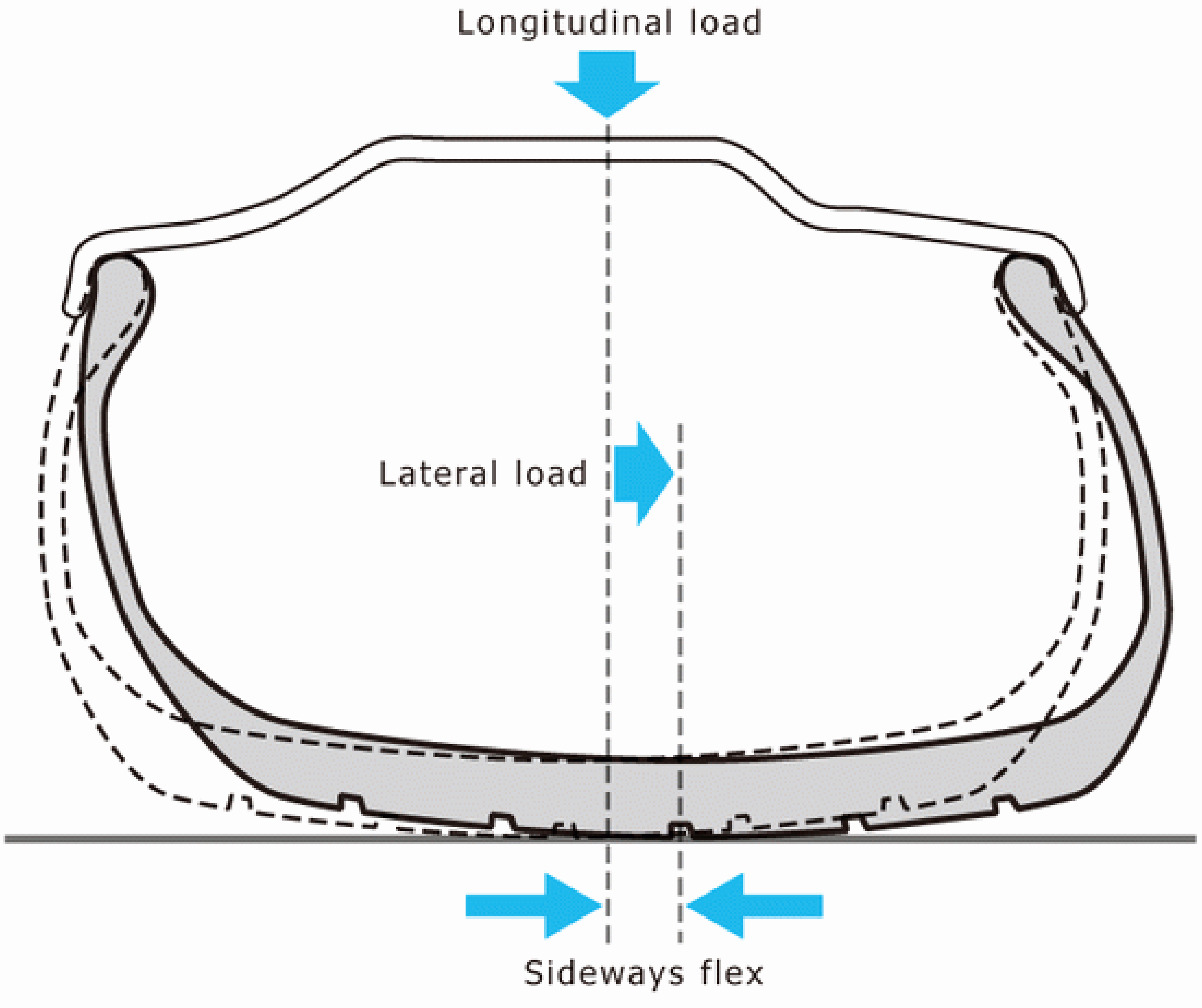


Tread pattern

The pattern of grooves carved into the part of the tire surface that makes contact with the road. The main purpose of these grooves is to rid the tire of water as the wheel turns, and many tires will have a set direction of rotation for the tire pattern that maximizes the water-shedding characteristic. On the other hand, as these patterns reduce surface rigidity, high-performance tires use a few large grooves rather than a complex pattern of small ones. There are also asymmetrical designs with fewer grooves on the outside edge to improve rigidity when cornering, but more grooves on the inside to rid the tire of water.

Casing rigidity

The casing is the entire surface of the tire, including the tread, sidewalls, bead etc. The forces acting on the tread from the road surface are transmitted to these various parts, until it reaches the base of the bead. It is important to have a rigid casing to avoid unnecessary warpage in situations such as acceleration, deceleration and cornering, when the casing is under heavy load. However, as rigidity and driving performance is increased, passenger comfort decreases, so tires are specifically tuned according to their characteristics and their application.



Aluminium Road Wheels

A 1kg reduction in unsprung weight is equivalent to a 15kg reduction in sprung weight. Lightweight road wheels help get the best performance when accelerating, decelerating, braking and cornering.

Unsprung Weight

Although often seen as a decorative item, aluminum wheels affect driving performance significantly.

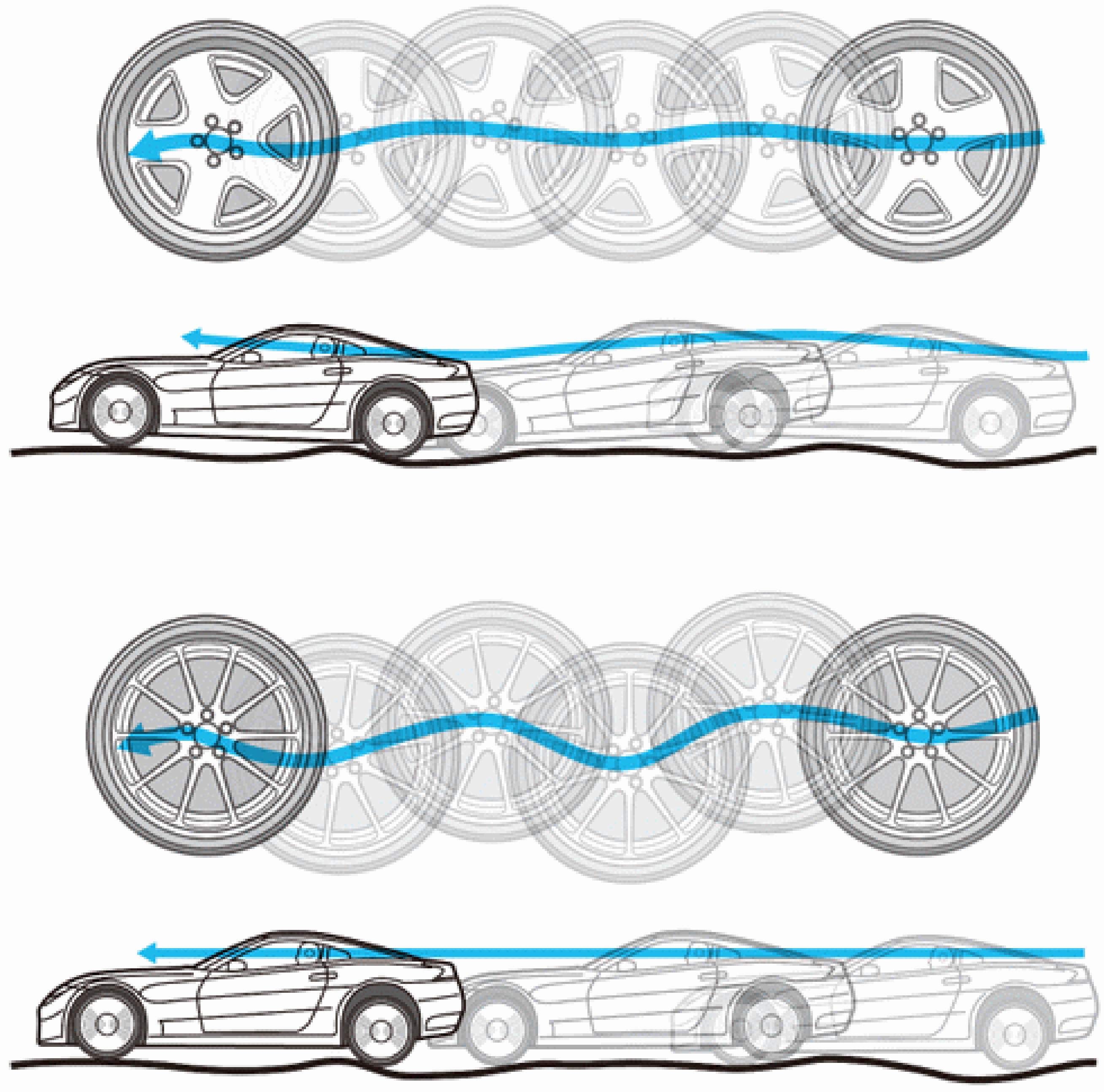
A car requires most power of all when accelerating from a standstill. It takes a lot of energy to make the wheels start to turn from a stationary position, and the heavier the wheels, the more energy is required. Lighter wheels require less energy, and therefore less engine power.

Weight not supported by the suspension is known as "unsprung weight,," and has a significant impact on the drive performance of a car. If the wheels and tires are light, acceleration and acceleration from a standstill is improved, braking efficiency increases, as it is easier to stop the wheels turning. Suspension will also be smoother, improving passenger comfort and movement over the road surface. Improved fuel efficiency is another benefit.

The popularity of aluminum wheels in sports cars is testament to the performance advantages they offer. 1kg less of unsprung weight is equivalent to a 15kg reduction of sprung weight, and in the world of motor sports, unsprung weight is sometimes reduced further with the use of magnesium alloy wheels, which are even lighter than aluminum.

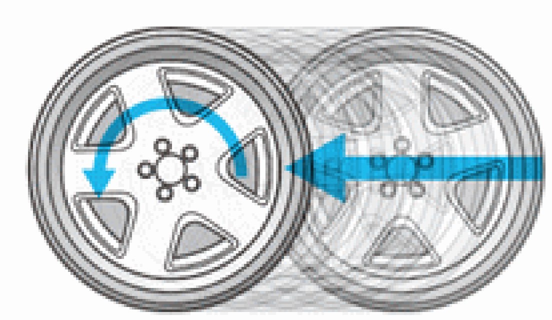
Mainstream aluminum wheels have the benefit of efficient heat conduction, and can effectively discharge the heat generated by the brakes. They are also more resistant to corrosion than steel wheels.

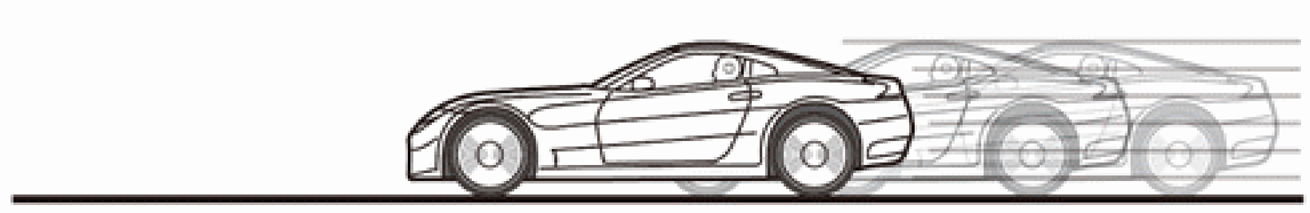
But when changing to new wheels, you must be careful in your choice as increased size may cancel out the weight benefits of using a lighter material. A major increase in size of the wheel will have the inevitable effect of increasing unsprung weight, and the advantages of lower profile tires need to be weighed carefully against the disadvantages of this increased weight.

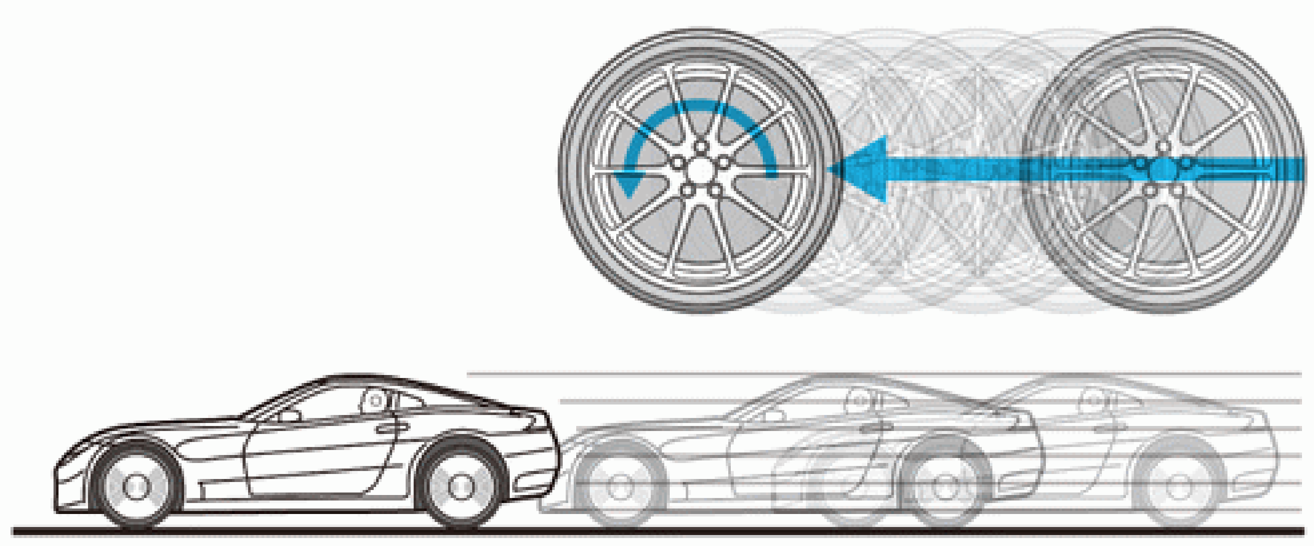


The lighter in weight the wheel is, the greater the tracking of the tire to the road surface, leading to a flat, comfortable ride.

The light weight of the wheel can also reduce the engine power needed to place the car in motion.







Types of Lightweight Wheel

One-Piece

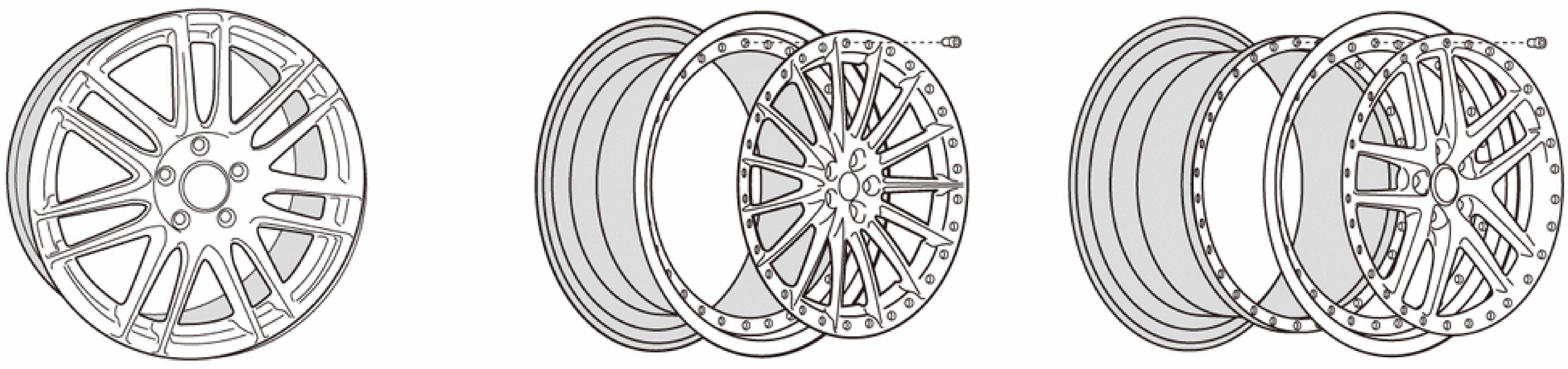
In this basic construction, the rim and disk are made from a single piece of metal. The wheels are machine-cut after casting (or forging), giving them a high degree of precision. There is relatively little freedom in design, but the fact that they are made from a single piece of metal makes them lighter and more balanced than 2- or 3-piece wheels.

Two-Piece

The disk and rim are made as two separate parts, which are then joined with nuts and bolts or welded together. The materials used to make the disk and rim can be different (aluminum, magnesium, titanium etc.), as can the manufacturing method (forging or casting). These wheels have the benefit of offering a wide choice in terms of disk design and the amount of offset.

Three-Piece

The back and front of the rim are welded together, and the disk is attached with pierce bolts. The three-piece design has the same advantages as the two-piece design, although it is slightly heavier because of the pierce bolts. However, it has even more freedom in design than the two-piece, and wheels built for style are often of this type.



Manufacturing Methods

Casting

A method whereby molten aluminum is poured into a mould. In two- and three-piece wheels, the high degree of design flexibility of the disk is an advantage. However, the metal needs to be quite thick for sufficient strength, which makes the weight advantage over steel wheels only slight. Despite this, its low cost makes casting the most common method in the manufacture of aluminum wheels.

Forging

A block of metal is compressed it with thousands of tons of pressure (to align the molecules of the metal), creating a resilient, hard material. Compared to molding, the metal is much stronger, so the thickness of the parts can be reduced and made to be very lightweight. The increased rigidity means that tensile strength is high, but it is weak against bending forces. It is also more expensive to produce and the design possibilities are limited because of the manufacturing process. Materials are not limited to aluminum, and there are cases where racing cars and some sports cars use magnesium-forged wheels that are even lighter.

The Many Benefits of Reduced Weight

AERODYNAMICS

CHAPTER 02 Mechanism

Aerodynamics – The Effect of Air on the Body

Body design can completely transform high-speed performance, improving top speed, stability and efficiency. No discussion of car design would be complete without a look at the importance of aerodynamics.

Air Resistance and Lift

At high speed, the effect of air resistance is huge, at times making it feel as if an invisible wall of air is stopping the car from going any faster.

Once a car is travelling over 80km/h (50mph) the effect of air resistance cannot be ignored, as after that point, air resistance increases as a square of the car's speed. That is, if the car's speed doubles, the air resistance quadruples, and if its speed increases by three times, the air resistance increases by nine times. There is also the roll resistance of the wheels, but this resistance is not as critical because when the engine's power can no longer overcome the wall of air, that is the effective top speed of the car. In racecars and sports cars that need to achieve high speed and ensure performance in the high-speed range, and even in road cars that need to achieve maximum efficiency, the reduction of air resistance is a major concern.

Cars lower to the ground cars have less air resistance than taller cars, and flowing shapes or wedge shapes that allow air to pass smoothly over them are also less resistant. Designs with flush body surfaces that have no protruding bumps or parts will also allow air to pass more freely.

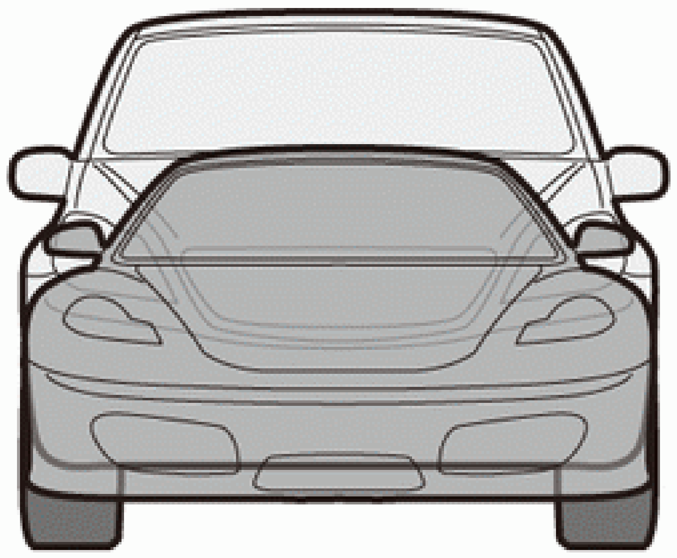
On the other hand, it is important to bear in mind that the majority of low-resistance body shapes resemble aircraft wings when viewed from the side, and exactly like wings, air flows faster over them than beneath them, generating lift which causes the car to lose contact with the ground. But suppressing lift increases air resistance, and an important part of design development is determining where to place the balance between air resistance and lift.

Furthermore, the disruption to straight-line stability by crosswinds also needs to be taken into consideration, meaning that an aerodynamic body requires consideration for a total balance between air resistance, lift and yawing moment.

Frontal Surface Area

▶ Frontal area

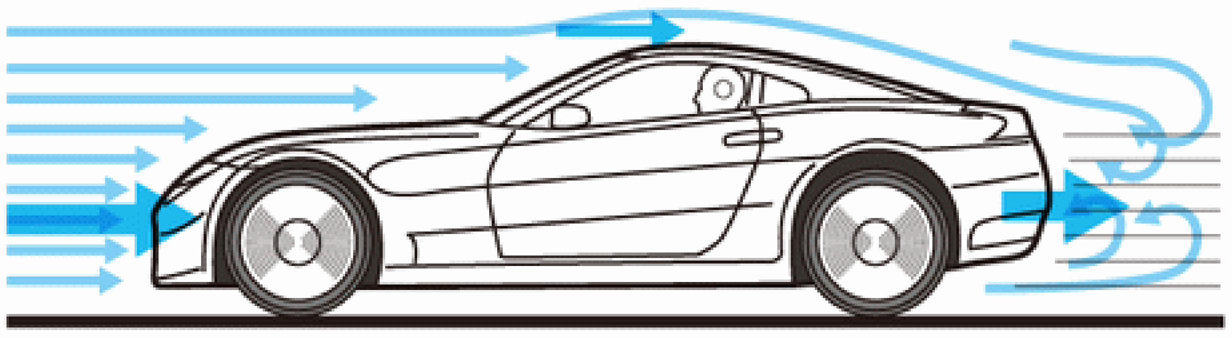
The silhouette of the car's body when viewed from the front. The greater this area, the more air resistance will be encountered. The reduction of frontal surface area, or wind resistance, is one of the reasons that sports cars tend to have lower bodies. A Large frontal area is a disadvantage of boxier cars and mini-vans.



Cd – Drag Coefficient

▶ Constant drag

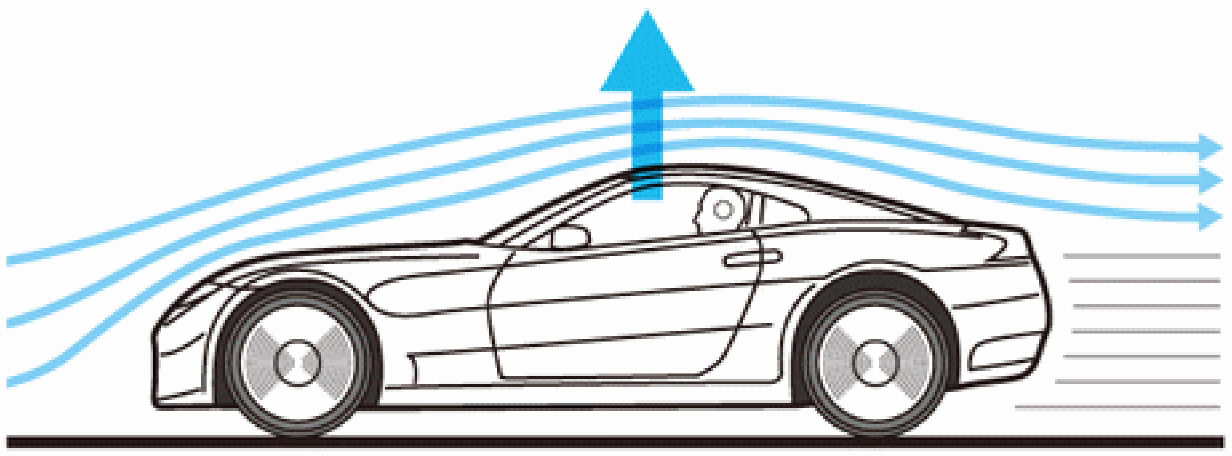
A number that represents how smoothly air passes over an object. This is a fixed value, and as such, is not affected by speed. Air resistance is calculated by multiplying the drag coefficient by the frontal area. Accordingly, if Cd is large but the frontal area is small as in many small sports cars, air resistance will still be small. The reverse can be said for sedans that have a larger frontal area.



Cal – Lift Coefficient

▶ Constant lift

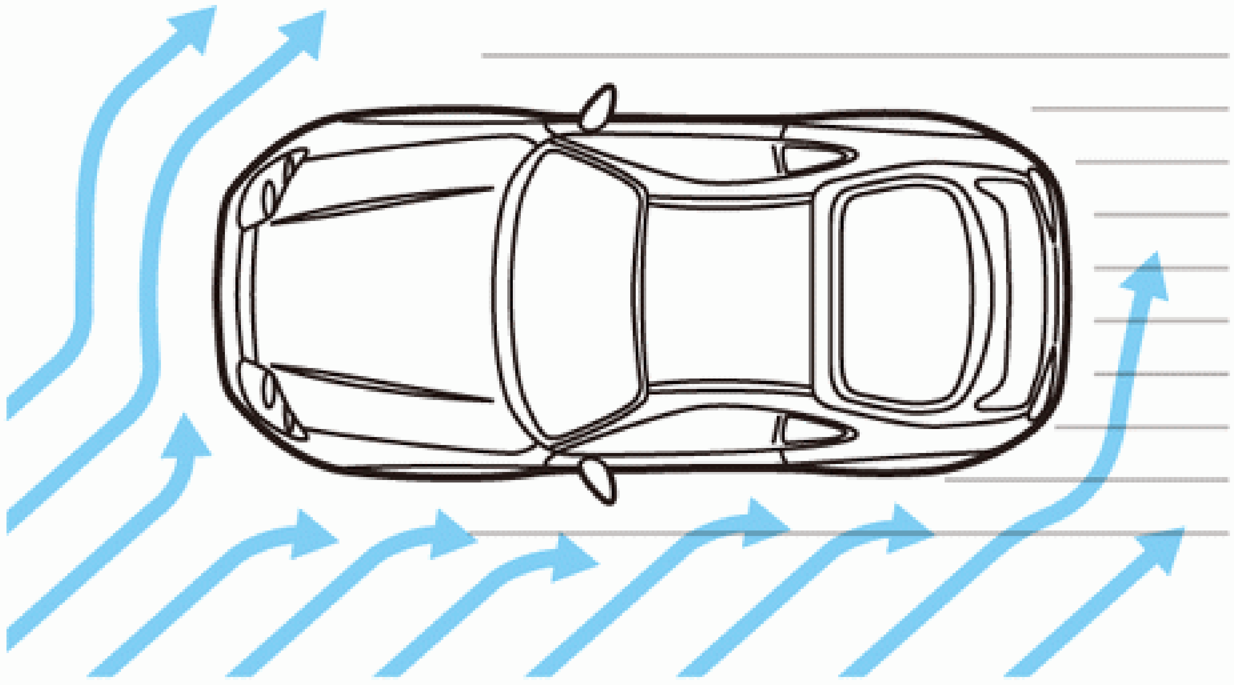
This is a number that represents the upward force on a car caused by air when travelling at speed. The opposite force is called "downforce" or "negative lift." Achieving downforce means increasing resistance, and ensuring stability is a matter of finding the optimum balance of downforce in the front and rear.



CYM – Constant Yawing Moment

▶ Yaw Moment Coefficient

When driving, winds do not always meet the car head-on. The force that occurs at the center of the car acting to spin a car hit by crosswind, is called the "Yawing Moment." Cars with a small CYM will be resistant to crosswinds, and in general, tall cars with a higher center of gravity are more affected.



Factors That Inhibit High-Speed Performance

Review: Tuning & Settings

3

ENGINE

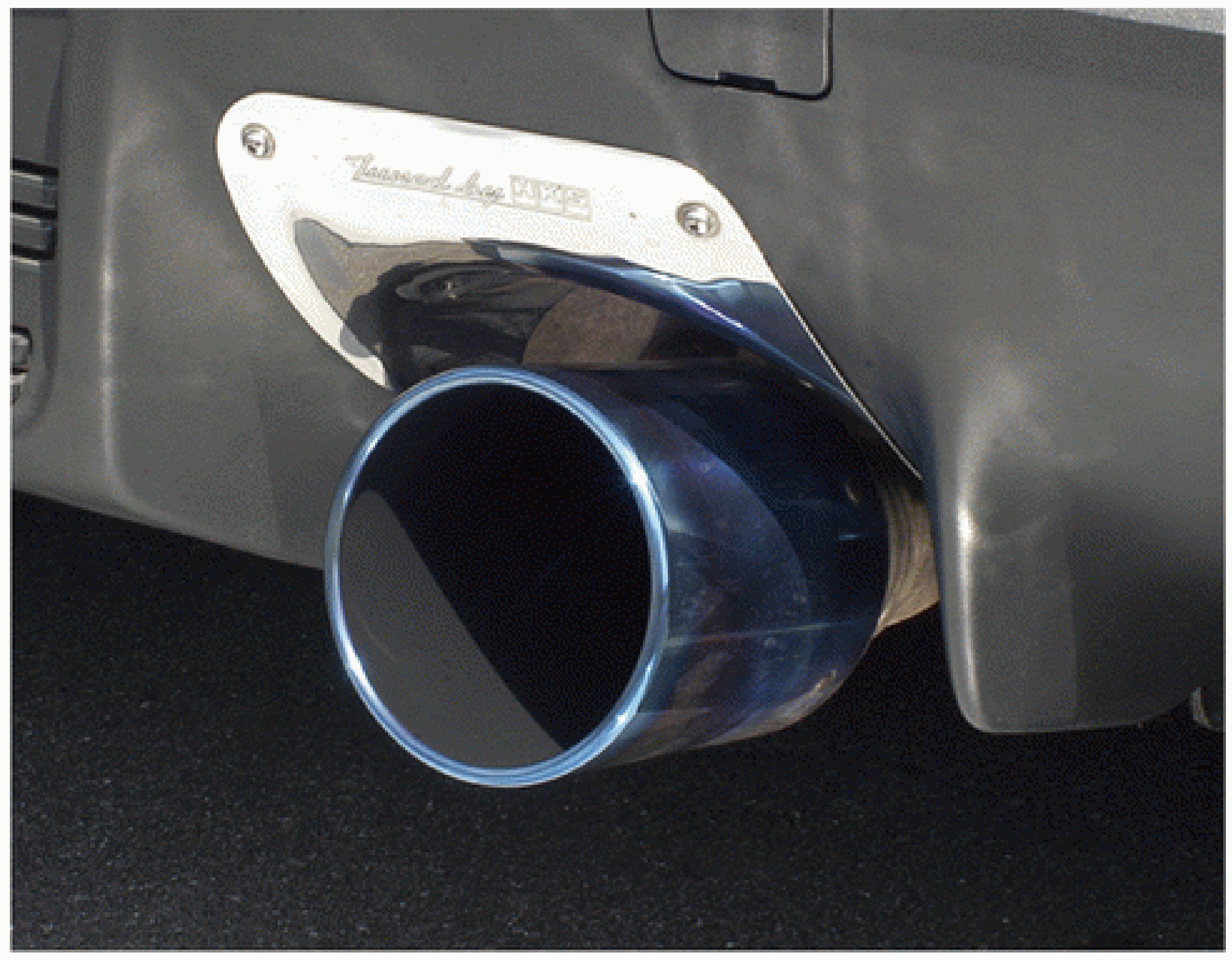
CHAPTER 03 Tuning & Settings

Improving Engine Performance

Tuning an engine for maximum power alone will result in a car that is hard to handle, and it won't perform well on the track. Tuning is a matter of trying to achieve the optimum settings for your vehicle based on the individual track and your particular racing style.

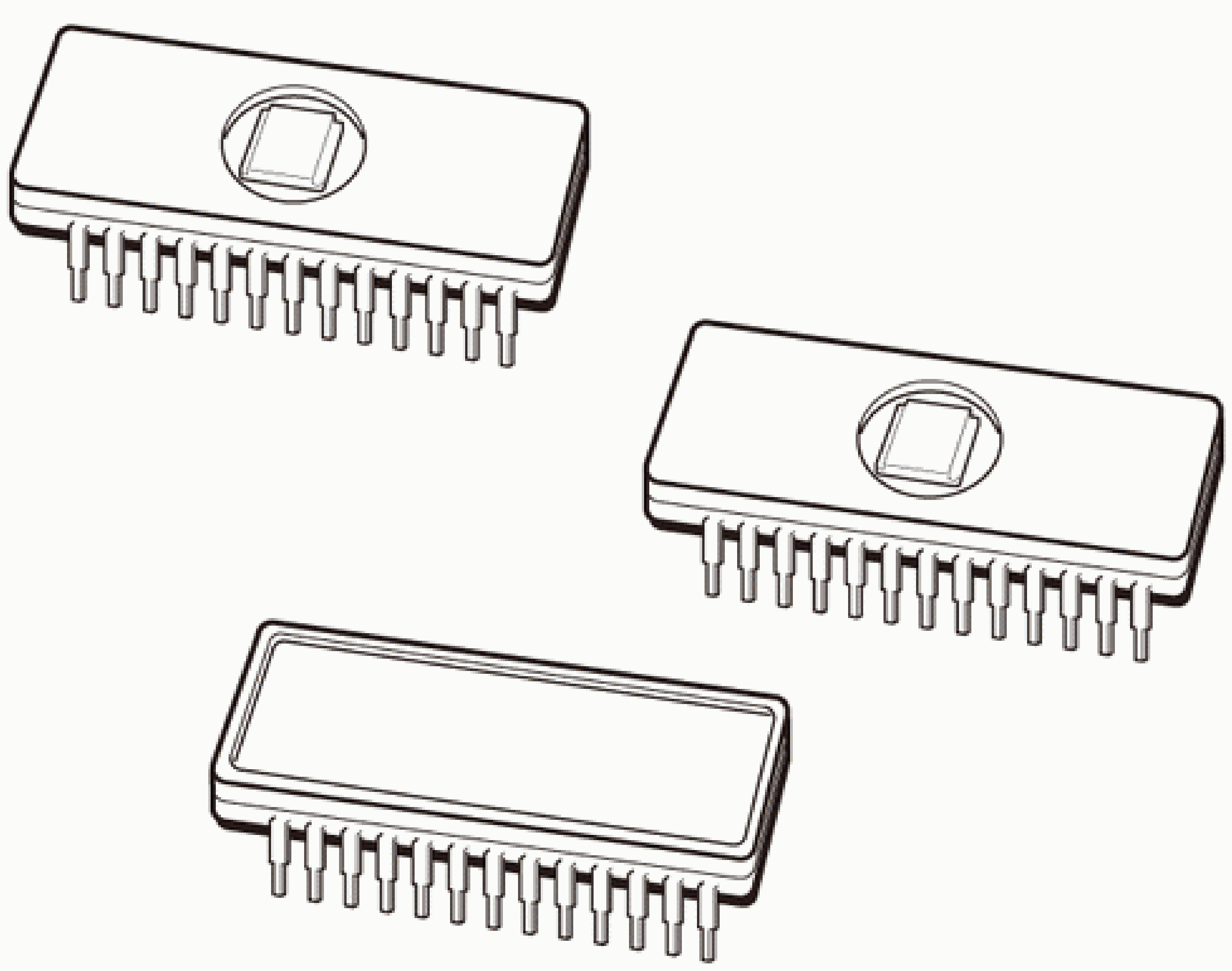
Fine-Tuning

Replacing the Engine Control Unit (ECU) and improving the efficiency of the exhaust system are some of the first basic steps in improving an engine's performance. Once these first steps have been taken, they set the base for making more serious modifications such as mechanical tuning or fitting a turbocharger. These first steps may not achieve a huge increase in power, but they will lead to a smoother revs and quicker response. The stress added to the engine through these modifications is fairly small - and in fact this will actually protect the engine when placed under high load.



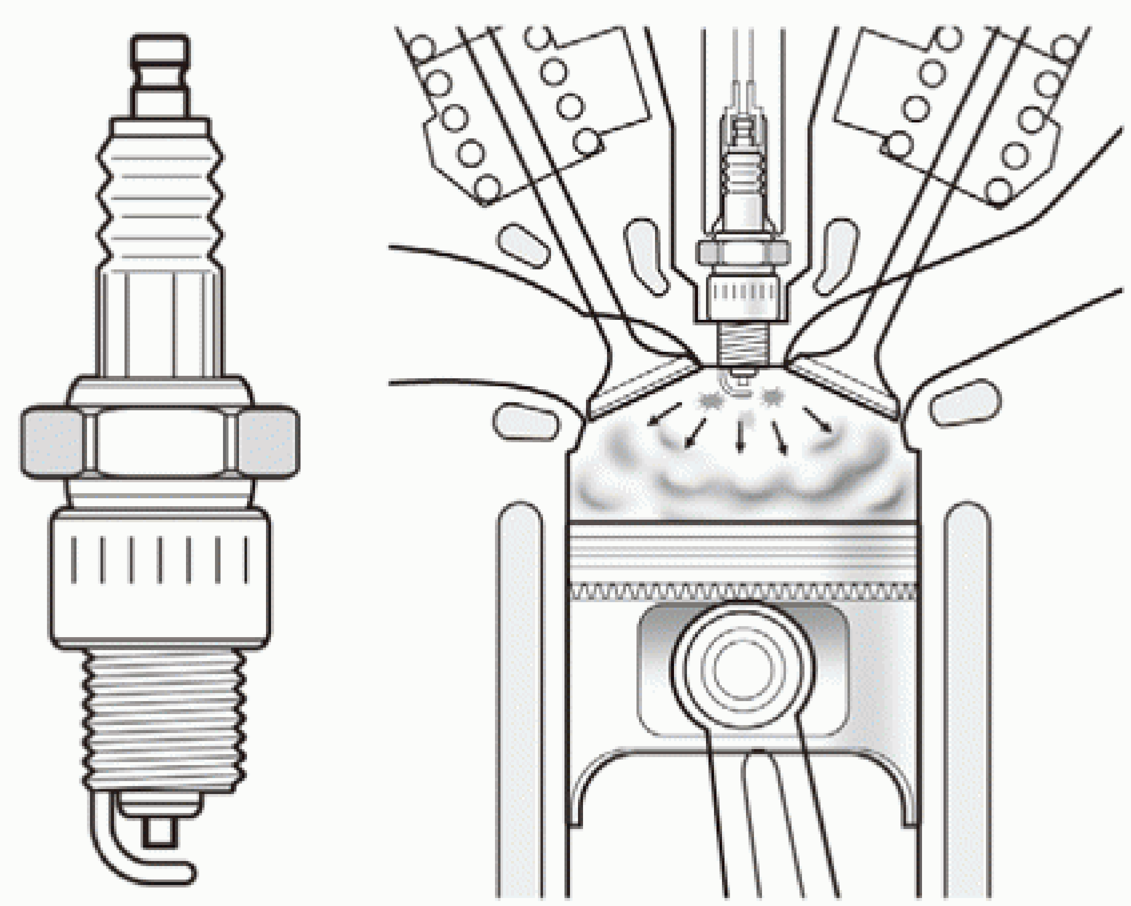
Engine Control Unit (ECU)

Updating the engine-control data saved on the ECU's ROM is known as "chip tuning" or ECU Tuning. In addition to ignition timing, the fuel-air ratio, fuel injection volume and valve timing can also be calibrated. ECU tuning is necessary whenever you raise the turbo pressure, replace any intake or exhaust system parts, or make any modifications to the engine itself.



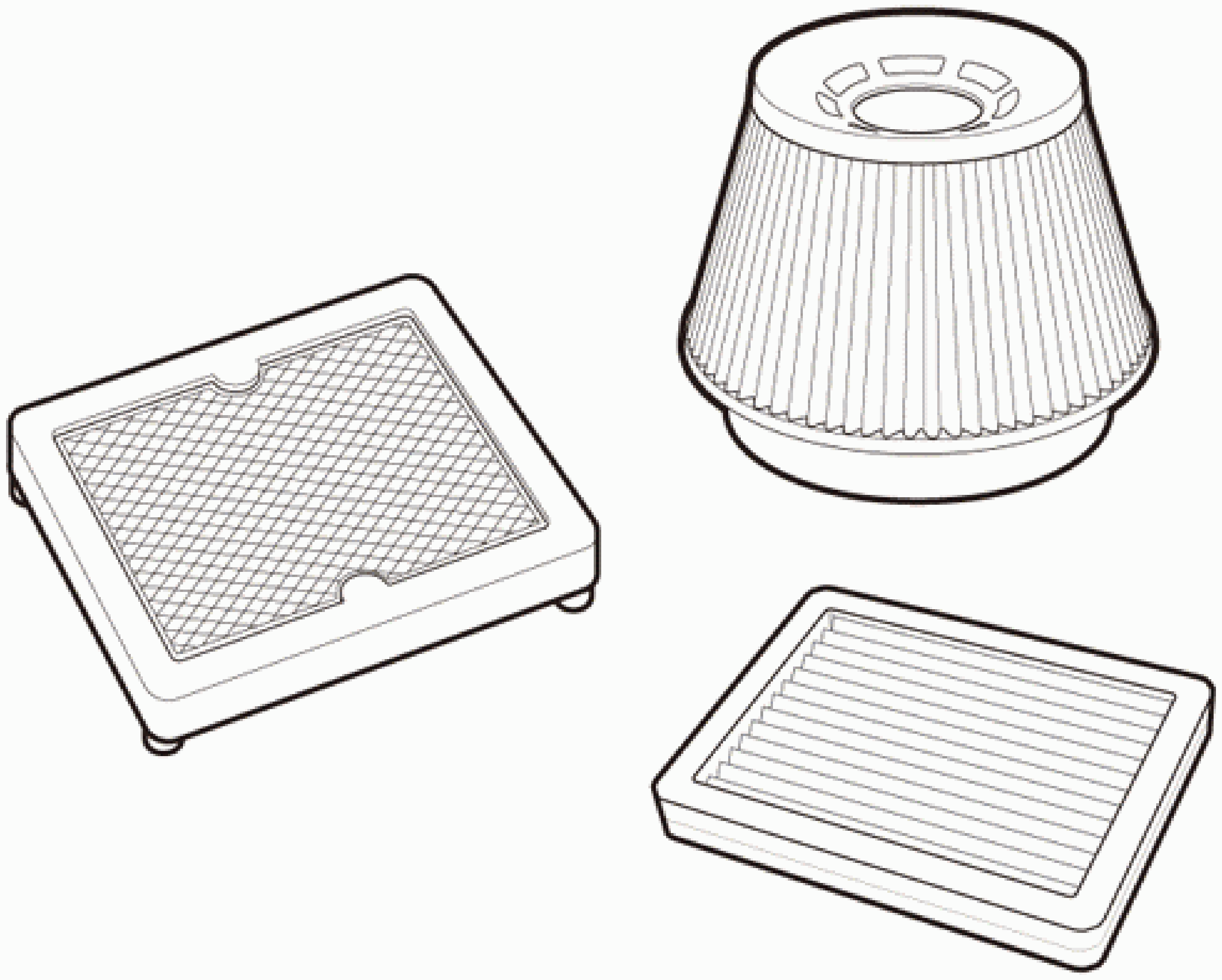
Spark Plugs

A strong spark is essential in order for the mixture of fuel and air in the combustion chamber to ignite properly. Even on a stock, unmodified engine, if it is run under high load continuously with regular spark plugs, the plugs will be strained with too much heat. This makes it especially important to upgrade your spark plugs when your engine has been tuned to produce more power. The increase in the engine's combustion will raise the temperature in the combustion chamber, making it more prone to abnormal combustion (pre-ignition). To avoid this, a more heat-resistant spark plug with a higher heat range must be used.



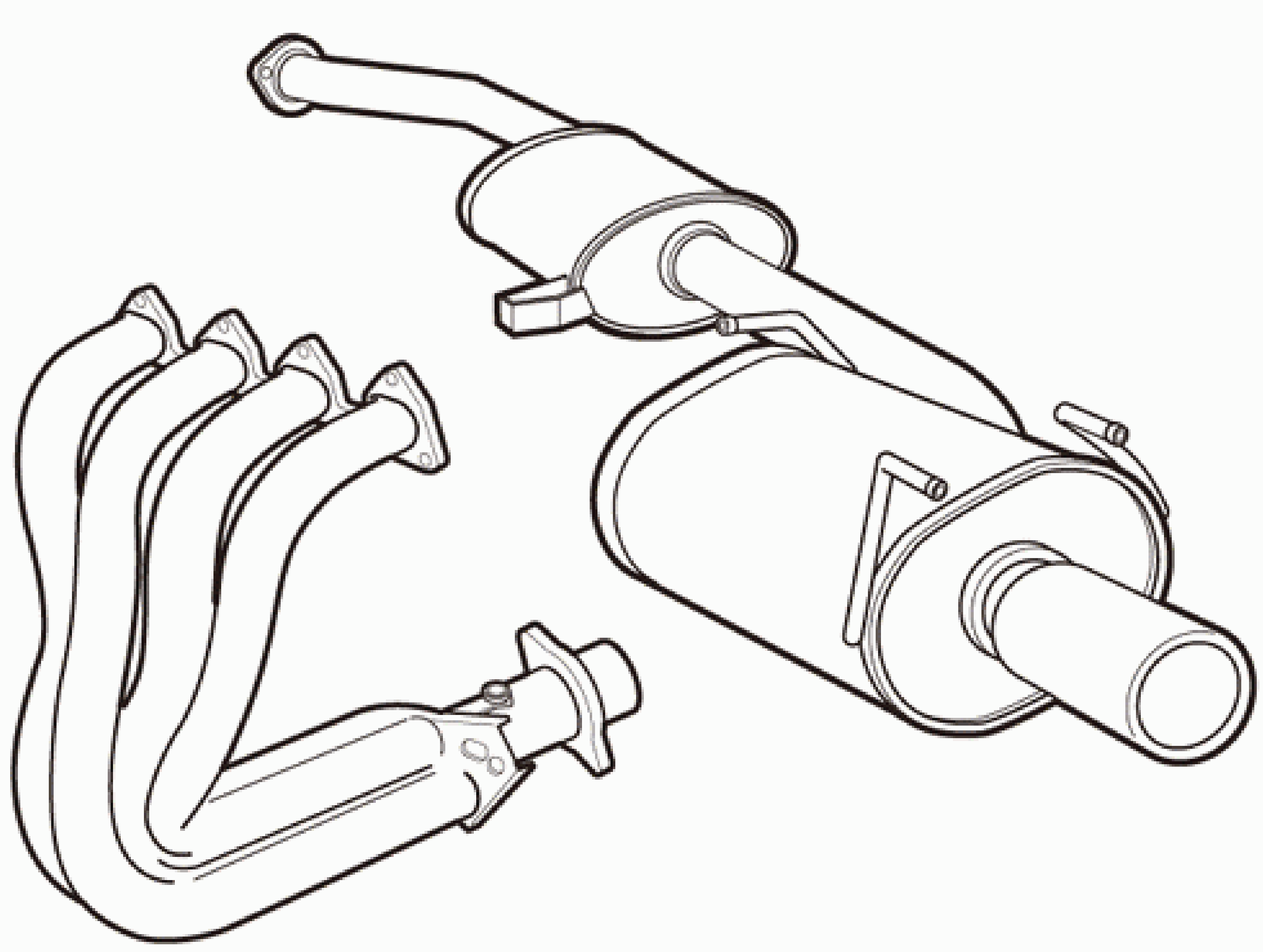
Air Filter

The standard air filter for avoiding dust and other impurities being taken into the engine has a high level of resistance, and is inferior in terms of power output. It is therefore preferable to switch to a low-resistance air filter specifically designed for racing. Rather than boosting engine power, this has more to do with improving pick-up during acceleration and improving responsiveness at high RPM. Don't be surprised when the sound of the engine drawing in air gets louder, though.



Exhaust System

By reducing exhaust resistance, the engine will rev up faster and the accelerator response will become markedly sharper. Turbocharged engines in particular, which make use of exhaust energy, can see power increases of 10-20% just from a muffler upgrade. However, be aware that changing exhaust components will affect the engine's torque characteristics, so it's always important to have a clear image in your mind of what effect you are trying to achieve.



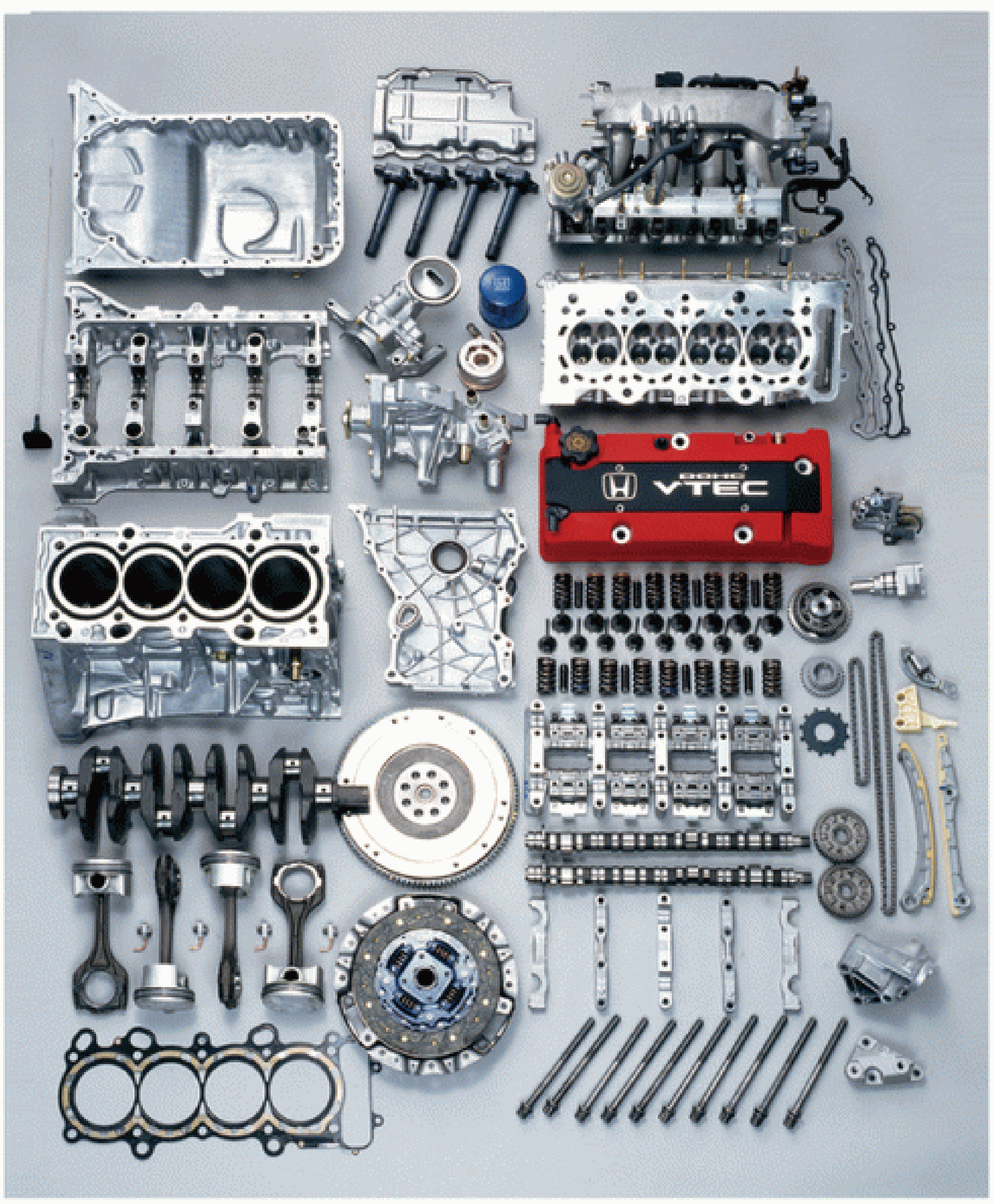
Engine Oil

High-output engines put immense strain on their components, particularly their internal parts, so high-performance engine oil is absolutely essential. Engine oil functions as a lubricant, a cooling agent and a barrier maintaining an airtight state. If the oil is not able to coat surfaces properly, the cylinder will not be able to maintain pressure and the engine will lose power. The loss of lubrication between fast-moving metal parts can also result in those parts seizing or melting together. Also, Oil viscosity is an important factor that can increase friction loss (power lost through excessive friction), and chemically synthesized low-viscosity oils that maintain performance even under harsh operating conditions are now widely used.

Overhauling the Engine

Mass-produced engines cannot be said to boast perfect precision in their assembly, and there are cases in which they are not performing to their full potential. Completely disassembling the engine down to its smallest components and rebuilding it from the ground up with absolute precision, can raise overall engine performance. While overhauling the engine in this way, you can boost its capabilities even further by replacing certain parts with more lightweight alternatives, and balancing various parts at the same time for added effect. If you're not restricted by limits on engine displacement, you can even use this opportunity to increase the engine's displacement capacity, improving output and torque even further without stress.

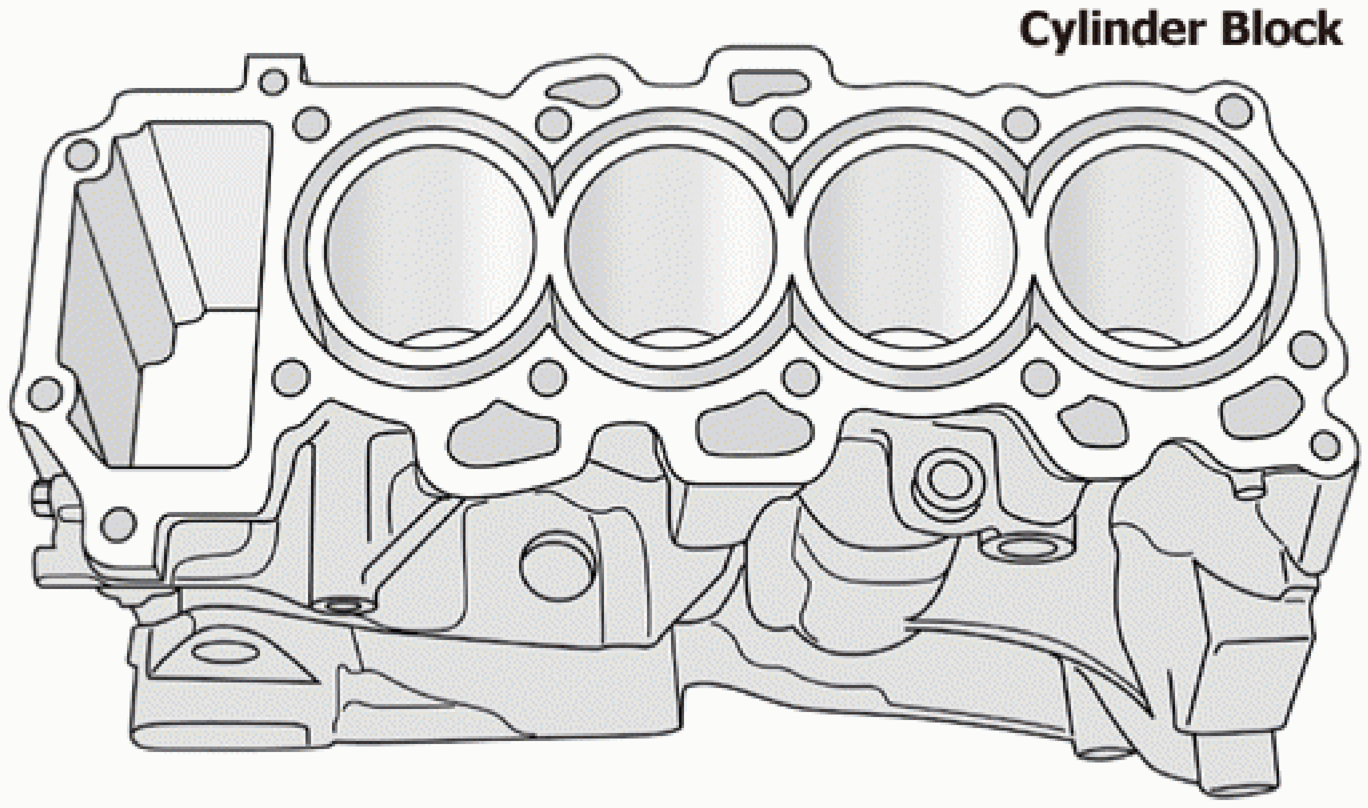
Some modern engines are so finely balanced when they roll off the production line that they don't leave a great deal of opportunity for improvement through overhauling.

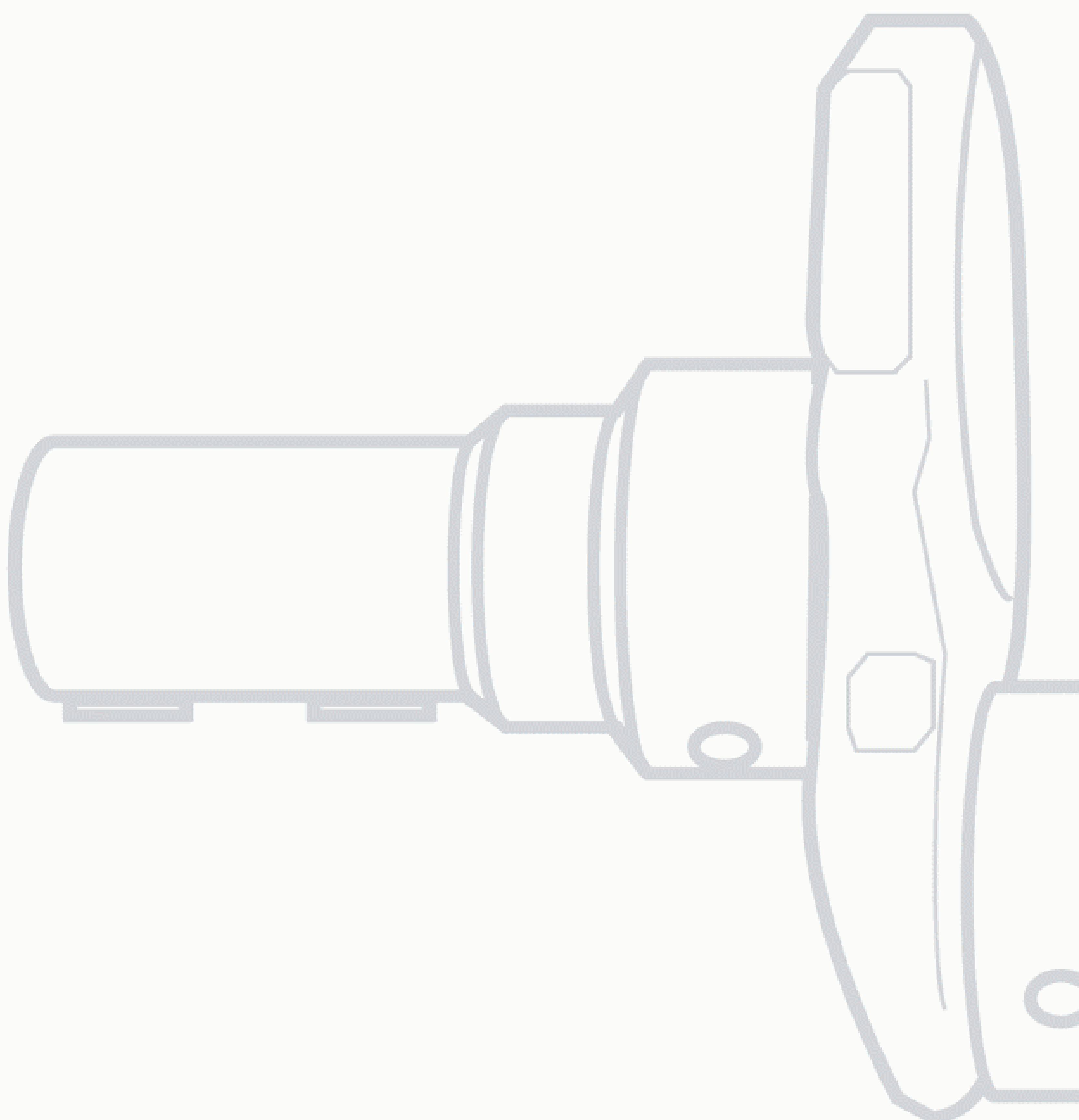


Increasing Displacement

This is the most effective way of improving performance when modifying the engine itself. By increasing the amount of fuel/air mixture burned, the engine output can be improved. This can be achieved by "boring up" the cylinder, making the cylinder bore larger and installing larger diameter pistons, or "stroking up," making piston stroke longer by replacing the crankshaft and connecting rods. Although both have the effect of increasing engine displacement, they each have different characteristics. Boring up is more suited for increasing engine RPM to give higher output, while stroking up increases torque at low and medium revs. However, as modern engines have become more lightweight, cylinder blocks have become thinner, making boring up to any great extent increasingly difficult.

Cylinder Block

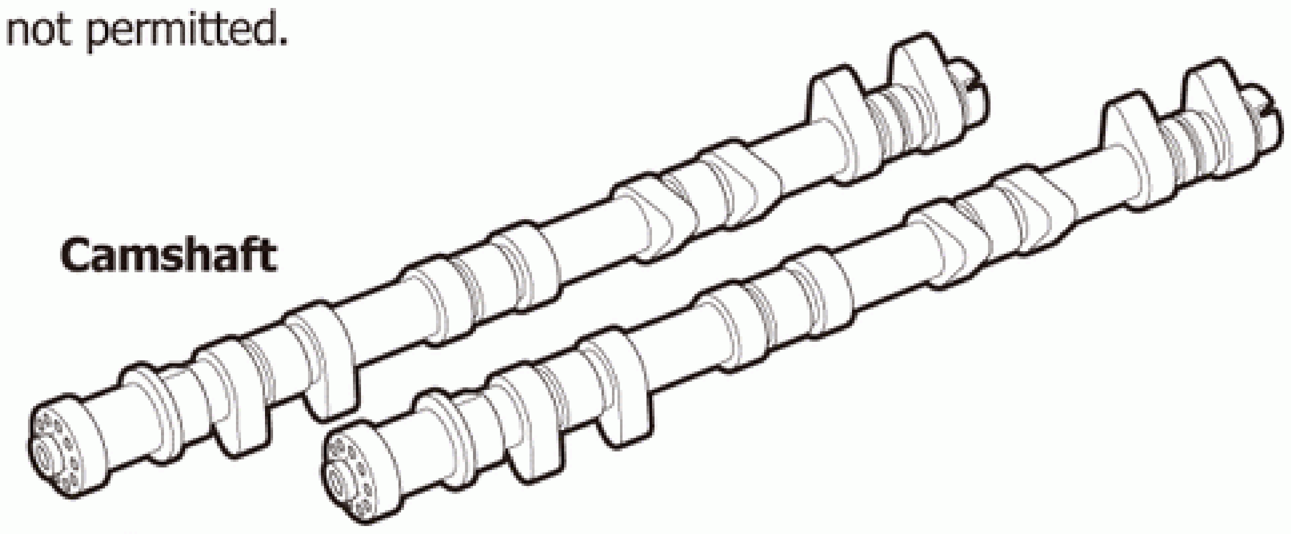




Balancing

In a normal engine, the weights of the pistons and connecting rods in each cylinder are all very slightly different. Also, if there is any deviation in the rotational balance of the crankshaft, this can cause resistance, which is a major cause of power loss. Balancing the engine involves disassembling the engine and carefully weighing each component. By making each part uniform in weight, and by correcting rotational balance to improve crankshaft movement, it can be made to run more smoothly and therefore more efficiently, to produce more power. In situations when modifying a part to correct the weight imbalance is not enough, the part is sometimes replaced altogether. This kind of tuning is absolutely essential for one-make racing, where major modifications to a car is not permitted.

Camshaft

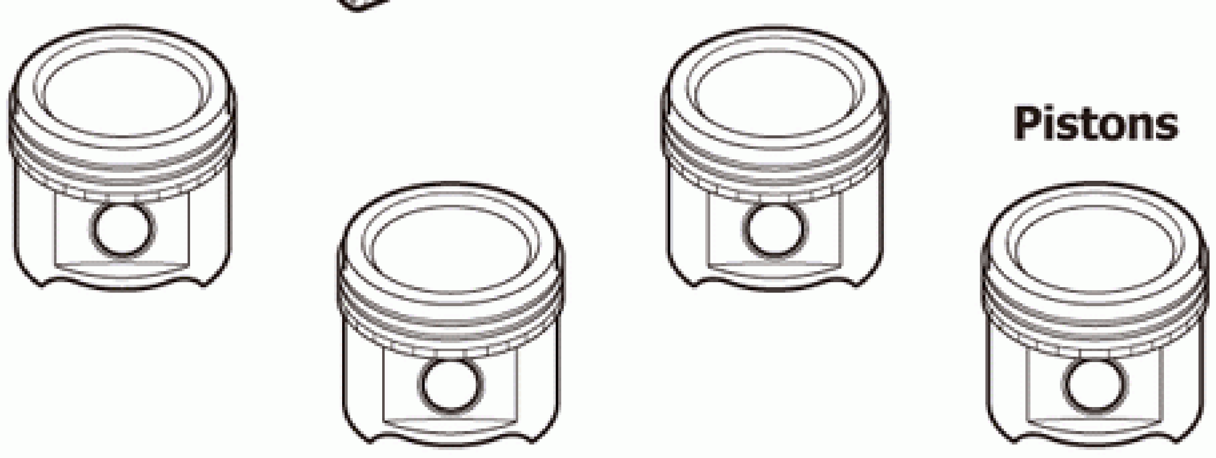


Reducing Weight

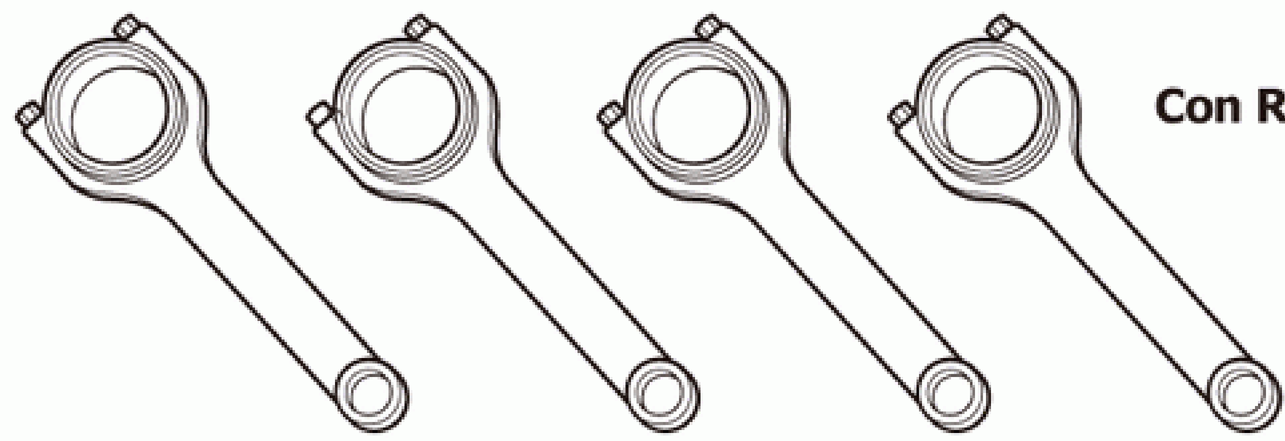
Engine parts that move at high speeds are acted upon by inertia, causing frictional loss and reducing power. This can be alleviated by removing material from parts to make them lighter. This is normally performed together with balancing, but if the parts are grinded down too thin, it can cause problems with durability.

Reinforcement

When major tuning work is carried out on an engine, the strain put on each individual part is greatly increased, and there is a greater risk of parts being damaged. This makes stronger parts essential, but it is also essential for these parts to be lightweight. Reinforced parts that make use of new forging techniques, as well as new materials such as titanium alloys, combine a lightness that far surpasses regular engine parts for strength and durability. In racing and tuned engines the use of aluminum forged pistons and titanium alloy connecting rods has become standard practice.



Pistons



Con Rod

Unleashing Your Car's Full Potential

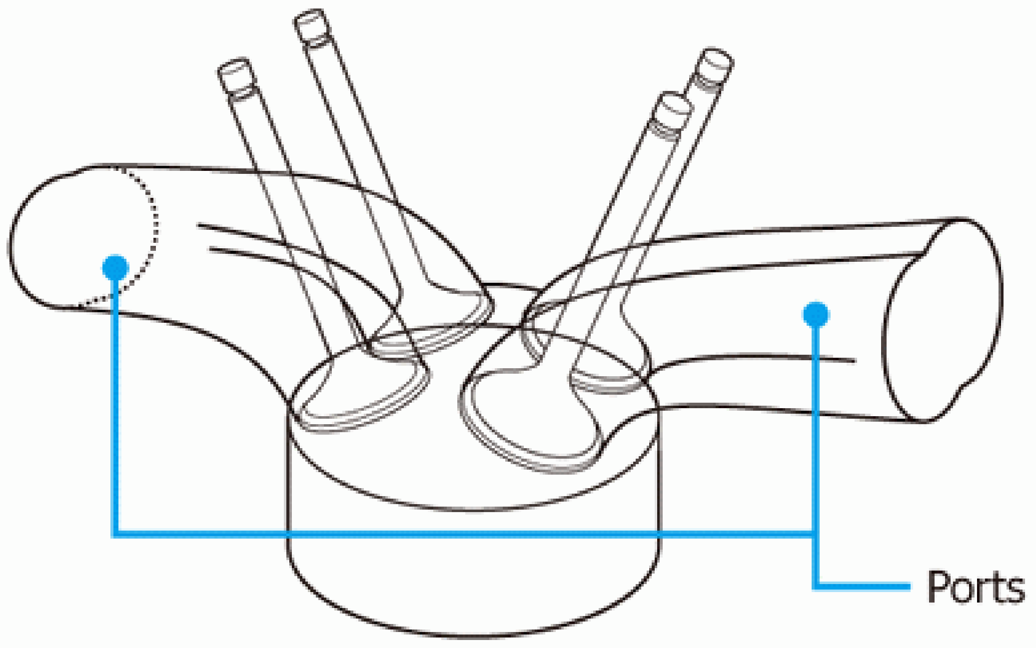
Increasing RPM

Engine output is a combination of torque and engine revolutions (power = torque x RPM). This means that boosting your engine's ability to reach high RPM will increase its potential output. The tuning needed to enable this centers on the cylinder heads, and the key to success lies in increasing the efficiency of air intake and exhaust at high revs. The standard way to achieve this is to replace the regular cam with a high-lift camshaft (p.129). Although this means that the components around the valves needs to be reinforced, it achieves the same effect as increasing the size of the intake and exhaust ports, improving power at high revs considerably. Incidentally, the engines most suited for high RPM are short-stroke engines, as their airflow efficiency is high, but their piston speed is not as fast as that of long-stroke engines.

You can increase your engine's ability to reach high RPM and produce high output in a single stroke, by switching to a high-lift camshaft. However, this will greatly reduce torque at low and medium revs, and some pure racing engines are not even be able to idle smoothly.

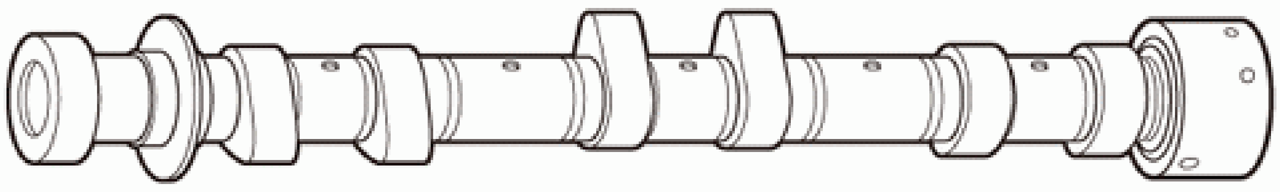
Ports

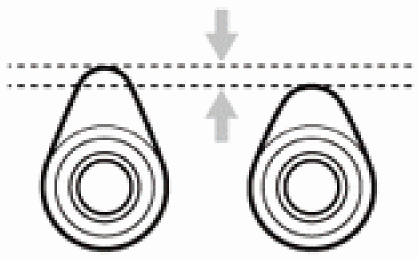
The intake and exhaust ports allow the fuel/air mixture to enter the engine, and provides an exit for waste gases after combustion. Ideally, the flow through the ports should be as smooth as possible, but due to issues of cost, this is usually not the case for the average engine. Rough surfaces characteristic of cast metals, the size of the passageways, distortion, etc. are all causes of intake/exhaust resistance. By polishing these surfaces to a mirror-like finish, a smoother flow of air can be achieved. Just polishing the port alone, the feel of the engine will improve in the high RPM range, but you are unlikely to feel its full benefit unless you combine it with a complete tuning of the cylinder head, including polishing the head and replacing the cams.



Camshaft

The camshaft is the shaft that opens and closes the intake and exhaust valves. A high-lift camshaft is one that has higher raised cam sections along its length, which cause the valves to open for longer. Effectively, this provides the same benefit as increasing the size of the ports, and while it reduces torque at low and medium revs, it increases engine power dramatically at higher revs. While the sudden surge of power at high RPM undoubtedly makes the car harder to control, it is a technique often used when trying to get extra power from a naturally aspirated engine.





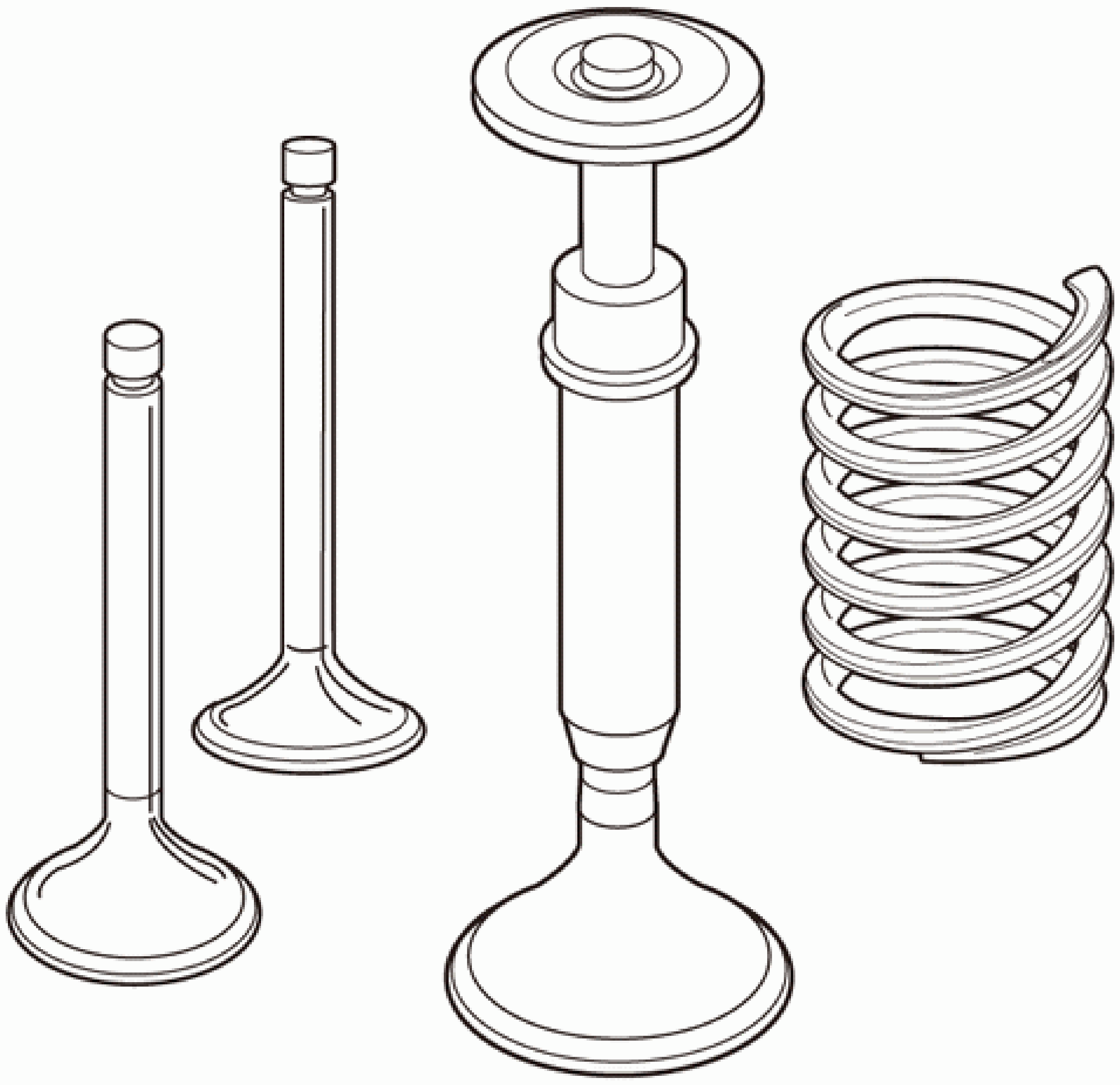
A normal cam on the right, vs. a high-lift cam on the left. The higher raised sections cause the valves to open for longer.

Valves

At the same time as polishing the ports and replacing the cams, you also want to consider increasing the size of your valves. This is a tuning method that enlarges the opening of the intake valve to allow more induction, and to improve intake efficiency. Because bigger valves weigh more and affected by more inertia, they are often made from ultra lightweight titanium.

Valve Spring

High engine revs can cause the springs that hold the valves closed to vibrate, leading to "surging," where the expansion and contraction of the springs cannot keep pace with the movement of the camshaft. In an engine that has been tuned for increased power, a valve spring upgrade is important in order to avoid this. The need becomes even greater when a high-lift cam is fitted, as normal springs may not be able to cope with the valve's increased lift and, in extreme cases, the spring can stick to the cam and cause it to lock, or the valve and piston can collide with each other. Bear in mind, though, that fitting strong springs increases resistance, and causes more wear to the area around the valves.



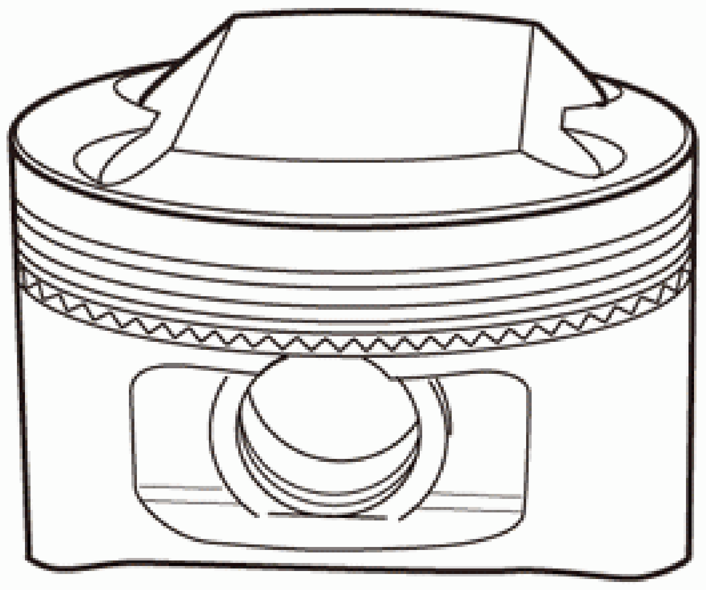
Increasing RPM to Improve Power

Increasing Compression

The greater the degree to which an engine can compress the air/fuel mixture, the more powerful the combustion that will take place when the fuel is ignited, and the greater the power and torque that will be generated. The main part of this tuning involves the redesign of the combustion chamber capacity in the cylinder head. However if the compression is raised too high, this increases resistance when the engine is turning (compressing), and can also lead to abnormal combustion. High-compression engines require various adjustments to combat these problems, such as adjusting the amount of fuel entering the cylinder, switching to "cold" spark plugs and delaying ignition, and reinforcing the pistons and connecting rods to cope with the increased combustion power of the engine.

Pistons

The most common way to raise the compression ratio of the engine is to switch to high-compression pistons. As you can see from the raised upper part of these pistons, the combustion chamber is actually smaller than when using a regular piston, resulting in an increase in the compression ratio. However, increased compression leads to a hotter fuel/air mixture, and higher temperatures during combustion, making "knocking" (incorrect combustion of the fuel/air mixture) more likely to occur. This makes it necessary to take measures such as improving the flow of air/fuel mixture.



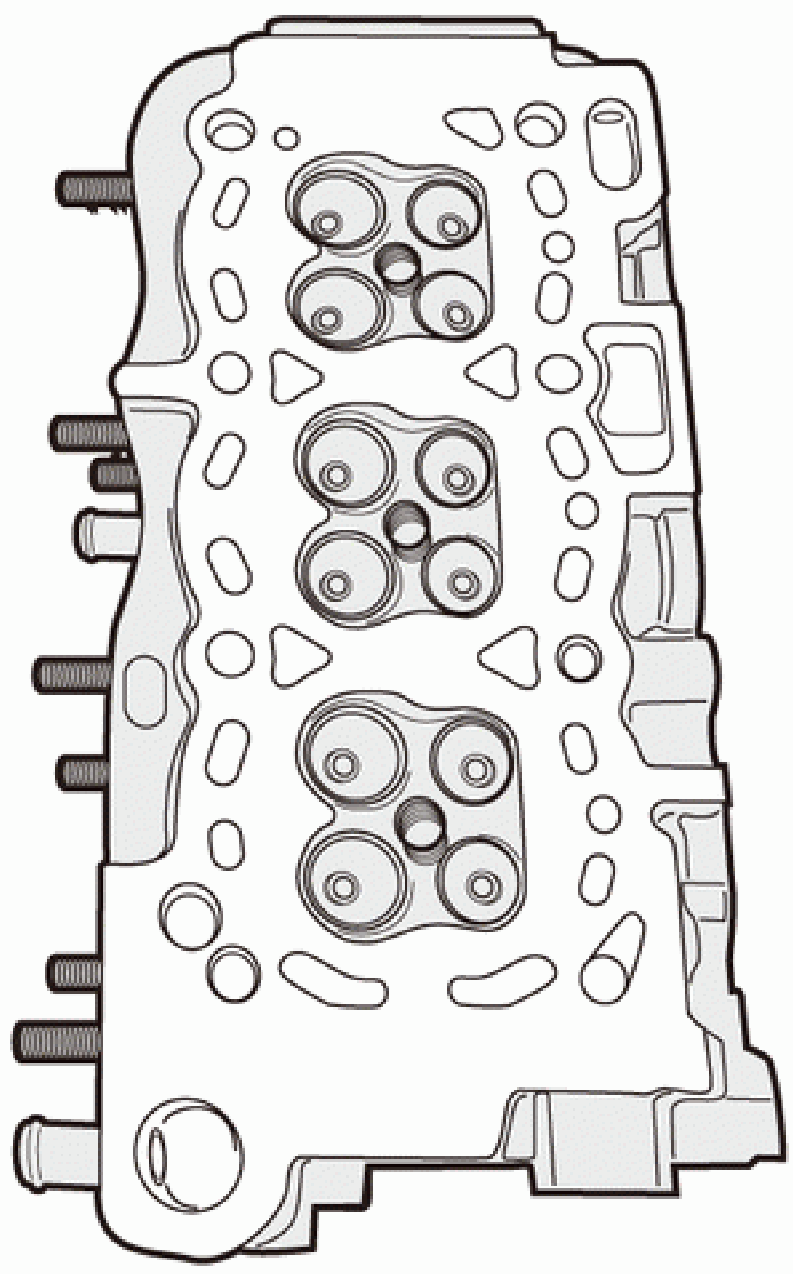
Increasing compression should ideally be performed in tandem with the increase of the engine's potential RPM. Also, as combustion will involve more force, the interior of the engine needs to be reinforced.

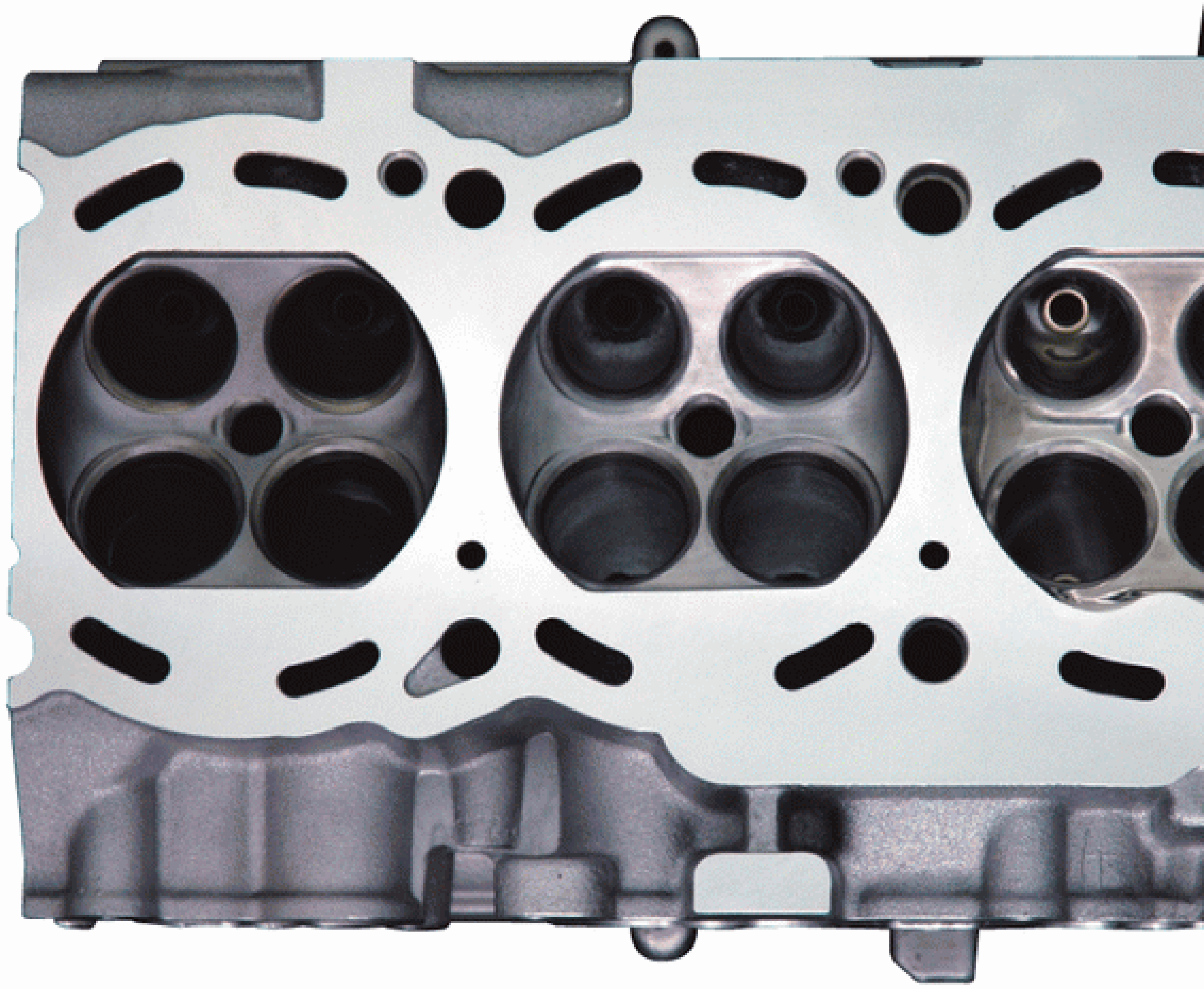
Combustion Chamber

There are various combustion chamber modification techniques, one of the major ones being the "pentroof" type which is superior in airflow and ignition efficiency, but the most common method for preventing knocking from high compression involves the use of "squish" or "quench" zones. These are areas cut into the combustion chamber where compression is concentrated, thereby serving to slightly reduce the overall compression ratio. However, creating squish areas can create discrepancies in the volumes of individual combustion chambers, so it's necessary to perform a precise measurement of the combustion chamber afterwards to make sure they are balanced

Cylinder Head

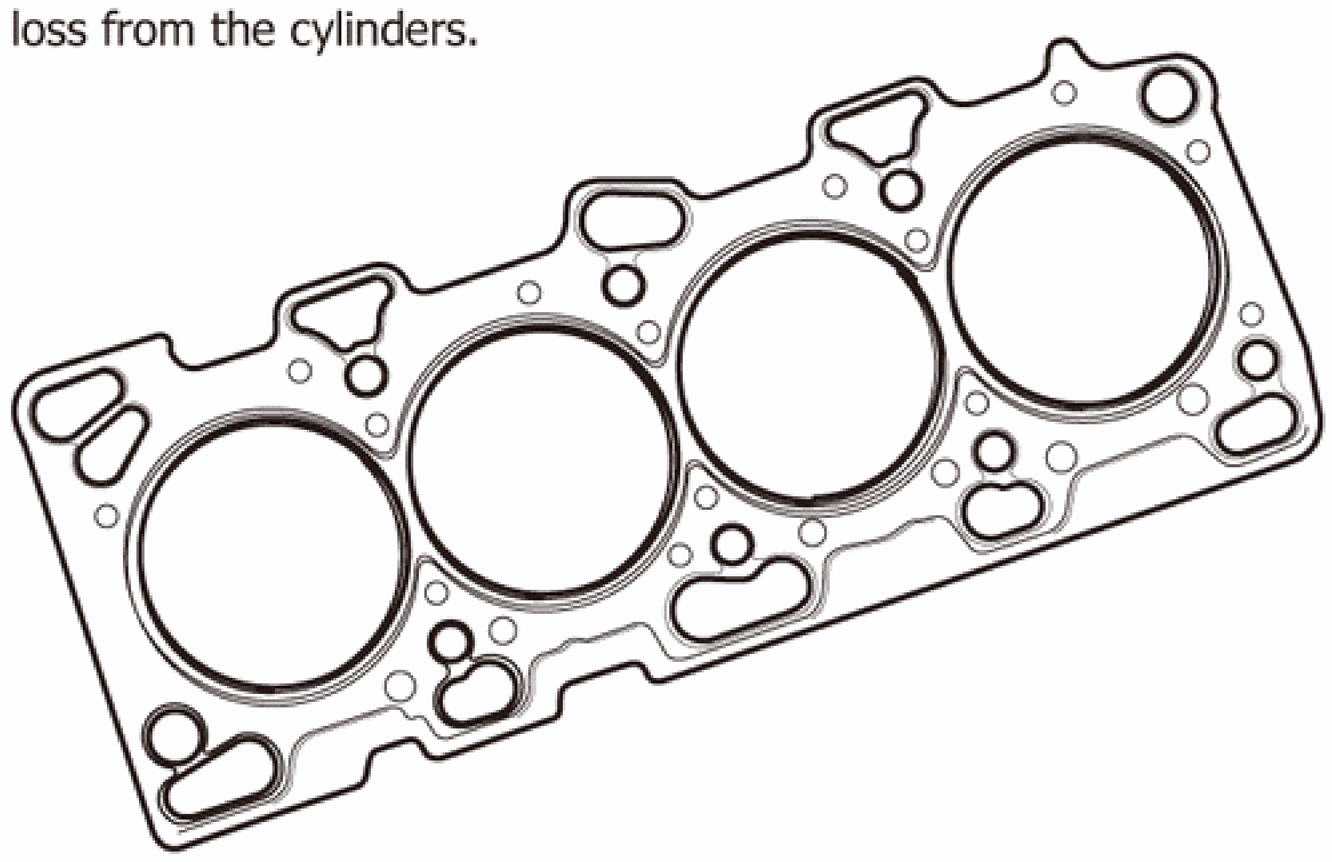
The underside of the cylinder head can be ground away in 0.1mm increments to gradually reduce the capacity of the combustion chamber, thereby increasing the compression ratio. This can also be carried out to correct any warping that may have occurred when running at extremely high temperatures, restoring the fit between the cylinder block and head and remedying any issues of compression loss.



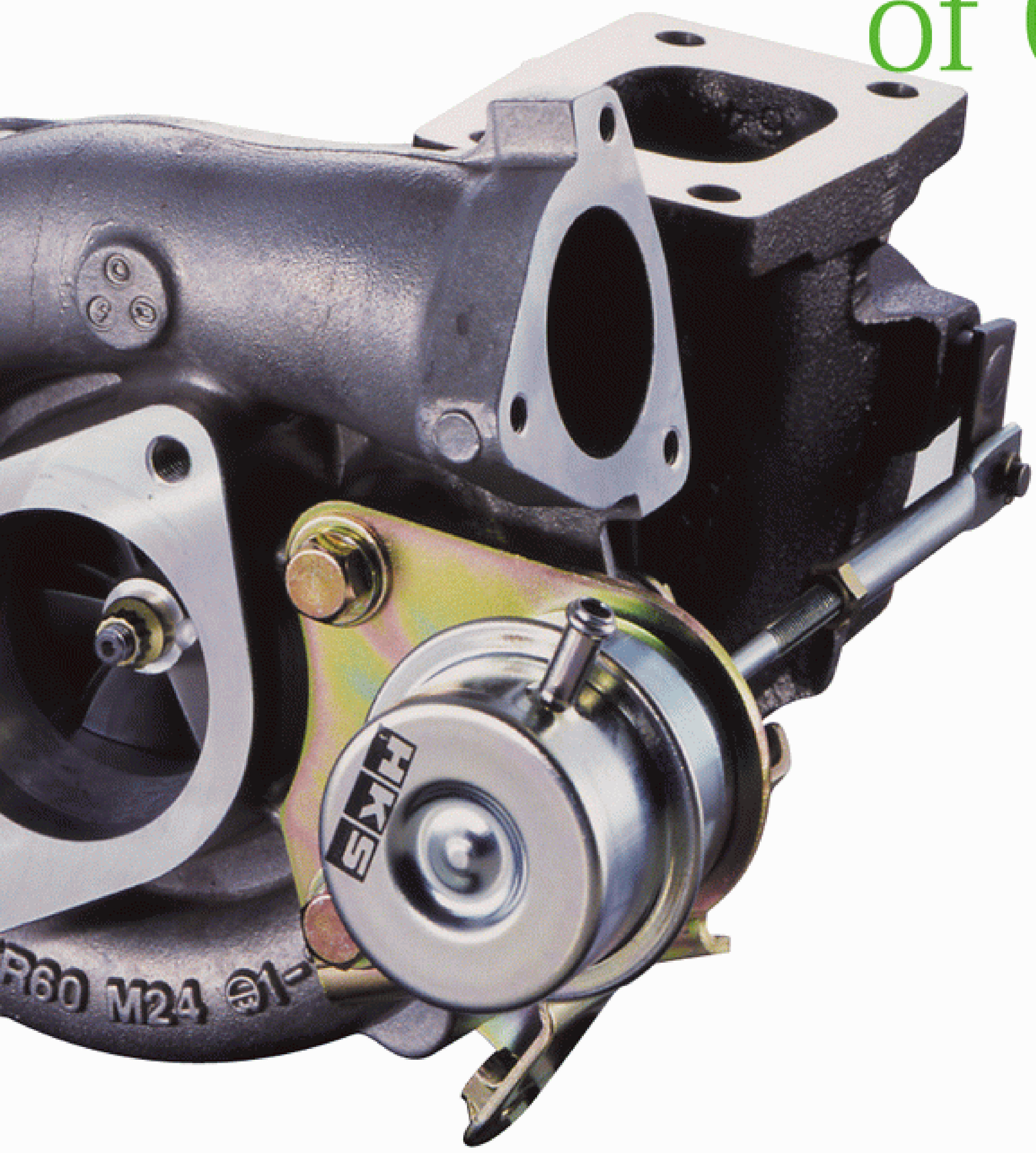


Hard Gasket

The head gasket is the plate that sits between cylinder block and head, ensuring a good seal between the two, and preventing compression loss. Reducing the thickness of the head gasket has the same effect as grinding down the cylinder head, in that it serves to reduce the capacity of the combustion chamber, thereby raising the compression ratio. Head gaskets are now generally made from stainless steel, as it has high strength, and boasts high levels of thermal conductivity. This allows compression levels to be optimized, and avoids pressure loss from the cylinders.



Delivering Large Quantities of Compressed Air



Boost Pressure

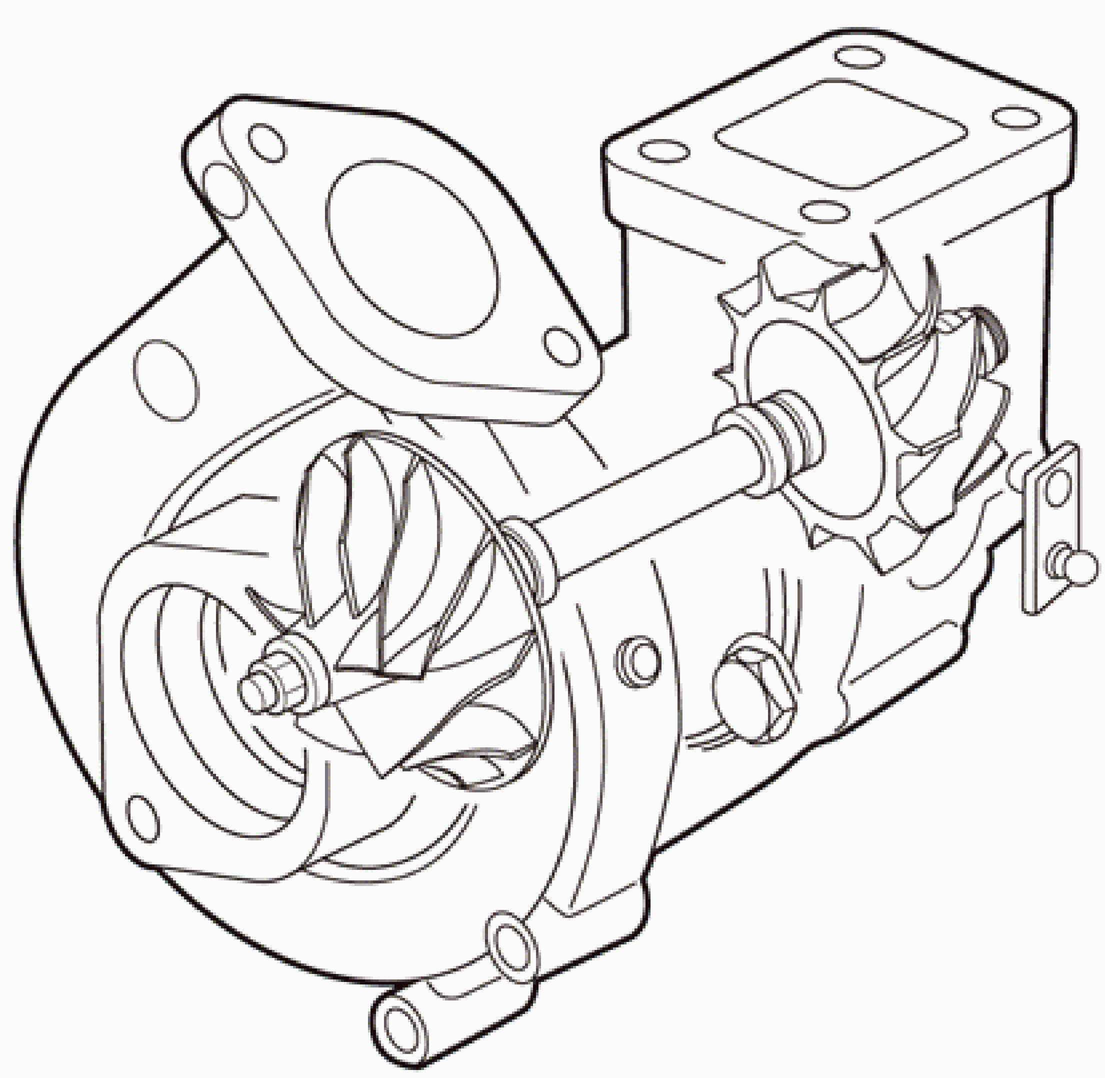
Boost pressure is a figure indicating the volume of air a turbocharger takes in and the compression it puts it under, and is expressed in units of kg/cm2, kPa or psi. The higher this figure, the more power is gained. However, the more air is taken in, the more fuel is needed to mix with it, which means that the ECU must be configured to add more fuel, and it may be necessary to change or add fuel injectors so that fuel can be delivered in larger quantities. It is also essential to reinforce the internals of the engine in order to cope with the stress caused by the increased combustion.

High-Flow Turbine

This is a turbo in which the size of the compressor wheel which compresses the air taken into the turbocharger is enlarged, greatly increasing airflow. A process known as "cutback" can be used to reduce inertia acting on the turbine wheel, thus allowing boost to be applied more quickly. This allows output to be increased with a minimum sacrifice of responsiveness.

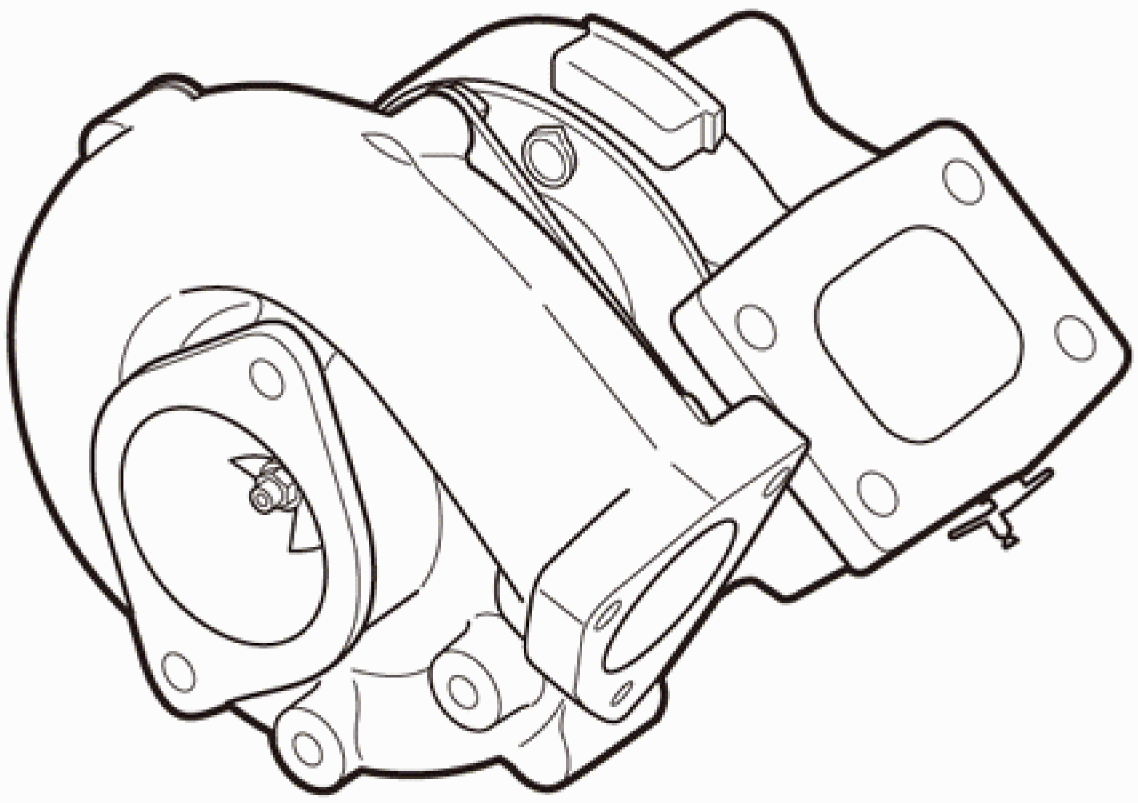
Forced Induction Devices

Increasing boost pressure or increasing the size of the forced induction device is a relatively easy way to achieve the same effect as increasing engine displacement without having to modify the engine itself. If you choose to combine this with mechanical tuning, you can achieve even better results. However it's important to remember that forced induction increases stress to the engine much more than naturally aspirated engines, and measures must be taken to account for this. In a naturally aspirated engine, a high compression ratio is the key to powering up the engine, but in an engine that is supercharged or turbocharged, compression actually needs to be lowered in order to prevent abnormal fuel combustion or damage to parts caused by the increased combustion. A lag in response is also an issue for turbocharged engines, and measures need to be taken so that the responsiveness of the engine is not critically affected.



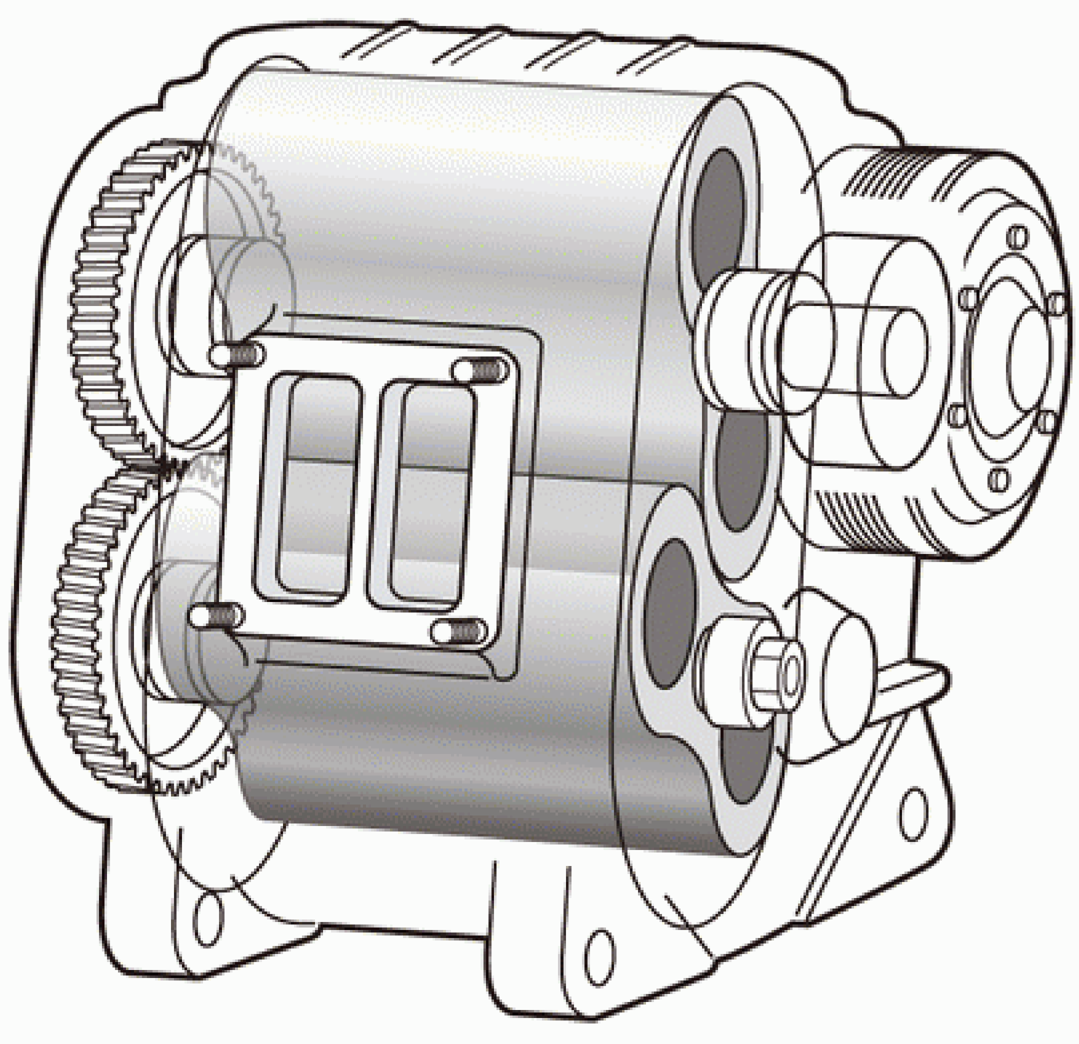
Increasing Turbine Size

This involves replacing the regular turbocharger with a larger one, since the size of the turbocharger is what determines the limits of a turbine's output. Although this delivers a marked increase in power, it has a disadvantage in that turning a larger turbine leads to a slower response of the engine. And you need to be aware that unless you have a large displacement engine generating a large amount of exhaust, and/or a powerful enough engine, torque at low revs will be very low, and the turbocharger will only be effective at very high RPM, making the car extremely difficult to control.



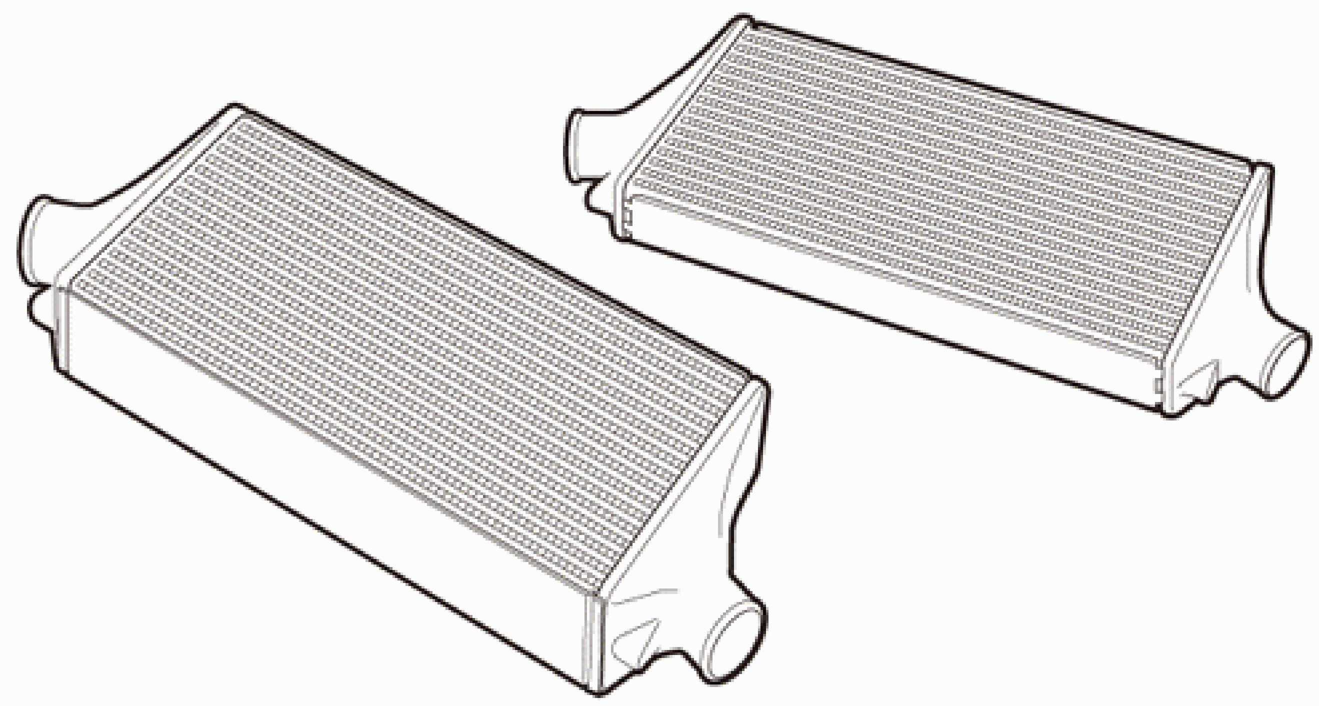
Supercharger

The principle behind the supercharger is similar to that of the turbocharger: essentially, it forces compressed air into the engine, giving it a boost in power. As with turbochargers, they can be bolted on to naturally aspirated engines, making them a relatively easy way to increase output. Because a supercharger does not cause a lag in accelerator response like turbochargers due to their mechanism, they are particularly useful on technical racetracks that require quick response.



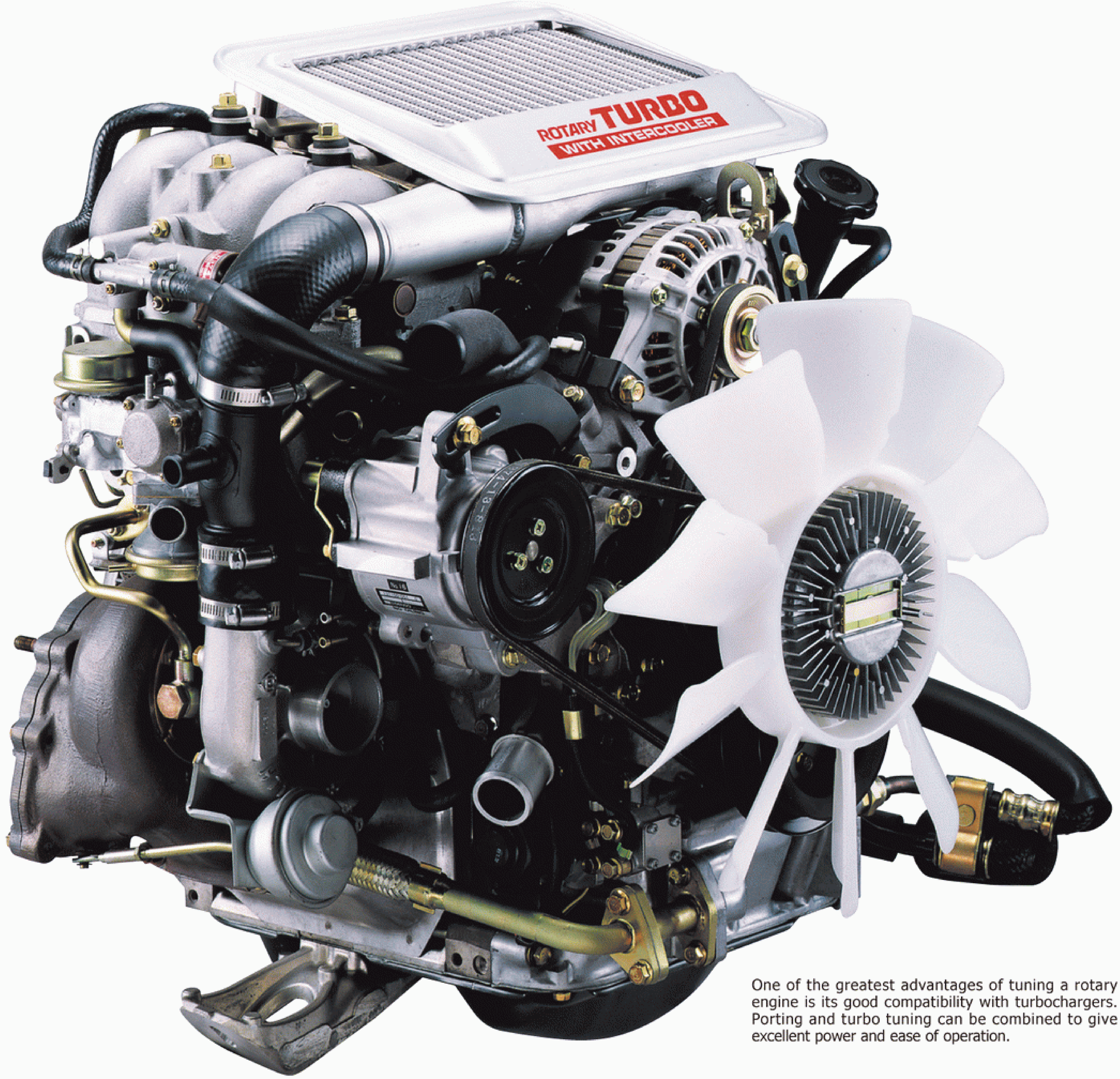
Intercooler

The intercooler plays an important role in a turbocharged engine, serving to cool the air heated up by the compression of the turbocharger and improving the engine's volumetric efficiency. Intercoolers are fitted standard even in many production vehicles, but increasing their size boosts their effectiveness and enhances their cooling capability. However, compressed air takes too long to travel through an intercooler that is too large, and starts to lose pressure. This can cause up to a 10-20% loss of boost pressure in some cases.



Rotary Engines

One of the main aims when tuning a rotary engine is to increase air intake efficiency. This is achieved by enlarging the intake ports, thereby delivering more air/fuel mixture to the combustion chamber. This effect is similar to that gained by fitting a high-lift camshaft to a reciprocating engine, but the nature of the power increase gained by relocating and enlarging ports can be very different. For example, peripheral porting, a technique used in competitive rotary-engine cars, causes an extreme loss of torque at low revs, and makes normal driving extremely difficult. Also on a rotary engine, the exhaust ports and turbocharger are very close together, allowing the exhaust gases to turn the turbine very efficiently. By combining both port and turbo tuning, the potential of this engine can be improved effectively.



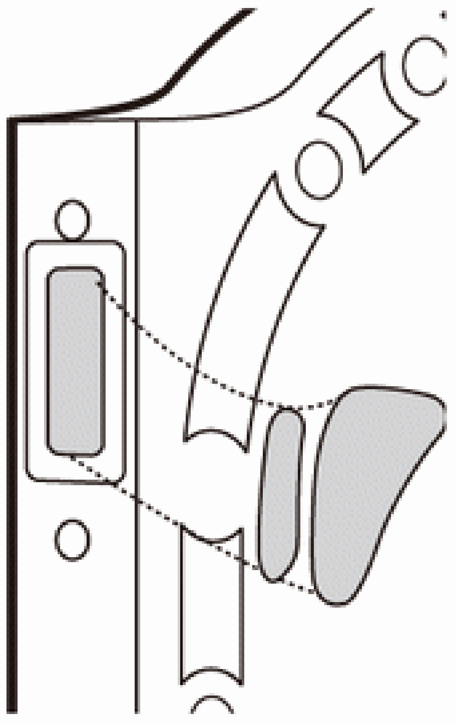
One of the greatest advantages of tuning a rotary engine is its good compatibility with turbochargers. Porting and turbo tuning can be combined to give excellent power and ease of operation.

Porting - the Key to Improved Rotary Power

Bridge Porting

This is one method of tuning the side port. It is called a bridge port because the shape of the enlarged port has a "bridged" section in the middle.

The reason for this bridge between the two openings rather than just having one large opening, is that when the port is enlarged to the very limits, it is necessary to leave this bridge to support the apex seal so that it does not warp or fall out when traveling over this section.

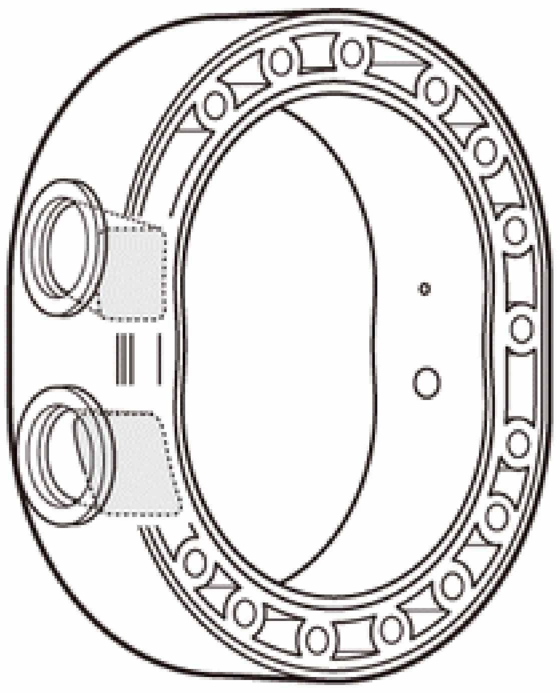


Balancing

Compared to a reciprocating engine, a rotary engine's structure is simple, and it has fewer components. A lot of extra potential can be unleashed simply by improving the precision of each of these parts and carefully reassembling the engine. The most important part of this process is the setting of the seals. The rotor's corner seals correspond to the piston rings on a reciprocating engine, and if they can be arranged so that they all have exactly the same clearance, the rotor will turn incredibly smoothly, while maintaining the perfect amount of compression. If seals are set poorly, this can lead to loss of power and, in the worst cases, engine seizure.

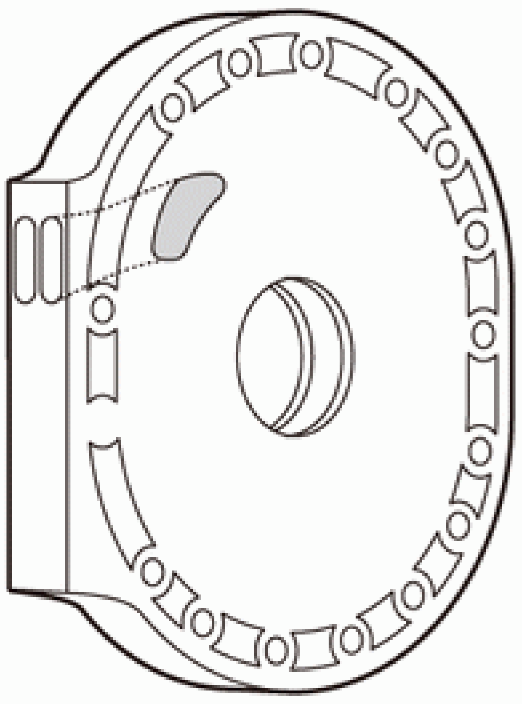
Peripheral Porting

This is a method of tuning a rotary engine by using a special adhesive to fill in the intake ports located in the side housing, and then relocating them to the upper part of the rotor housing. The advantage of this is that the air/fuel mixture is delivered directly to the rotor housing, significantly boosting engine power at higher revs. Unfortunately, it also means that the engine will be unable to maintain torque at low revs due to the loss of the ability to differentiate between high and low speeds and adjust the air/fuel mixture accordingly. This means that the increase in high RPM performance comes at the price of a huge loss in low-end torque, and results in extreme power output characteristics that will be difficult to control.



Side Porting

By widening the diameter of the intake ports positioned on the engine's side housing, air can be inducted into the engine at a faster timing than usual, increasing the total volume taken in and giving enhanced power. This offers similar benefits to fitting a reciprocating engine with a high-lift camshaft.



Combination Porting

Also known as "cross-porting," this technique combines side porting (or bridge porting) with peripheral porting. It takes advantages of both types of porting by using a sequential system that uses the side ports at low revs, and the peripheral ports at high revs.

Tuning the Drivetrain

A vehicle's drivetrain translates engine power into speed. It needs to be as efficient as possible in transmitting that power to the road surface, and robust enough to handle high output with ease.

Getting The Best Performance From Your Engine

Final Gear Ratio

Altering the final gear ratio will allow you to choose between applying your engine power to top speed or acceleration. For example, in a high revving, high output engine with an extreme difference in characteristics from low to high RPM, you can make it easier to utilize its performance by setting the final ratio lower. This can then greatly improve the acceleration of the car.

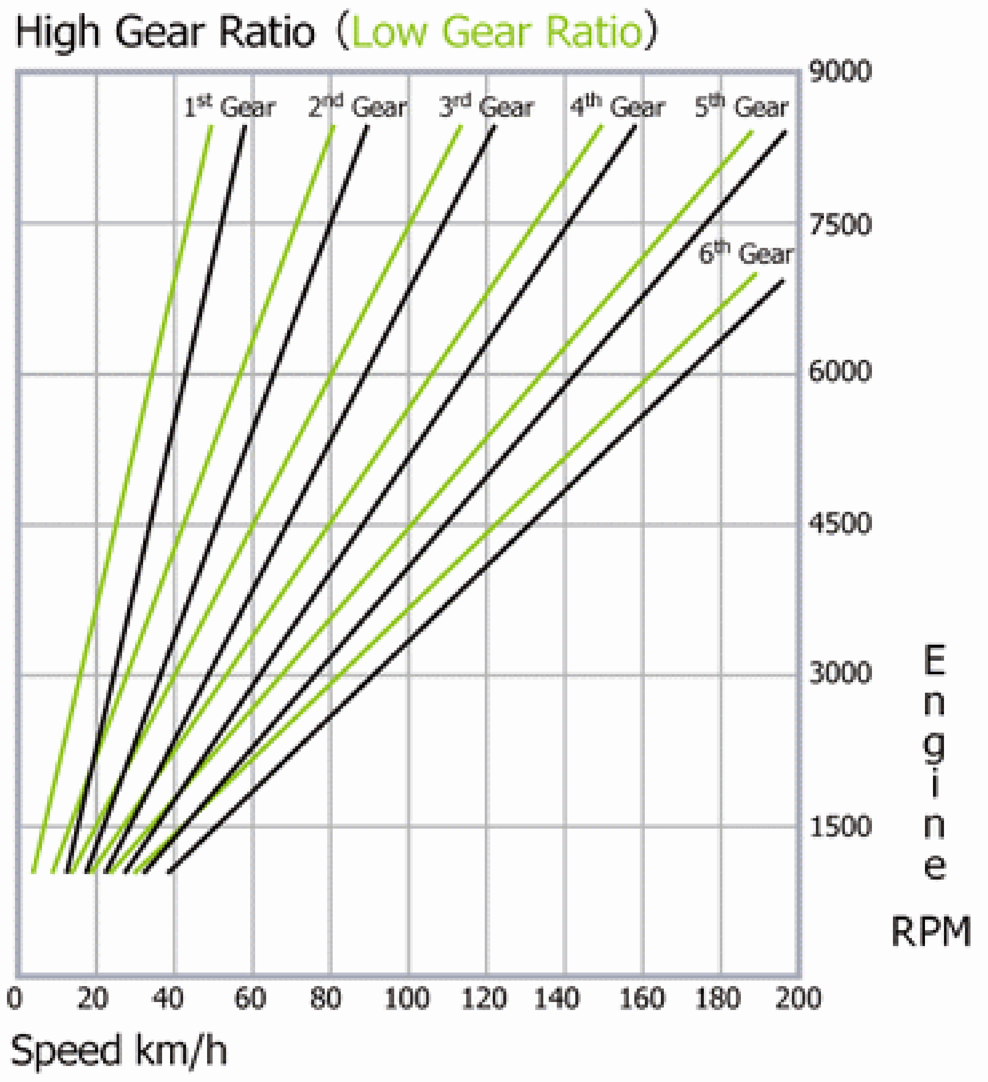
High Gear Ratio

This is a good type of tuning if your aim is to increase the car's top speed, as it increases the speed from low RPMs. It also has significant advantages in terms of fuel consumption. The downside is that it takes longer to get the engine in its effective power/torque band, which makes acceleration sluggish. It can be difficult to achieve the desired power and torque when exiting tight corners, and will be more difficult to gain adequate acceleration.

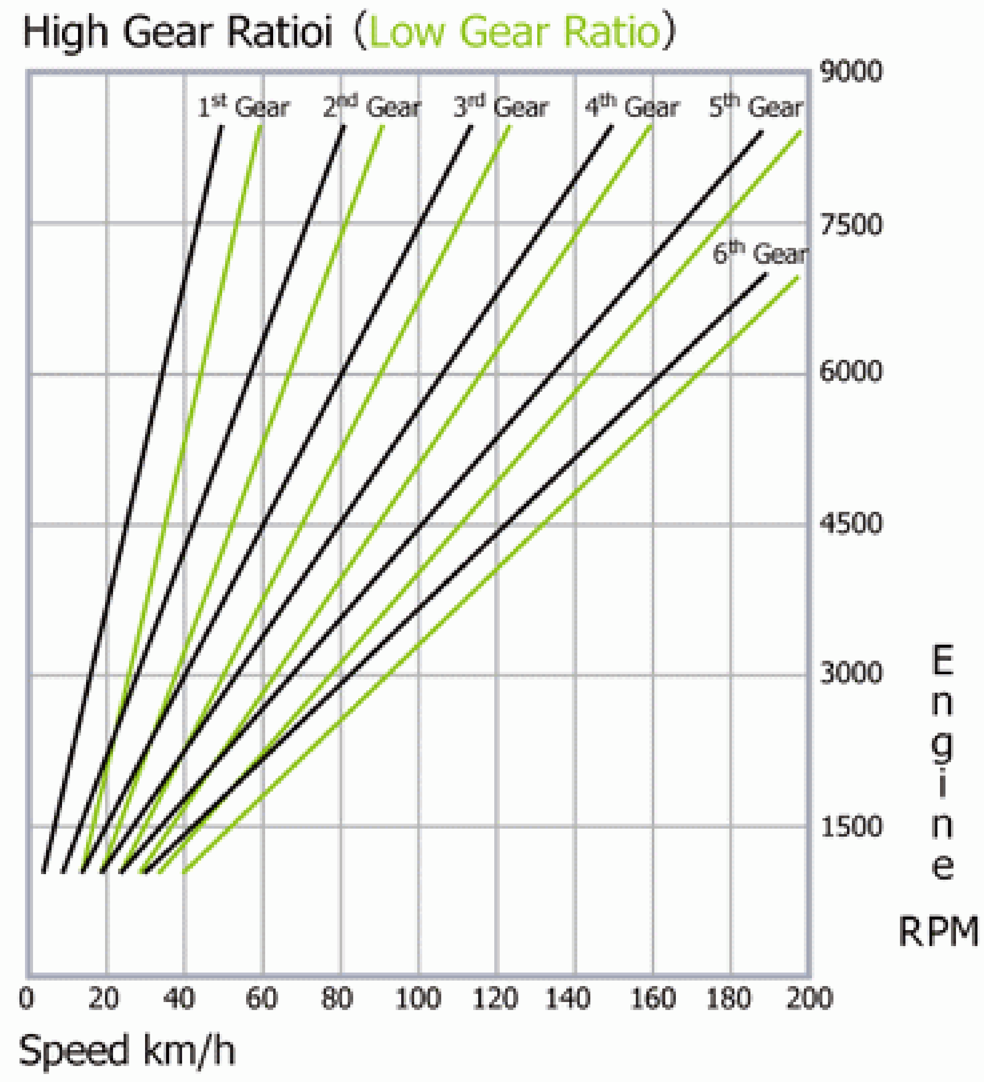
Low Gear Ratio

With a low gear ratio, the engine can sustain high revs even in high gears like third and fourth. While top speed will be sacrificed, this makes it easier to draw out power and torque, and will increase acceleration. You will be able to fully take advantage of the engine's performance when accelerating out of corners, and this makes low gear ratios particularly suited to technical courses with a lot of tight bends. The only downside is the tendency to over-rev due to the sharp increase in accelerator pedal response.

High Gear Ratio (Low Gear Ratio)



High Gear Ratioi (Low Gear Ratio)



Transmission Gear Ratio

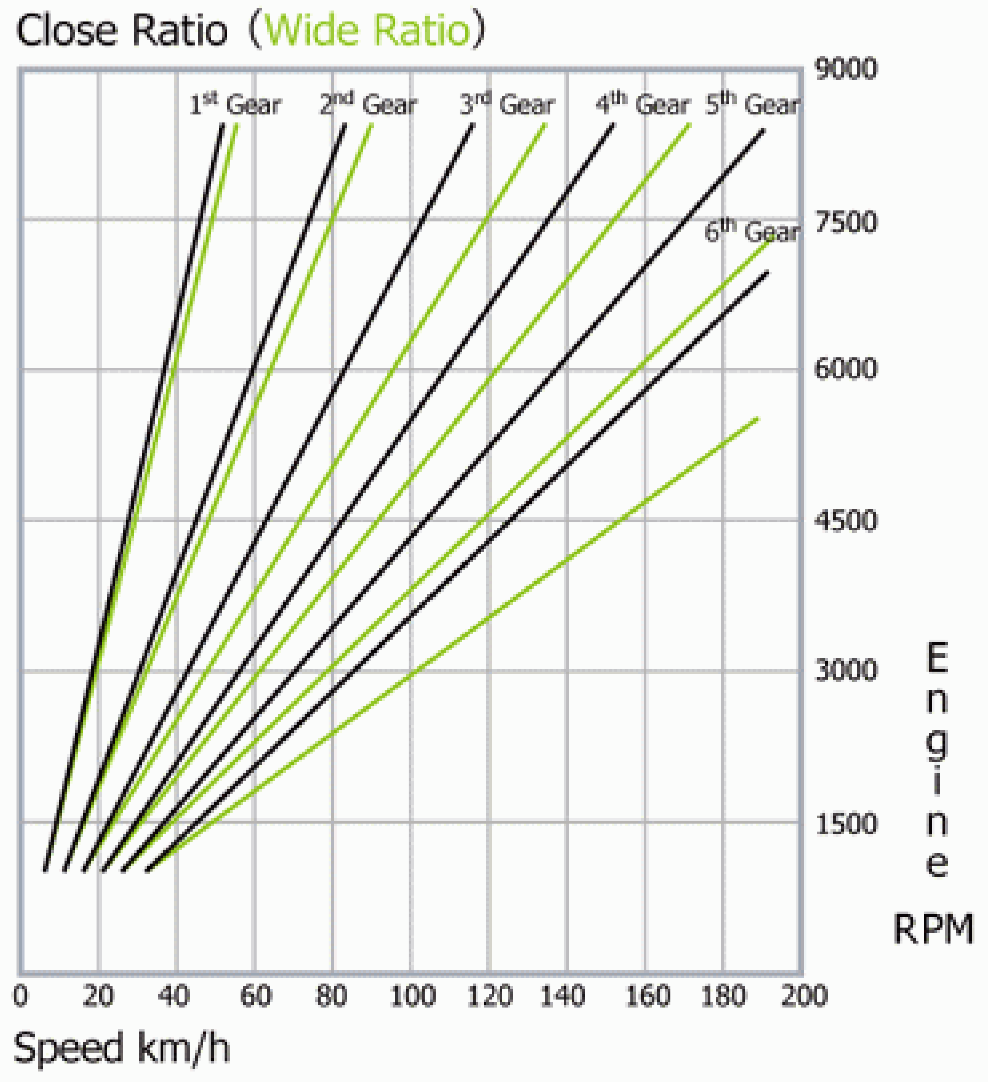
Transmission tuning generally refers to bringing the ratio of the gears of the transmission closer together (i.e., making their size more similar to create a "close ratio"). This makes it easier to stay within the powerband, and also greatly improves acceleration performance. However, depending on the final gear ratio, it can make the car more prone to over revving, and frequent gear changes will become necessary.

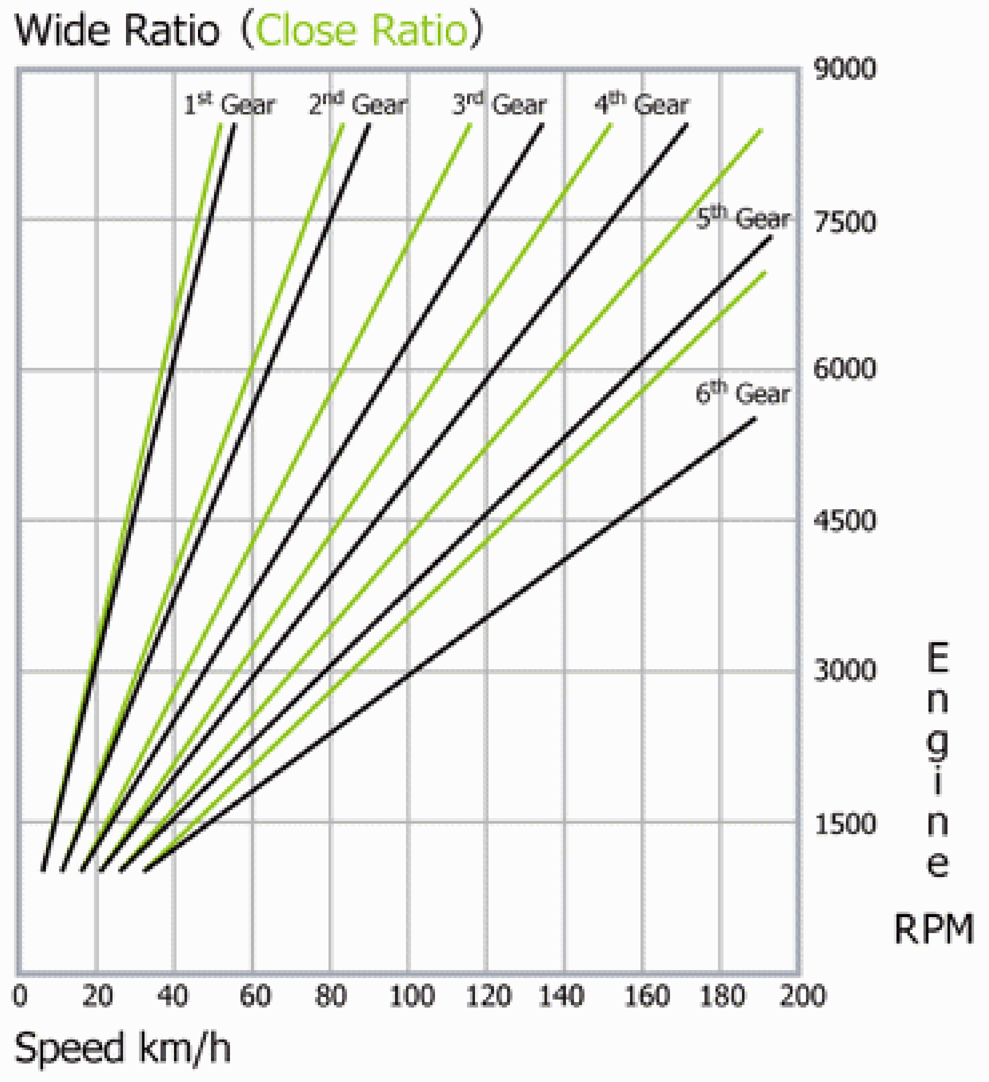
Close Ratio

A manual transmission with a close transmission ratio means that the difference in size between the gears is relatively small. The closer the ratio, the smaller the loss in RPM when shifting up through the gears, and the more efficiently the engine's power can be used. This gearing is particularly suited to naturally aspirated engines whose powerbands have been narrowed by changing to a high-lift cam or other tuning tweaks. This is generally set up according to the course layout, combined with the matching with the final gear ratio.

Wide Ratio

Most production cars are set up with a priority on fuel efficiency, and therefore aim to keep engine RPM low. For this reason, the difference in size between their gears is relatively high. Unfortunately, this means that when you shift up, the engine power transferred to the ground is mild, and acceleration is sacrificed. Normally, an engine will not be set up with a wide ratio between all the gears from 1 to 5 or 6, but will have a mixture of close and wide ratios to make the most of the engine's particular characteristics and deal with the layout of a track. For example, a close ratio may be used for the 1st and 2nd gears, as they are used for standing starts and accelerating, and then a wide ratio may be used for 3rd gear and above,

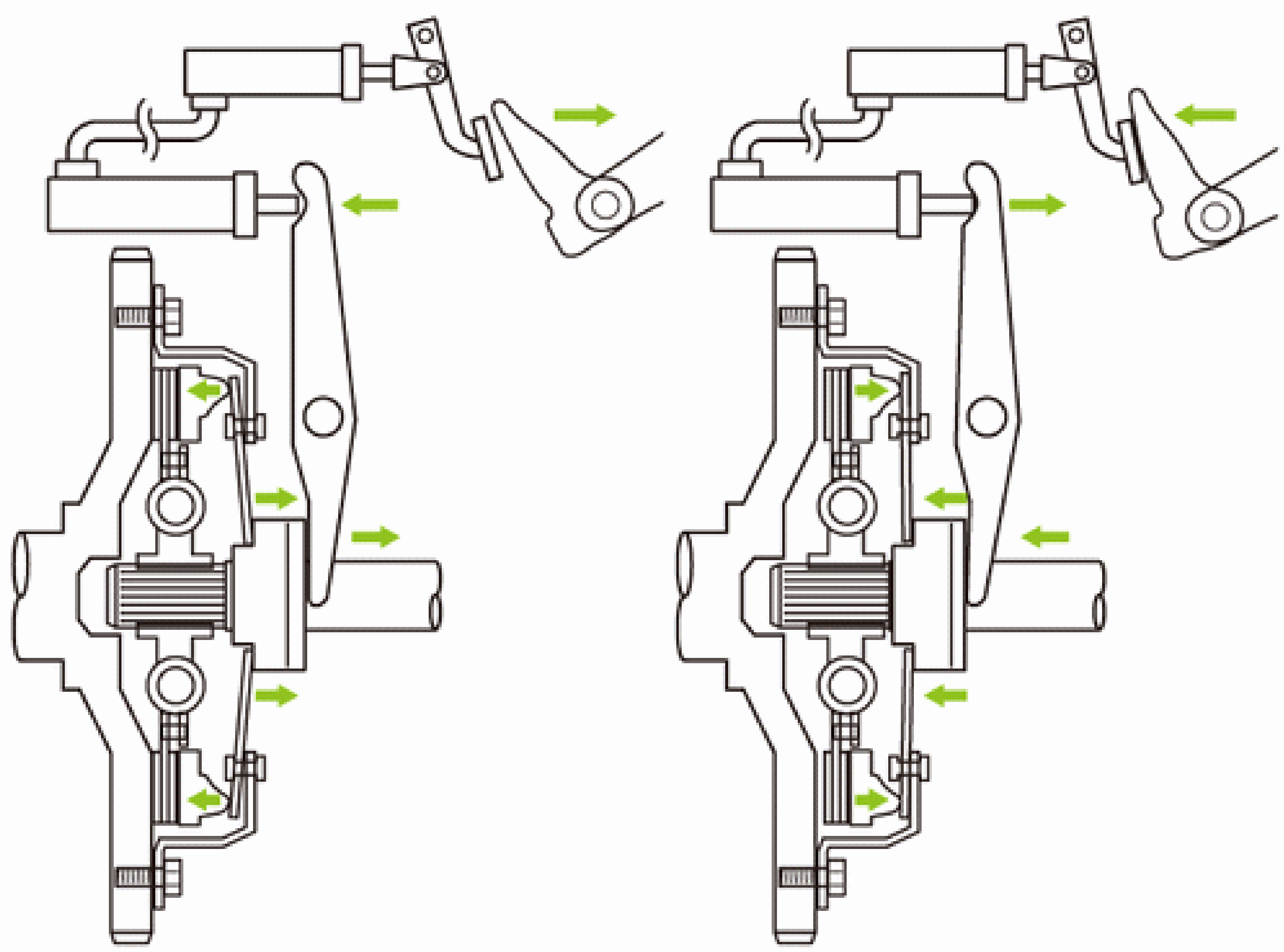




Limiting Power Loss and Increasing Responsiveness

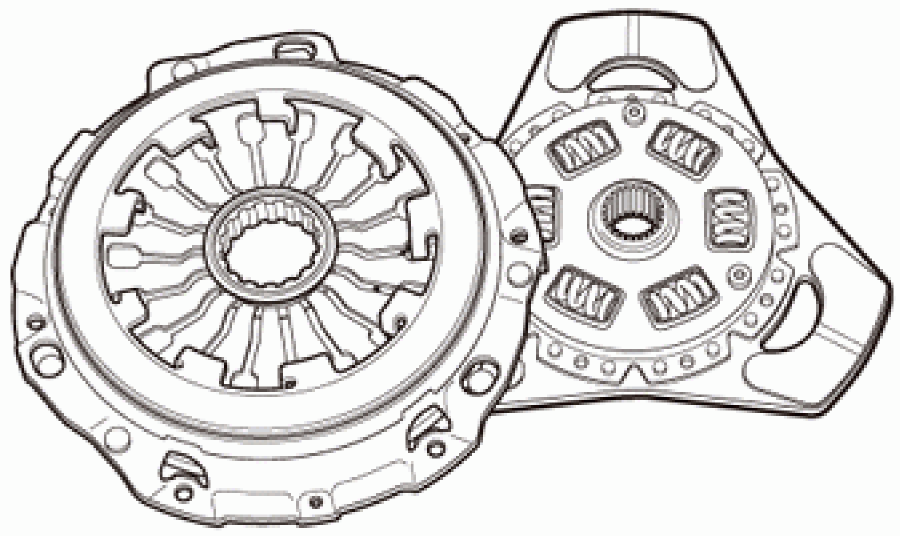
Clutch

Reinforcement of the clutch is essential in a highly tuned vehicle so that the increased engine output can be delivered to the transmission with the minimum power loss, and to shift gears effectively. Even the slightest amount of slippage will detract from acceleration performance. The idea is to increase the clutch disk's friction level and the clutch cover pressure in proportion with the increase in engine output and torque.



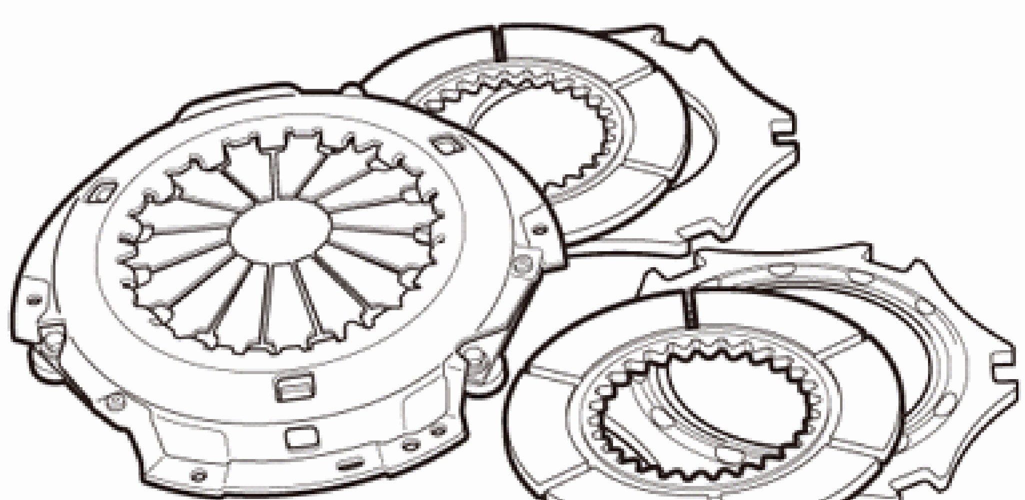
Disk & Cover

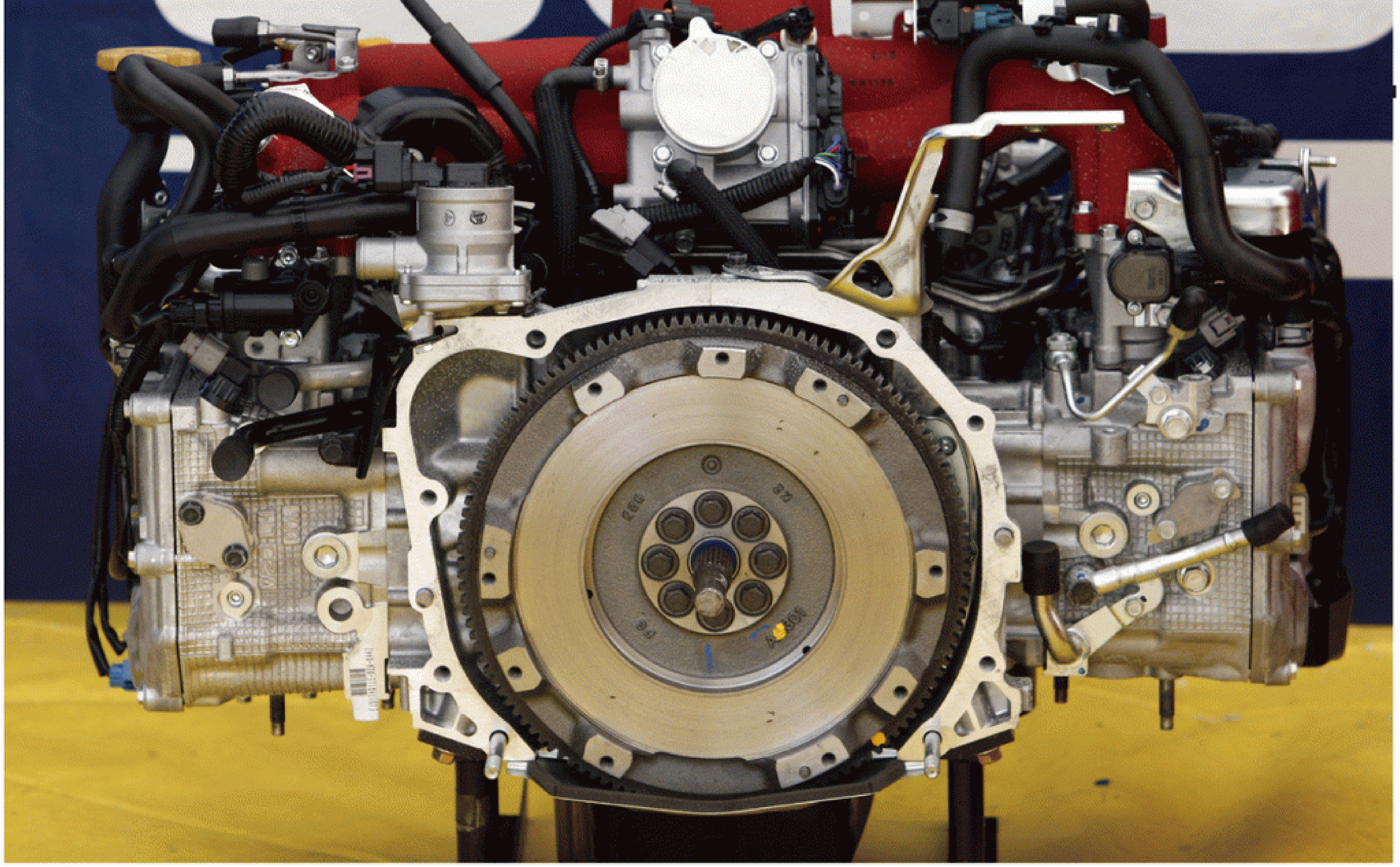
The most conventional method of reinforcing the clutch is to replace the existing clutch disk and cover with stronger parts. By increasing the friction of the clutch disk and the clutch cover pressure, the engine's power can be more reliably delivered to the transmission. These are vital components when enhancing engine power, and their advantage is that there is no delay in response even when they are aggressively used in sports driving. Metal clutch disks are now generally used because of their superior friction and resistance to wear.



Multi-Plate Clutches

Regular clutches only use a single clutch disk (also known as a "clutch plate"), but using a clutch with multiple plate's serves to increase the area causing friction. Reinforced clutches like this with a stronger clutch cover pressure and enhanced ability to transmit engine power use between two and four plates. Friction increases in proportion to the number of clutch plates used, so the most suitable number of plates can be selected depending on the amount by which engine output has increased. While responsiveness and durability are increased, the downside of using multi-plate clutches is in their operation. They require more force to disengage, making the clutch pedal very heavy, while requiring more precision when engaging.



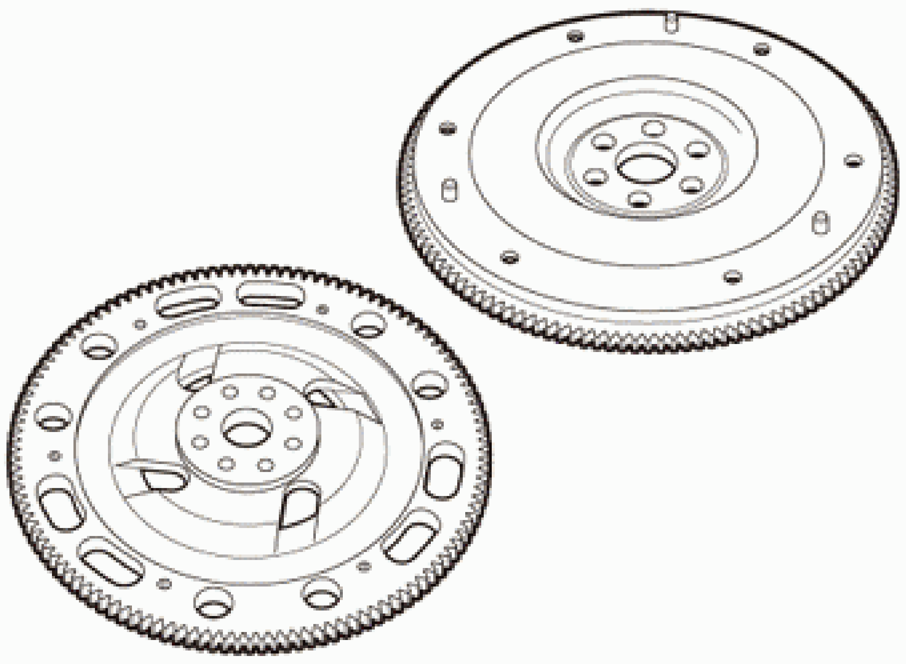


Flywheels & Propeller Shafts

Making the drivetrain more lightweight can be a highly effective way of improving acceleration response and acceleration. However, an extremely lightweight flywheel can make it difficult for the car to gain sufficient levels of torque when driving uphill, and additional tuning is required to compensate for this.

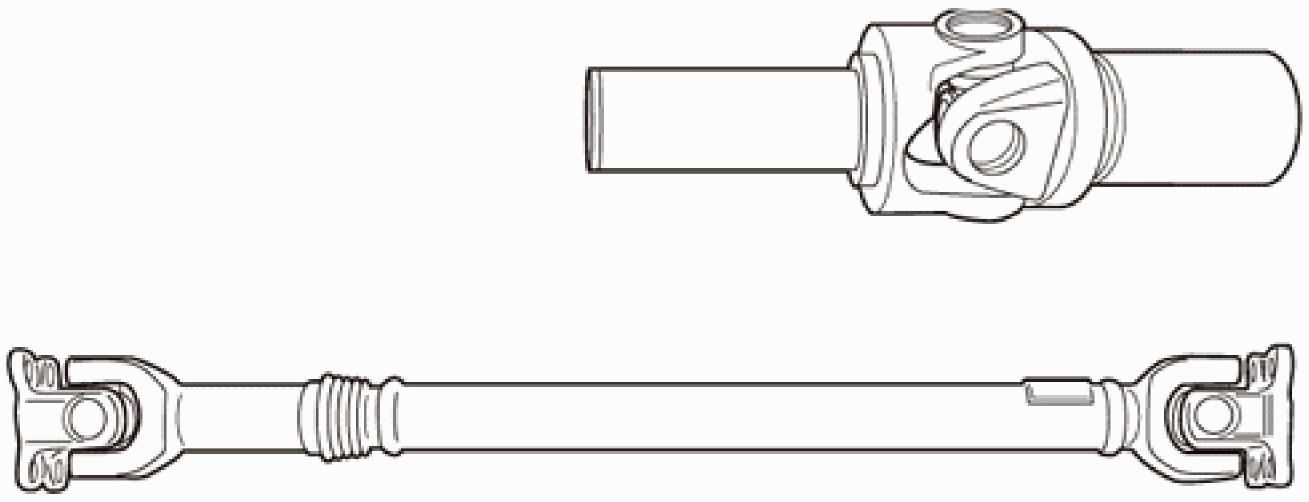
Lightweight Flywheels

The flywheel is attached to the aft end of the crankshaft just before the clutch, and its main role is to prevent irregularity in the engine's rotation. The heavier the flywheel, the more smoothly the engine will turn. However, a heavy flywheel can be detrimental when speed is your objective, and it is preferable to replace the existing flywheel with a more lightweight one. Although this can make the engine rev less smoothly and reduces torque, it gives the advantages of improved response in acceleration.

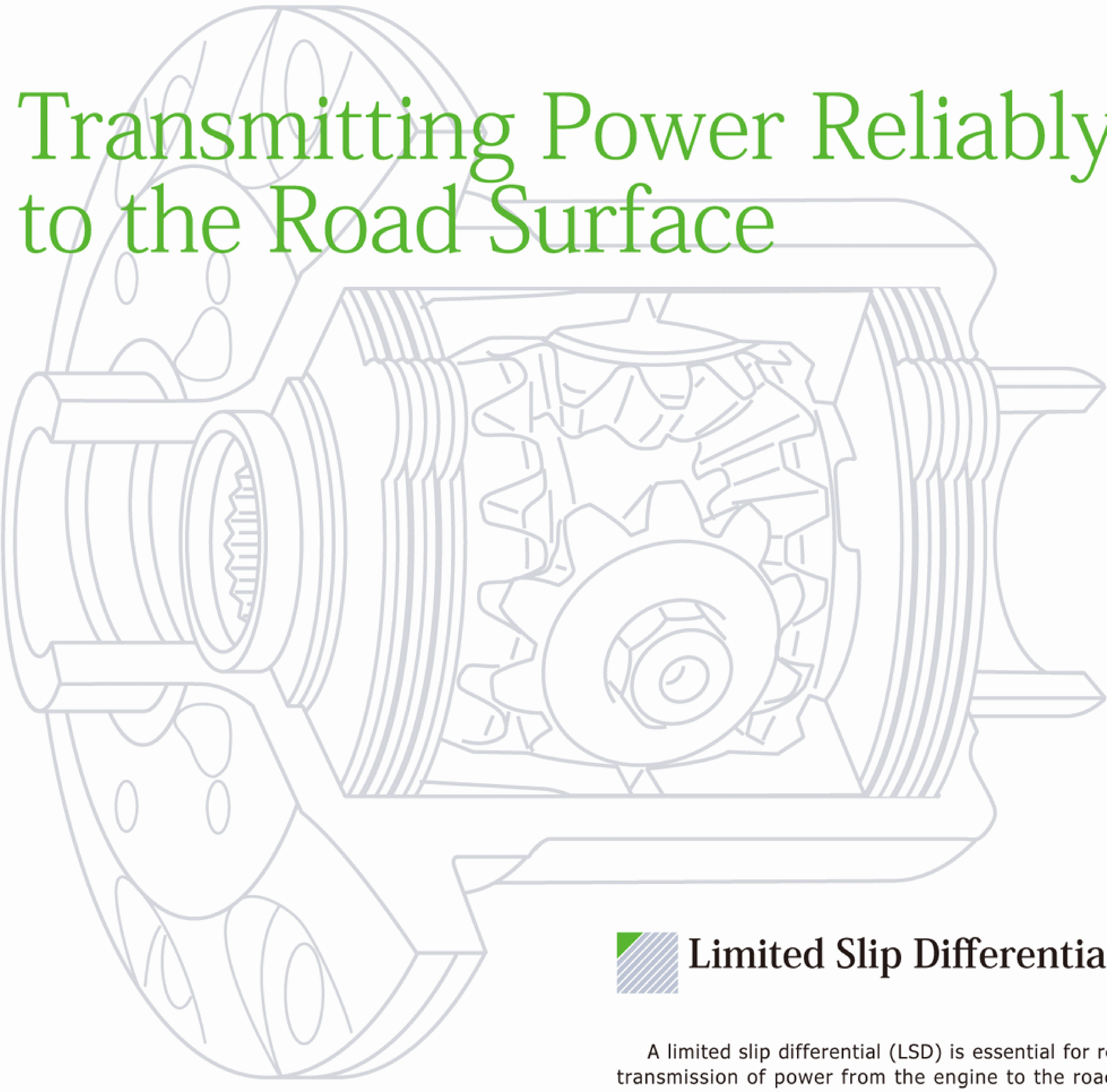


Lightweight Propeller Shafts

A propeller shaft (also known as a drive shaft) transmits engine power from the gearbox to the differential. Replacing the regular propeller shaft with a more lightweight model can improve engine response and acceleration. Lightweight propeller shafts are generally made from carbon or fiberglass (FRP), and can be about half the weight of standard shafts. Reduced weight is of course the main benefit, but smoother rotation is another bonus of a lightweight shaft.



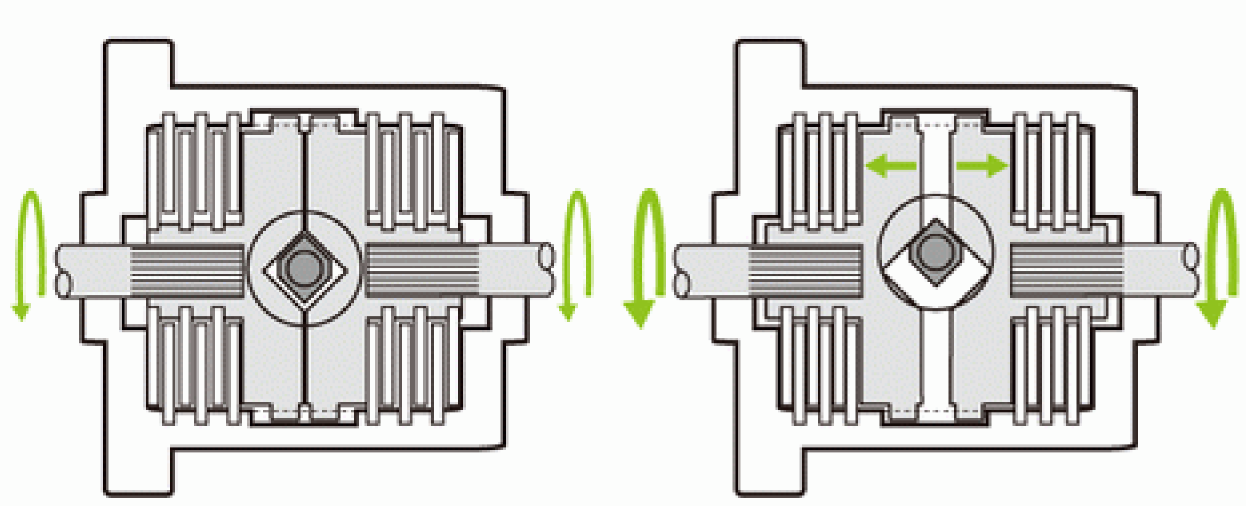
Transmitting Power Reliably to the Road Surface



Limited Slip Differential

A limited slip differential (LSD) is essential for reliable transmission of power from the engine to the road, and enabling of high-speed cornering. Of the several types of LSD available, the most effective at limiting the rotational difference in drive wheels can be achieved with the mechanical type that makes use of a multi-plate clutch. This is because it allows the most freedom in setting the limit of rotational difference, and can therefore be adjusted to give the best traction based on drivetrain layout, the peculiarities of a particular car or driving style, course layout, and a whole host of other factors. The downside to this freedom of choice is that the high load on the parts means that this type of LSD needs constant oil changes and periodic maintenance.

Mechanical LSDs allow the greatest freedom in setting the limit of rotational difference between wheels, but are specialized motorsports components, and as such, do not generally come fitted as standard.



Locking Factor

The locking factor describes the point at which a limited slip differential will limit the rotational difference between two wheels. In a normal (open) differential, the locking factor is 0% (i.e., the wheels can rotate entirely independently of one another), whereas 100% represents total lock (i.e., the wheels are forced to always rotate at the same speed). The higher the locking factor, the greater the limit placed on the amount of rotational difference allowed. A higher locking factor is not necessarily better. Rather, the locking factor needs to be carefully calibrated based on factors such as drivetrain layout, vehicle height and track width, and will change depending on the driving characteristics required. If the locking factor is set too high, understeer will be increased, leading to a loss of cornering ability. Generally speaking, a locking factor of around 50% gives the easiest control while still allowing the LSD to have an effect, but trial and error is the only way to find the perfect setting for a given situation.

Initial Torque

Initial torque refers to the amount of pressure acting on the disks inside the differential gear housing. Increasing or decreasing the initial torque will affect the amount of time it takes for the LSD to lock. The higher it is, the better acceleration response will be, as the LSD will lock almost instantly. The lower it is, the more gently the LSD will lock, and the easier it will be to drive. Usually, tuning an LSD will involve increasing the initial torque, but this can impair cornering ability, and in FF vehicles can worsen so-called “torque steering," so this is not always the case. Recently, LSDs with low initial torque settings and high locking factors have become more common.

Types of Mechanical LSD

1WAY

This type of LSD only works when the car is accelerating. As it doesn’t function without accelerator input, it allows the inside wheel to turn freely on the approach to a corner, just as an open differential would, which makes for smoother cornering. This type of LSD is particularly well suited to FF cars, as they are prone to understeer, but produces a marked difference in handling depending on whether the accelerator is applied or not.

2WAY

This type of LSD functions whether the accelerator is pressed down or not. This produces fairly strong initial understeer, but allows the car to maintain stability when decelerating, making more extreme corner approaches possible. It also boasts excellent responsiveness, and allows the driver to aggressively turn the heading of the car using the accelerator.

1.5WAY

This type of LSD combines the characteristics of both 1-way and 2-way systems. The LSD works as normal when accelerating, but its effect is reduced during deceleration in order to enable easier turning during the approach to a corner. It is an all-round solution without the quirks that affect the other types of LSD.

Shaping Up the Body

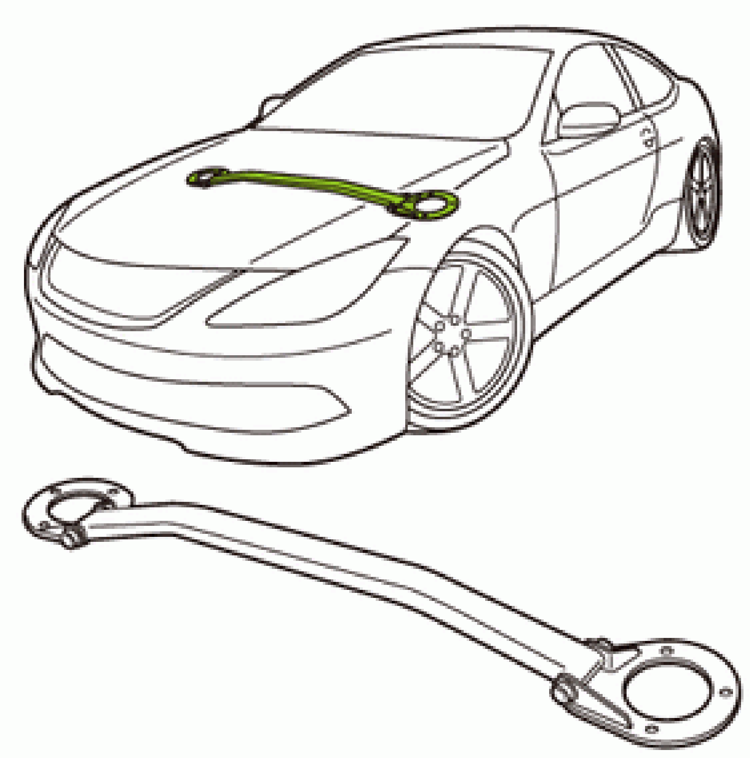
Having a light, rigid body for acceleration and controllability is essential for motor racing. No matter how much you power up your engine, if your car's body is too heavy and flexible, it's unlikely that the increased output will translate into real speed.

Weight Reduction & Rigidity

When aiming to increase your car's speed and agility, the reduction of weight and the reinforcement of the body are absolutely crucial. Reducing weight serves not only to increase acceleration, but also yields significant benefits when braking and cornering. Increasing rigidity is also essential for the suspension to move correctly even when a large load stress is applied to the car, and to maintain firm contact of the tires with the road. And in order for a driver to understand the movements of a car in extreme driving conditions and to control the car precisely, a rigid body that will not deform is essential. On tracks such as the Nürburgring where the traction coefficient (μ) is low and strong G-forces are acting both laterally and vertically, it is impossible to achieve a single satisfactory lap in a car lacking sufficient body rigidity.

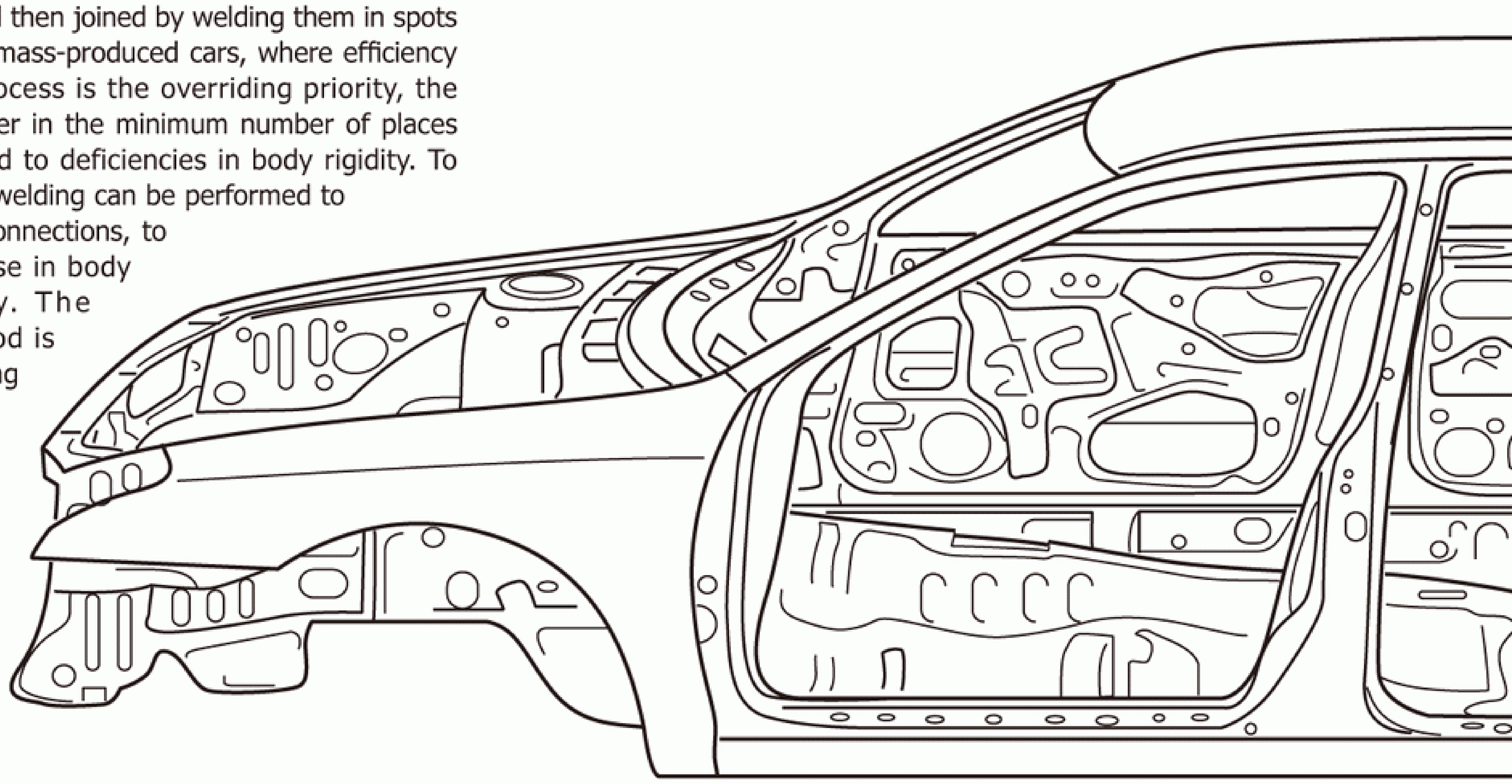
Strut Bar

This is a bar fitted to connect the attachment points of the suspension (above the wheel housing) on the left and right sides of the body. It serves to enhance the rigidity of the front part of the body and ensures precise movement of the suspension, while also sharpening steering response. In general, a strut bar should be fitted in conjunction with upgrades to the springs, shock absorbers and bushings. It's common for strut bars to only be fitted at the front of the vehicle, but it's best to fit on in the rear as well for balanced rigidity.



Spot-Welding

A car's body is constructed from metal panels that have been pressed together and then joined by welding them in spots at regular intervals. With mass-produced cars, where efficiency in the manufacturing process is the overriding priority, the panels are welded together in the minimum number of places necessary, which can lead to deficiencies in body rigidity. To overcome this, additional welding can be performed to increase the number of connections, to give a significant increase in body strength and rigidity. The advantage of this method is that it doesn't entail adding new components, so you don't have to be concerned about adding to the car's weight.



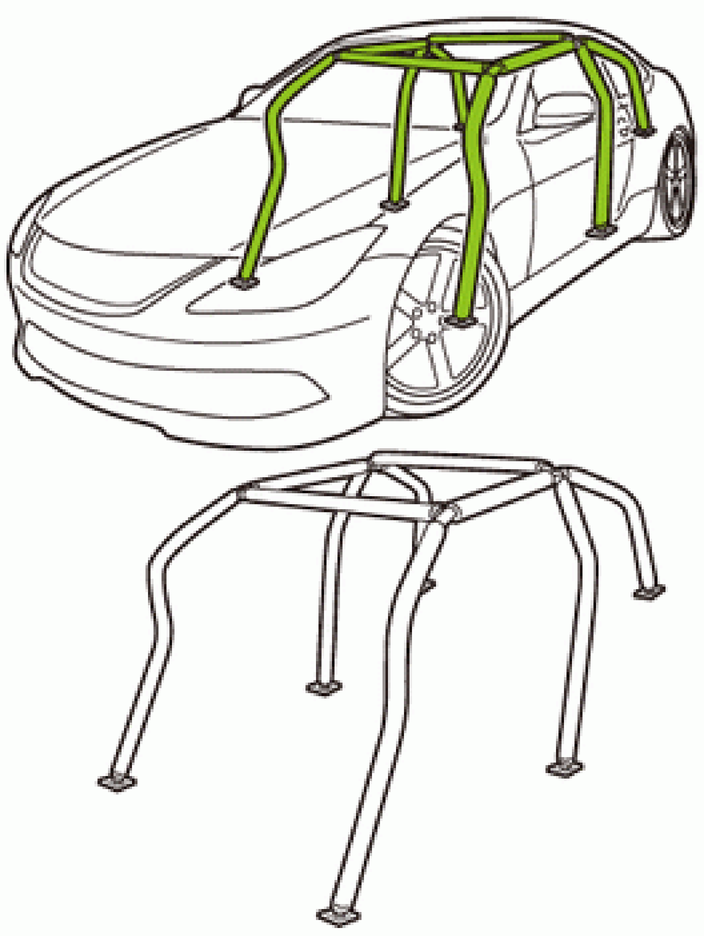
For Precise Handling

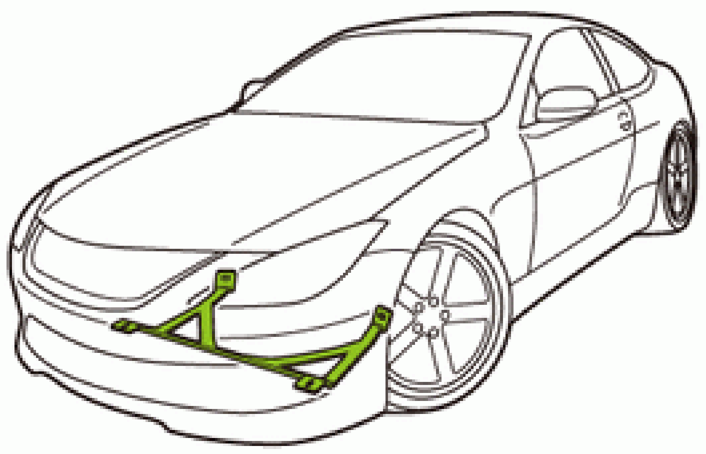
Roll Cage

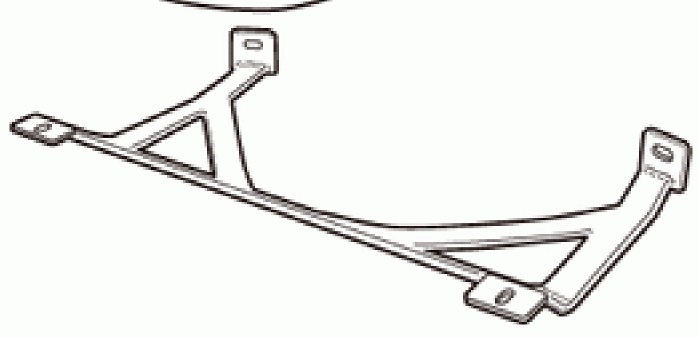
Roll cages are designed to protect passengers during a crash, but they are also effective in increasing body rigidity. But in order to achieve this, the roll cage must not have any space between it and the roof and pillar sections, and must be firmly welded, rather than simply bolted on. The roll cage must also have plenty of struts and support points in order to actually provide a significant increase in rigidity.

Member Brace

A member brace is a metal bar that is highly resistant to bending and twisting. It enhances the rigidity of the floor of the vehicle, while at the same time serving to connect the suspension to the underbody, limiting any unwanted movement, to maximize suspension performance. So, just as a strut bar supports the suspension and body inside the bonnet, a member brace supports the car from underneath the body. When used in conjunction with a strut bar the stability of the car's behavior will improve even further.

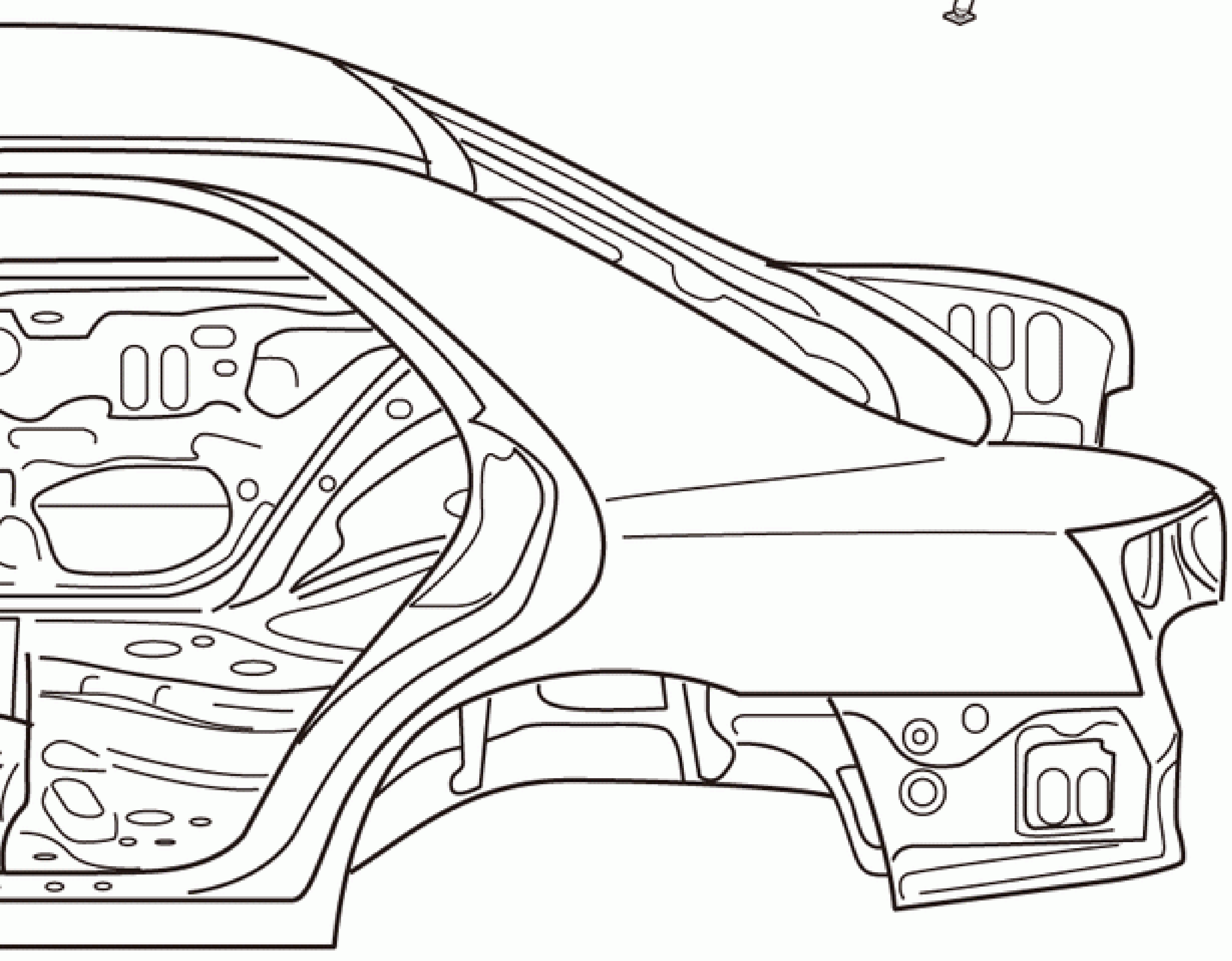






Reducing Weight

The most effective way to improve a car's acceleration, braking and turning is to make the body more lightweight. Modifications can range from basic means such as removing the air-conditioning system and any sound-insulating materials, to replacing body panels with those made from lightweight materials such as aluminum or carbon fiber. Taken to the extreme, it can entail replacing the whole body shell with carbon fiber, and the chassis with aluminum. However, always bear in mind that in order to maintain balance in the car's controls and handling, its rigidity needs to be increased as well. In order to keep a low center of gravity, it is more efficient and effective to start by focusing on reducing the weight from the upper parts of the car first.



BRAKE

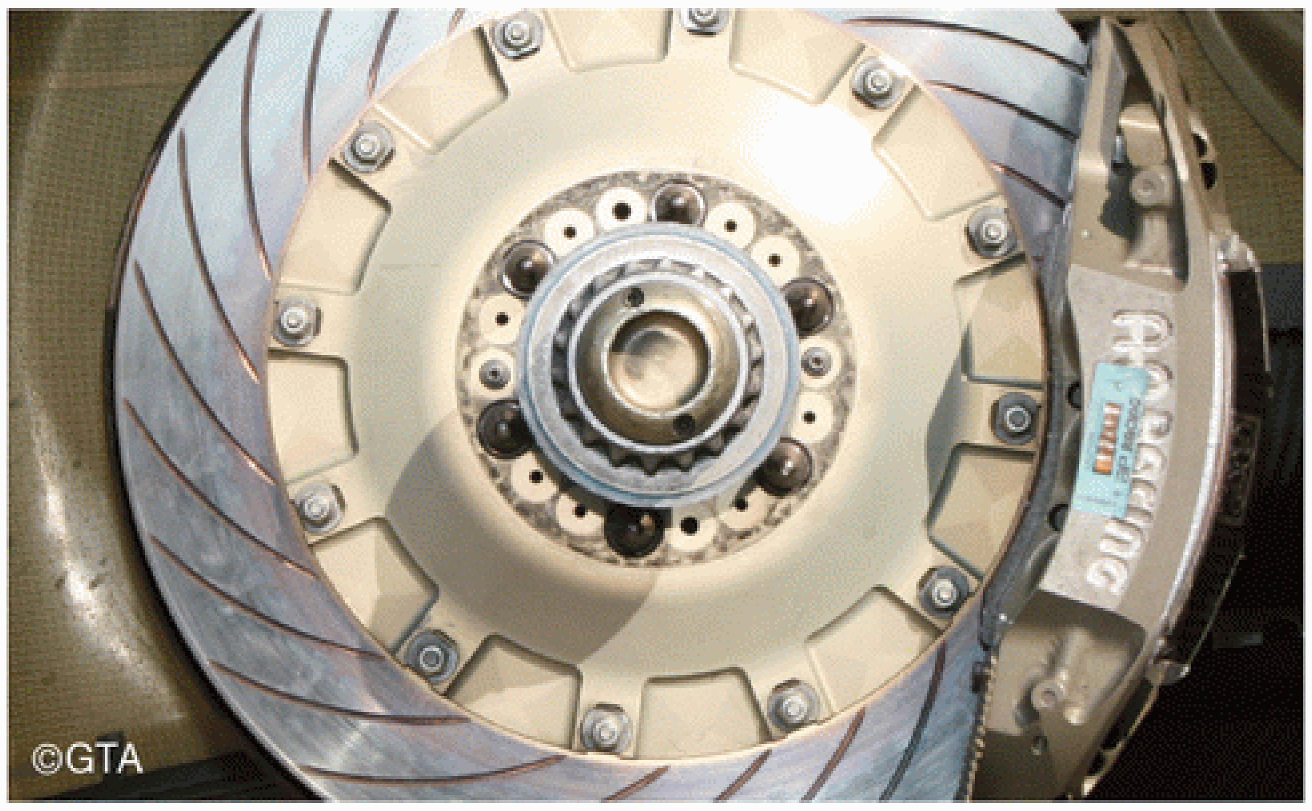
CHAPTER 03 Tuning & Settings

Improving Stopping Power

Improvements in engine output need to be coupled with an increase in braking power. The confidence to really put your foot down can only come from knowing that you are able to stop effectively. However, stronger brakes mean that more effective ways of dealing with excess heat also need to be employed.

Boosting Brake Power and Avoiding Brake Fade

A tuned engine with a higher top speed requires a more powerful braking system that works stronger and is more resistant against brake fade. At the most basic level, brakes can be improved by replacing the brake pads, and at the most extreme level, improvements can entail replacing the entire braking system with a high end system designed for motor racing. Just be sure to remember that the braking systems in racing cars are not necessarily ideally suited for all applications, making it important to select parts that are tailored to your specific needs. Also, bear in mind that larger brake pads or brake calipers will increase the unsprung weight of your car, which can have a negative effect on maneuverability. The golden rule is that brake power should always exceed engine power, but installing too effective a braking system in a lightweight car can cause an unbalance in its driving performance.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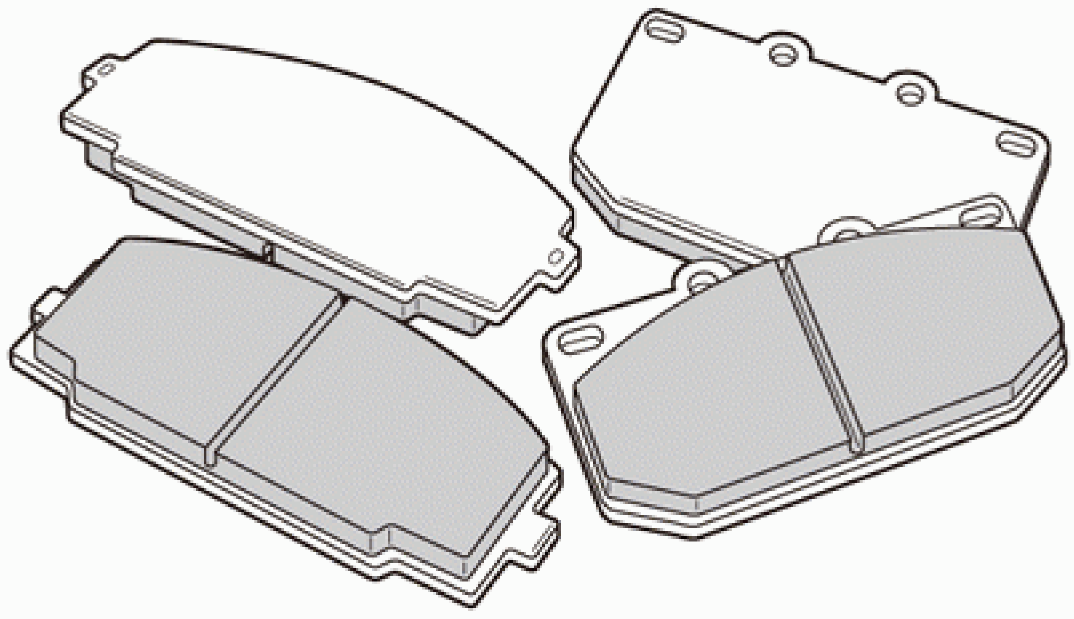
Brake Pads

The most basic components when tuning the brakes are the brake pads, which govern braking power and resistance to brake fade. The range of brake pads on offer is huge, from pads designed for the street to top-end motorsports pads. Each of these has a different optimum temperature at which braking power is greatest, and a different level of heat resistance. Choosing the wrong brake pads for your needs may not give the results you hoped for, and could even have a detrimental effect on how your car drives. Higher-end pads also wear quickly, and increase wear on brake discs due to the increased friction. When changing brake pads, as a rule they should all be changed at the same time to ensure even braking.



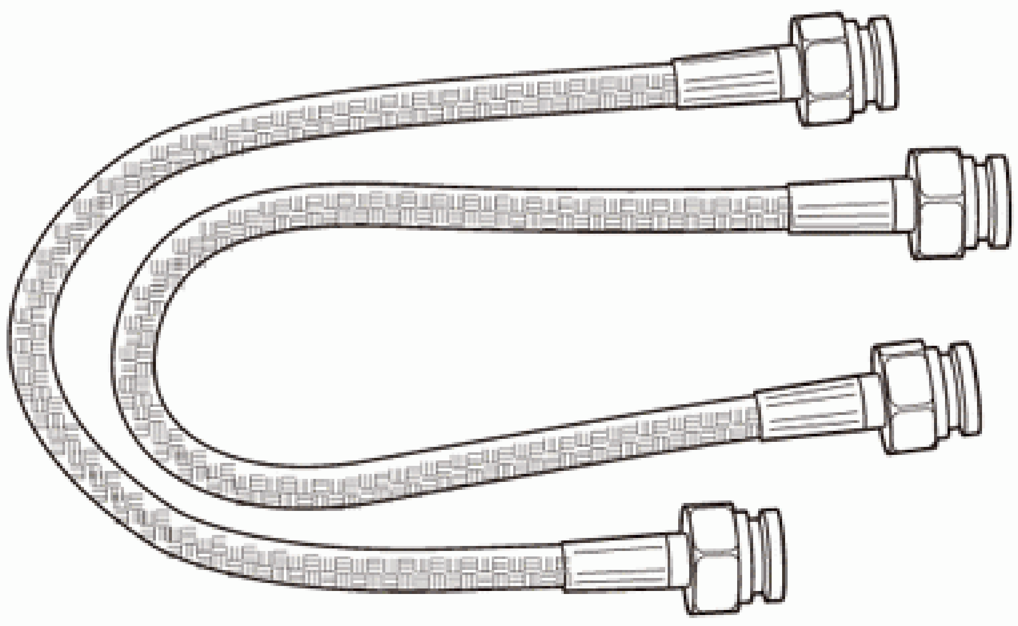
Brake Fluid

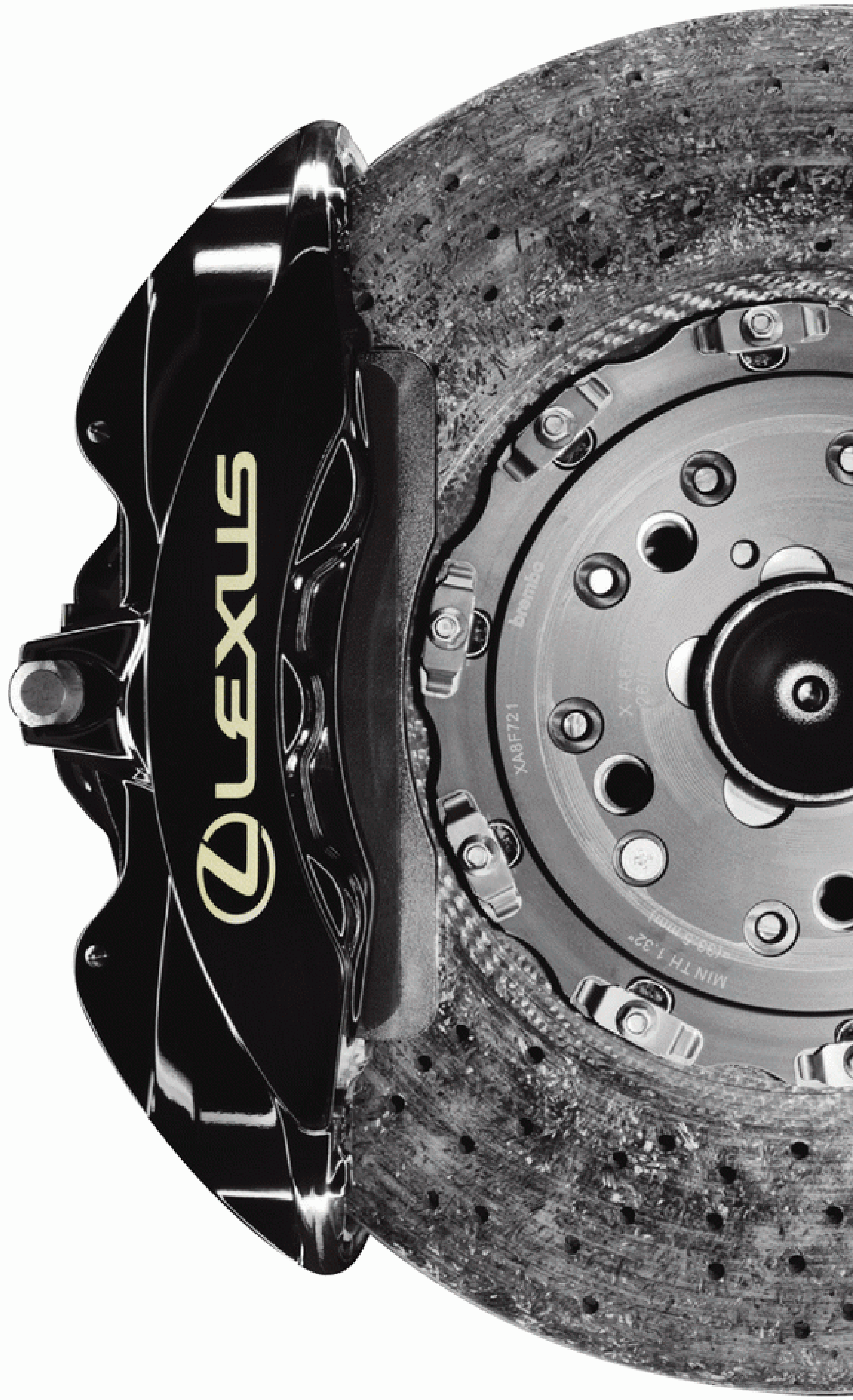
This is the operating fluid used in hydraulic brake systems. It has a boiling point in excess of 200℃ in order to prevent vapor lock, but it also has extremely high moisture absorbency, meaning that it can deteriorate very easily. Brake fluids are graded by DOT grade. The boiling point increases the higher the DOT grade is, but so does the tendency to absorb moisture, meaning that the fluid will degrade more easily (which lowers the boiling point). For this reason, the DOT 5 brake fluid used in racing cars needs to be replaced often. Be aware that braking power does not increase with the DOT grade.

Upgrading Your Brakes

Brake Hoses

Brake hoses are the pipes through which brake fluid travels. Normally, they are made from rubber, but hard braking can cause them to swell, reducing responsiveness. This can be avoided by using stainless steel meshed brake hoses. These are Teflon hoses covered with a stainless mesh sheath that combine the flexibility of rubber with an increased resistance to swelling. They are fitted as standard in racing vehicles to ensure that the brakes are always responsive to driver input.



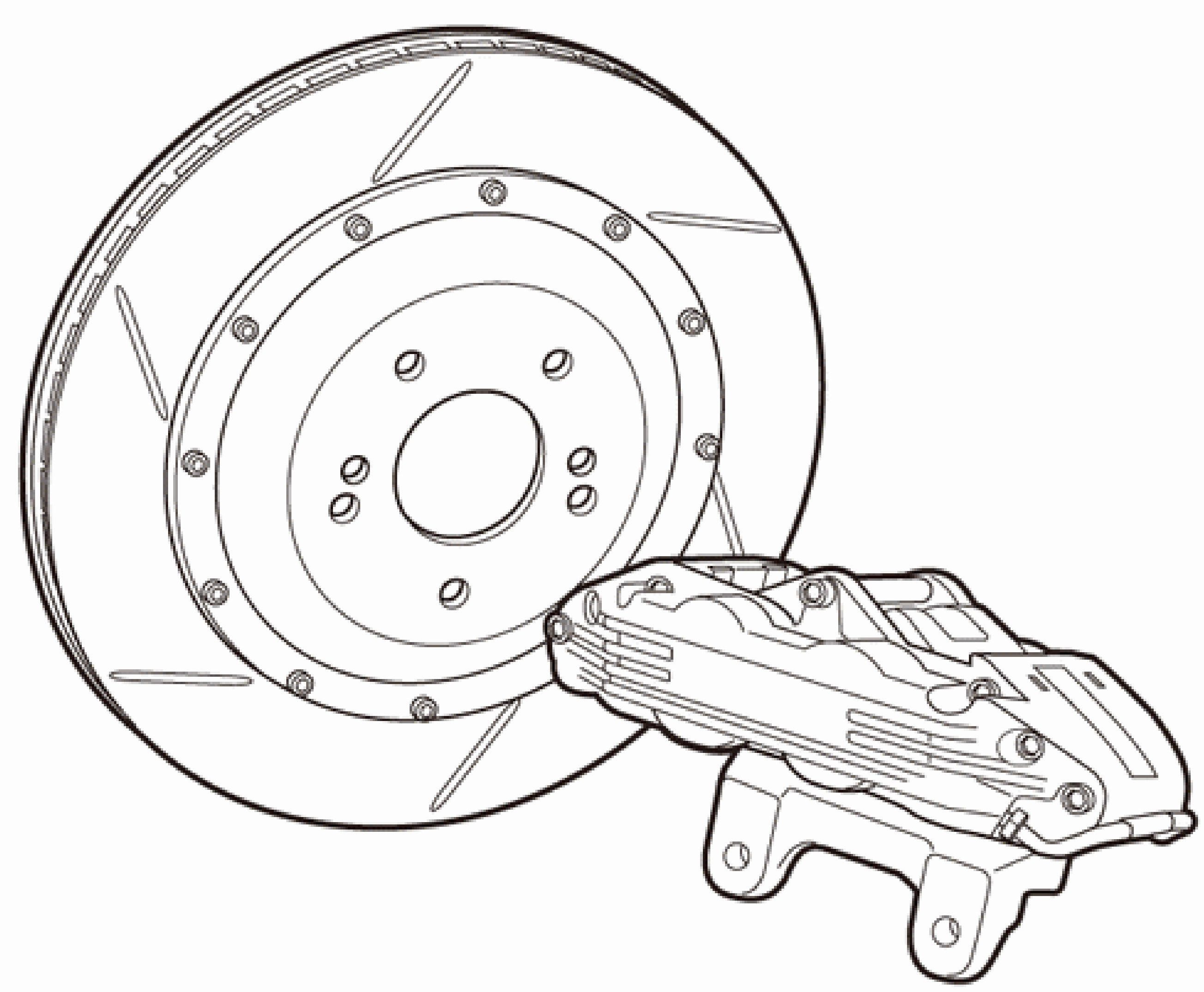


Brake Disks

The most effective way to increase braking power is to increase braking capacity. This involves using larger diameter disks to create more friction. However, large cast-iron brake disks will increase unsprung weight, which can negatively affect how your car drives. To prevent this, lightweight ceramic and carbon fiber disks are starting to become commonly available. Because brake disks become worn through use, they must be regularly replaced or resurfaced to retain their braking power.

Calipers

Upgrading brake calipers often involves replacing the entire braking system. Normal calipers press the brake pads against the brake disk from one side, and one way to upgrade them is to replace them with opposed-piston calipers, which presses from both sides. Some production cars now come fitted with brakes that have six pistons, as the larger number of pistons exerts more uniform pressure on the brake pad, increasing braking power. Opposed-piston calipers are made with a mono - block construction, and the high rigidity of the caliper itself provides stable braking even under harsh operating conditions.



Improving Suspension

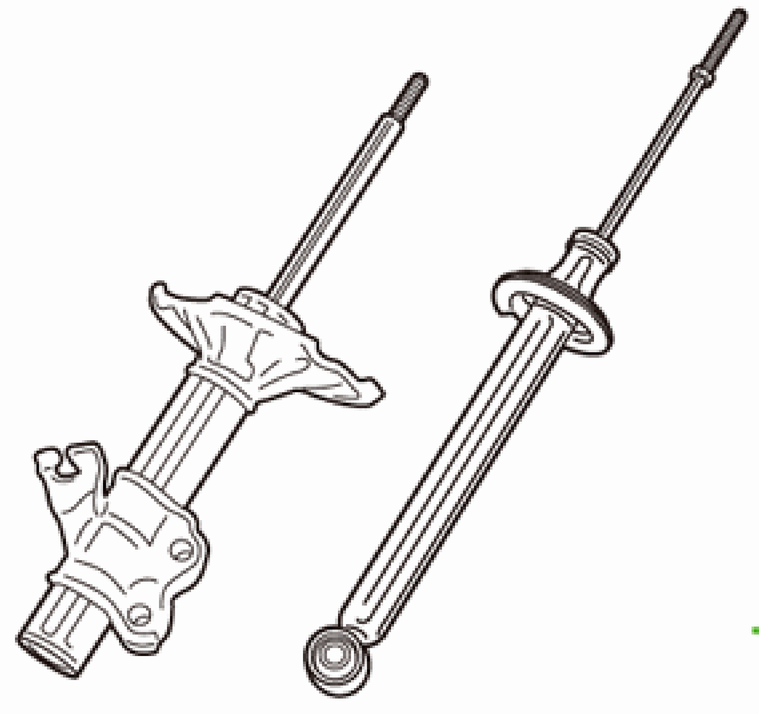
In demanding driving conditions, it's vital to be supported by well-tuned suspension to maintain stability and improve maneuverability. Tuning the suspension can totally transform the character of your car.

Adjusting Handling Characteristics

Tuning your suspension for sports driving means sacrificing some of the comfort for speed. As long as the car is on a flat surface like that of a racing circuit, the lower the body is to the ground, the lower the center of gravity will be, and the more stable its behavior. Harder suspension makes for less wasted movement during acceleration, deceleration and turning, which keeps the handling sharp. However, if the suspension doesn't move at all, the car will not be able to deal effectively with load transfer, and drivability will be extremely poor. The best solution is to make the suspension harder while also bearing in mind the degree to which weight will need to shift in all four directions. Depending on your vehicle and the surface you are driving on, you may sometimes need to make the suspension softer in order to improve grip.

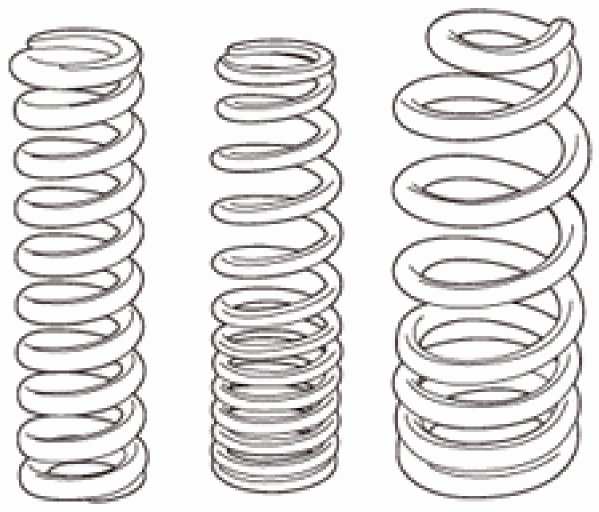
Shock-Absorbers

The objective of upgrading shock absorbers is to provide a higher damping force than the standard absorber which focuses on ride comfort. By doing so they can maintain stability of the car's behavior even at high speeds when they are under large loads, and its controllability will be improved. Replacement and tuning of shock absorbers should normally be performed at the same time as the springs.



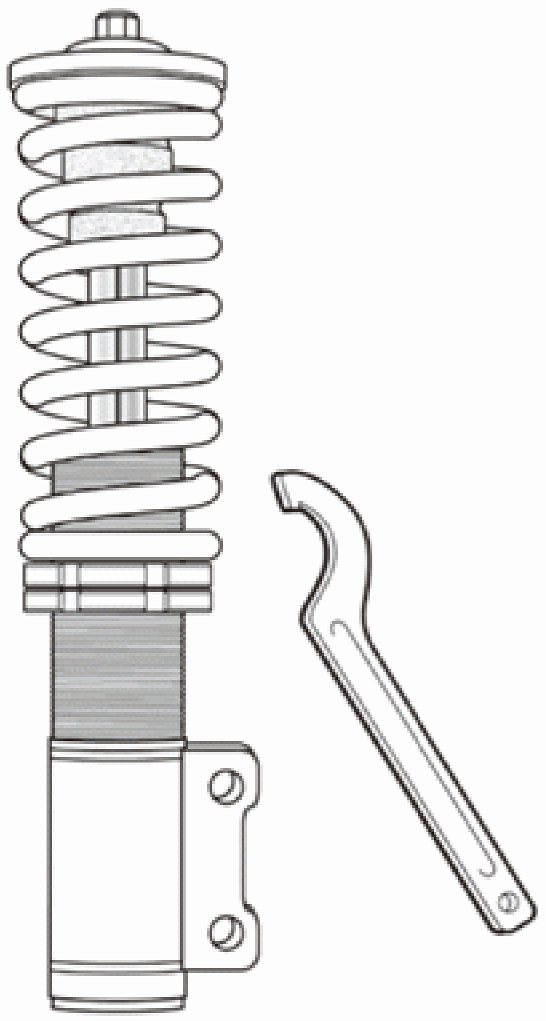
Springs

The springs improve handling by helping achieve a low center of gravity, and are also essential in maintaining stability by counteracting roll when cornering, nose dive when braking, and squatting when taking off from a standstill and accelerating.



Height-Adjustable Suspension

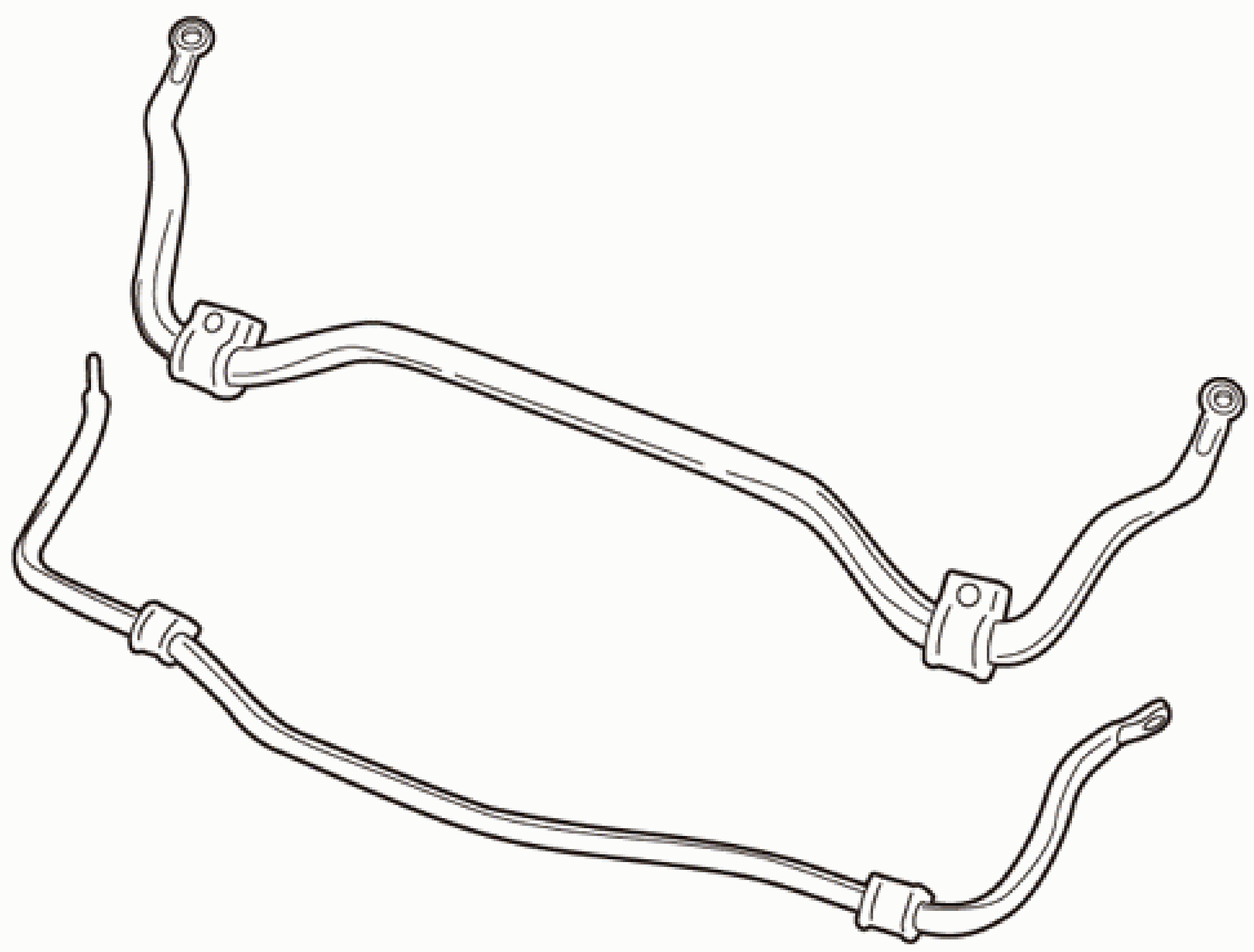
The main type of height-adjustable suspension allows ride height to be adjusted by using shock absorbers that can increase or decrease spring length, as well as allowing the damping force to be adjusted. This allows it to be adjusted precisely to suit any situation. There are several different methods for adjusting ride height, including adjustable screws, C-rings and the use of brackets.



Obtaining the Desired Level of Handling

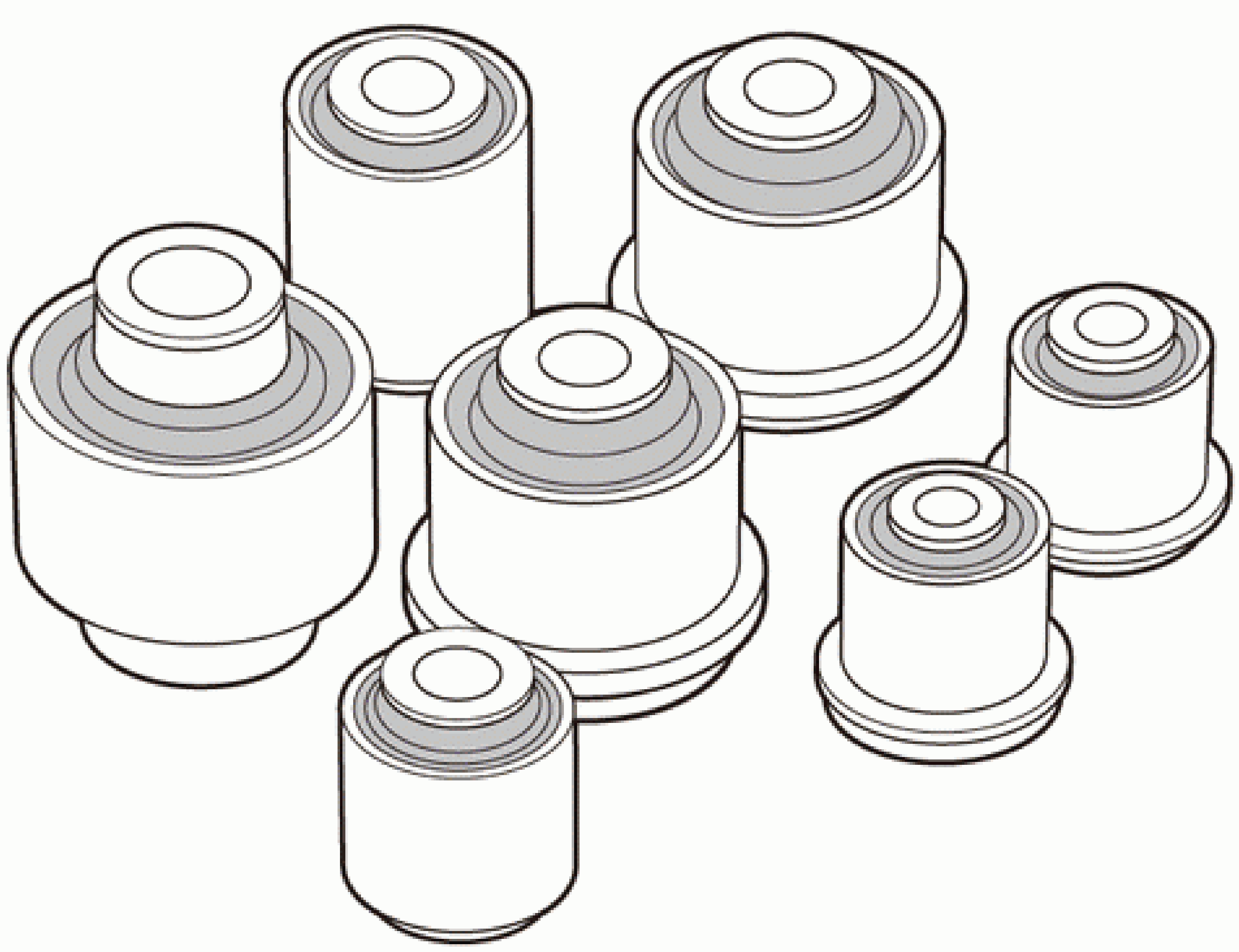
Anti-sway bars

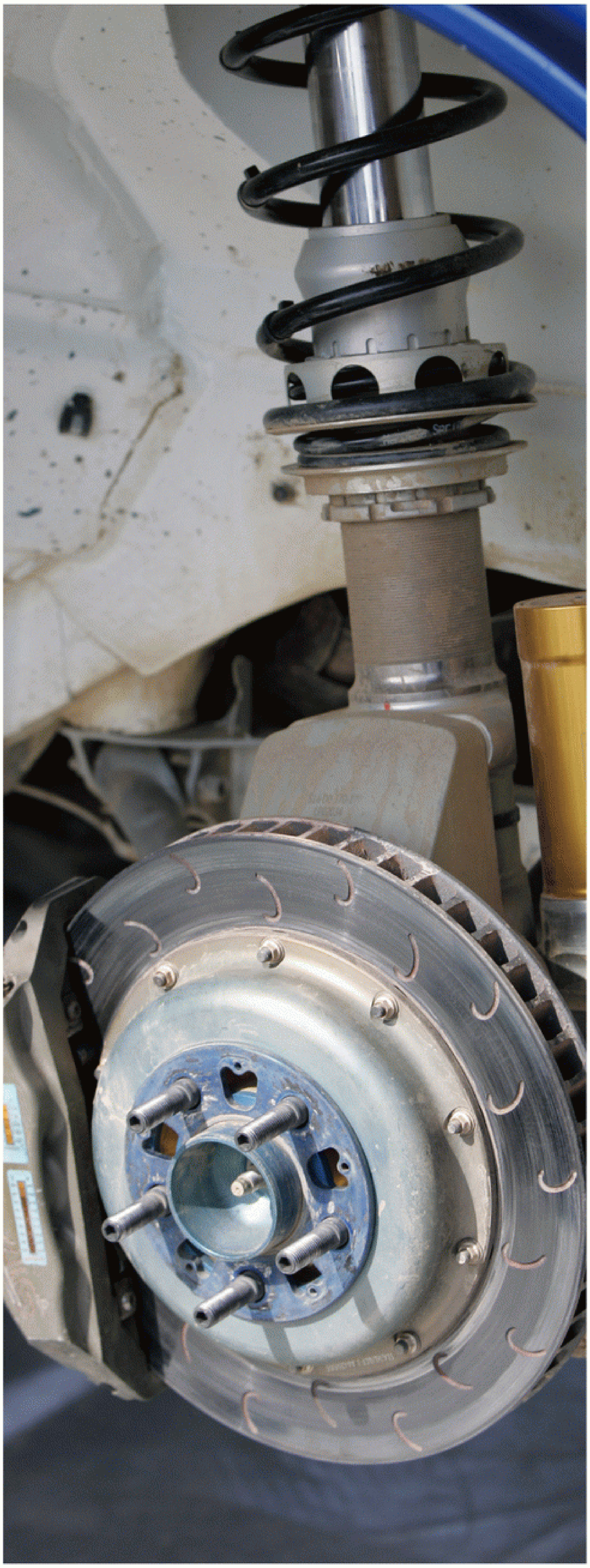
Stiffening the anti-sway bars can help reduce roll even more during cornering. If the front anti-sway bar is stronger, understeer is increased, and if the rear anti-sway bar is stronger, oversteer is increased.



Bushings

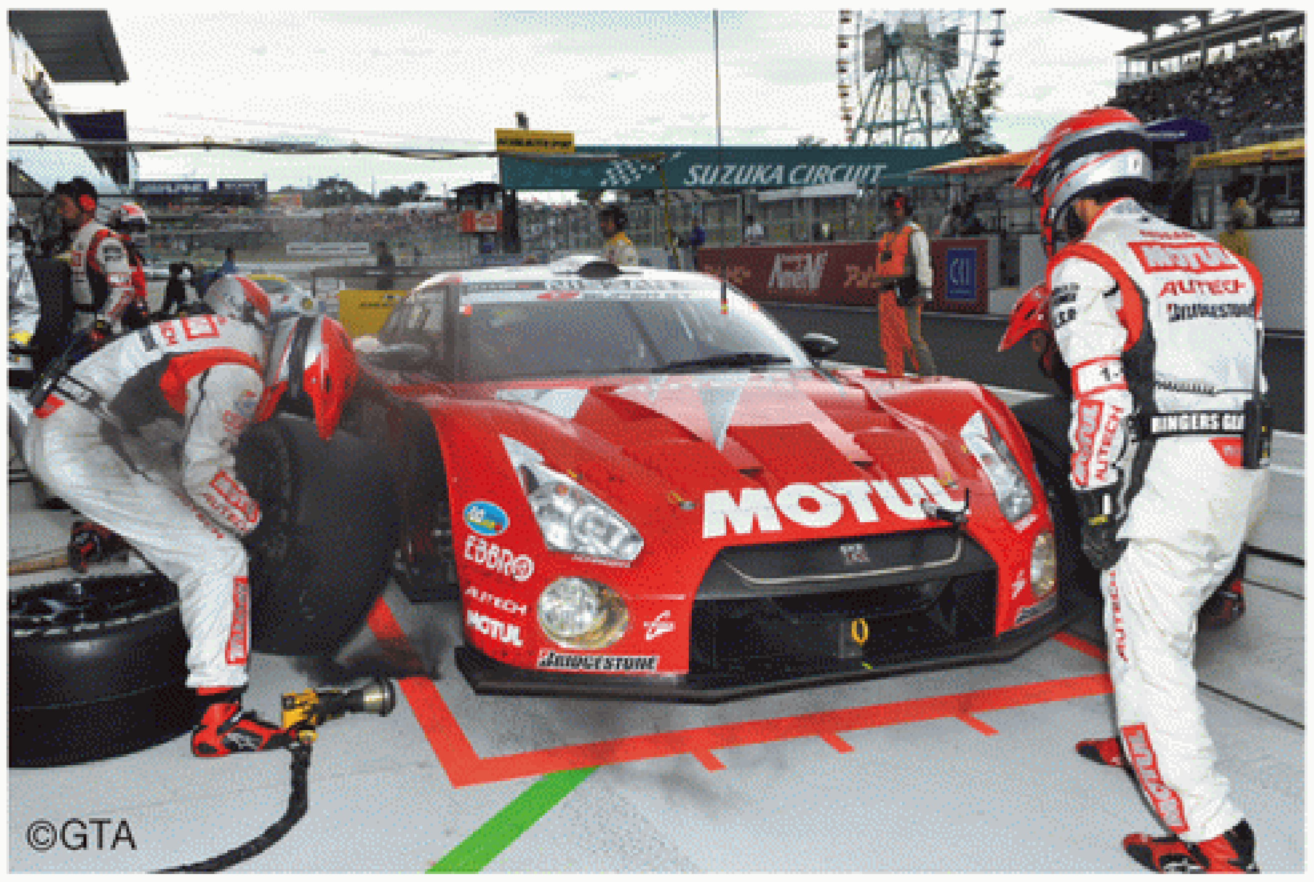
By using stronger bushings on dampers, suspension links and other body attachment points, as well as the bushings on a variety of linkage connections, unwanted movement of the suspension can be suppressed, and linear handling and steering responsiveness is gained. Suspension bushings are generally made from resin-based materials such as rubber or polyurethane, but there are also pillow-ball bushings, which use a metal sphere in the moving part.





Upgrading to High-Performance Tires

High-performance tires are a double-edged sword that improve grip greatly, but make control extremely difficult when they exceed their limits. Tires must be chosen by carefully considering how they will complement factors such as the vehicle's power and other characteristics.



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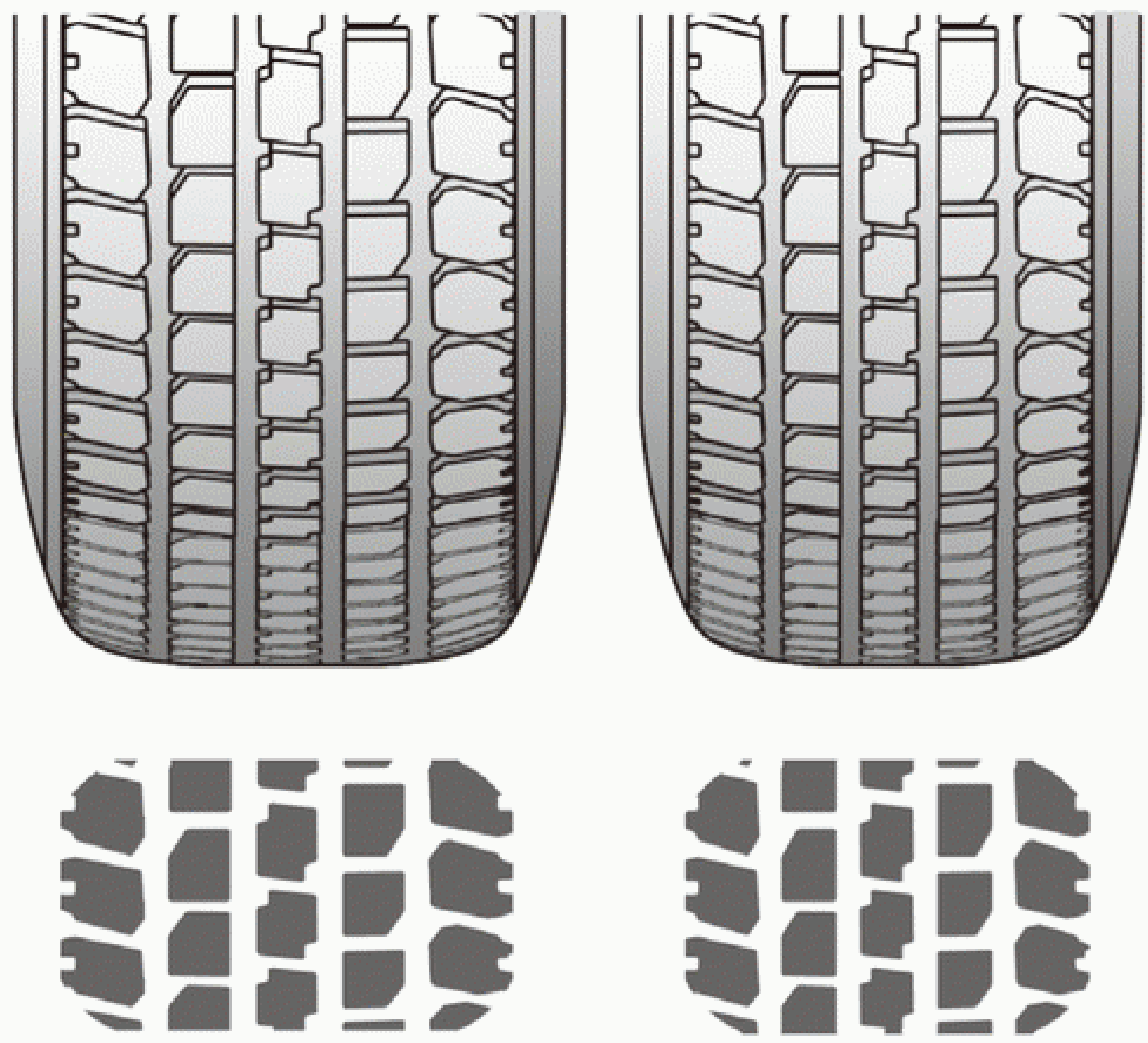
Width

Increasing the width of the tires increases the amount of tire surface that makes contact with the ground, and therefore increases grip. However, grip is not only affected by how much contact the tire has with the ground, but also by how much load is placed on the tire. Therefore, fitting super-wide tires to a lightweight car may not improve grip significantly, as there may not be enough weight pressing down on them. Another problem can arise when oversized tires are fitted to an underpowered car, in that so much power is used up counteracting the tires' grip that the car loses speed as a result. For these reasons, the choice of tire size should be based on the weight and output of the vehicle.



Increased Grip/Rigidity

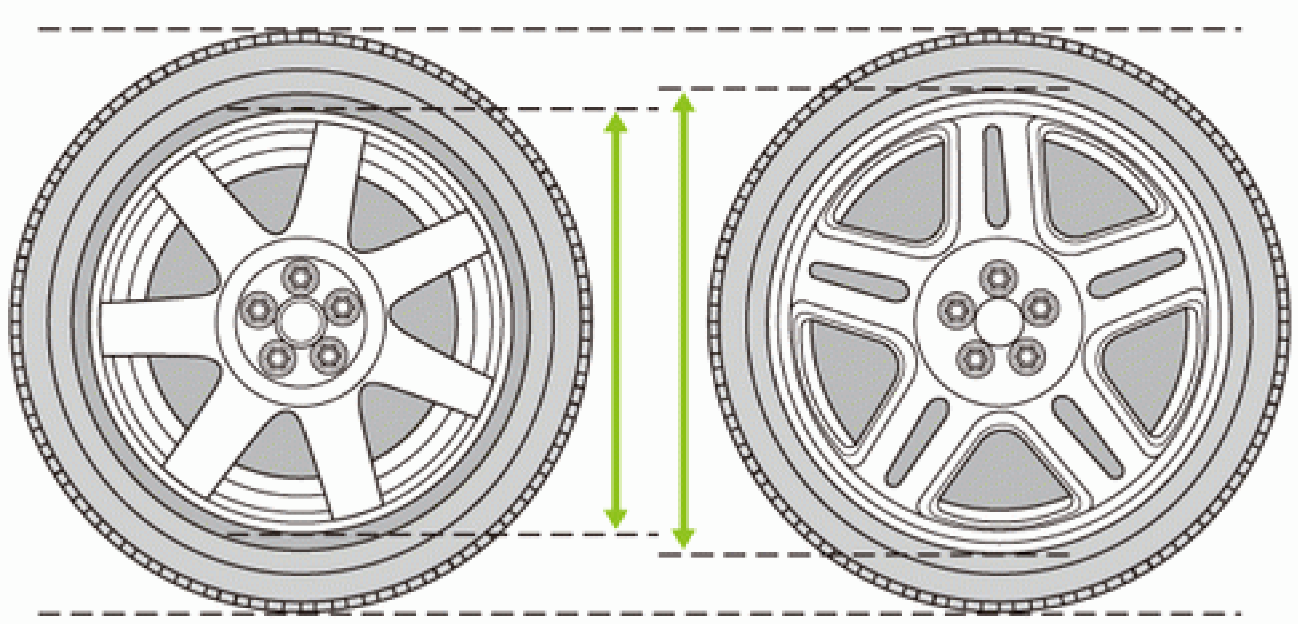
Grip and rigidity are the most important characteristics of high performance tires.

Slicks – tires designed especially for racing – boast the best of both. The rubber compound they are made from gives excellent grip by melting slightly and sticking to the track surface when it heats up, and in order to maintain rigidity in the part of the tire that makes contact with the road, they have no grooves. Road tires designed for high-performance driving take a similar, if slightly less extreme, approach, using softer rubber compounds, and tread patterns with very shallow grooves. However, on wet surfaces, grooves are essential to ensure that the tires can effectively rid themselves of water, and the more there are, and the deeper they are, the better. Therefore, deciding to what degree to balance wet and dry characteristics is a key element of tire choice.

Gripping the Road Effectively

Low-Profile

The profile (or aspect ratio) of a tire describes its height compared to its width. Using low-profile tires is a way of increasing wheel size without increasing diameter, and does not necessarily mean increasing width as well. One of the main benefits of low-profile tires is that the shorter sidewall bends less during cornering and braking, and this higher rigidity results in improvements in steering response and handling. However, lowering tire profile increases wheel size, which can mean more unsprung weight if taken too far, and of course this can adversely affect maneuverability. In competitive driving, larger wheels and low profile tires are selected to make space for larger, more effective brakes.



Compound

The rubber used to make the part of the tire that makes contact with the ground is called the compound, and dictates the tire's grip. High-performance tires that prioritize grip use soft compounds that adhere to the road surface better, and racing tires even melt slightly under heat so that they can cling to the road surface better. However, while soft compounds have better grip, they wear down much more quickly, and harder compounds are more durable. It is important to understand the characteristics of the compound used in order to choose the right tire. Drivers should also be aware that rubber hardens over time, and new tires will gradually lose grip because of this, particularly those made from softer compounds.

Tread Pattern

The series of grooves cut into the surface of a tire is known as the tread pattern, and is designed to maintain grip in wet conditions by ridding the tire surface of water. However, in dry conditions, these grooves reduce rigidity, and can cause the surface of the tire to sway under heavy load, such as when cornering, braking and accelerating. Because of this, the slick tires used for racing have no grooves whatsoever, and semi-racing tires use the minimum number of grooves that are as shallow as possible, in order to maintain rigidity.

AERO PARTS

CHAPTER 03 Tuning & Settings

Improving Aerodynamics

Aerodynamic improvements are an essential part of increasing high-speed performance. Improper tuning however can cause more problems than it solves, so an extremely delicate approach is necessary.

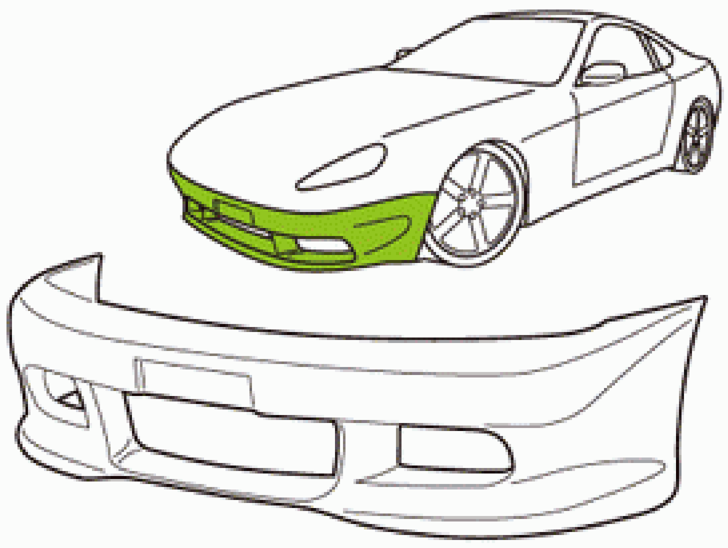
Harnessing the Wind

Aerodynamic Tuning

Aerodynamic parts are often fitted for purely stylistic reasons, but, when used properly, they are an essential part of tuning a car to perfection. Well-tuned aerodynamics will reduce the air resistance that limits speed and the forces acting to lift the body off the ground, greatly increasing driving performance. The downforce created by aerodynamic parts is crucial in improving stability and to maximize the gripping performance of the tires, and raises controllability of the car. However, it is essential to balance aerodynamic tuning with the suspension and the overall car, and it is not uncommon for improper tuning to actually hinder driving performance.

Front Spoiler

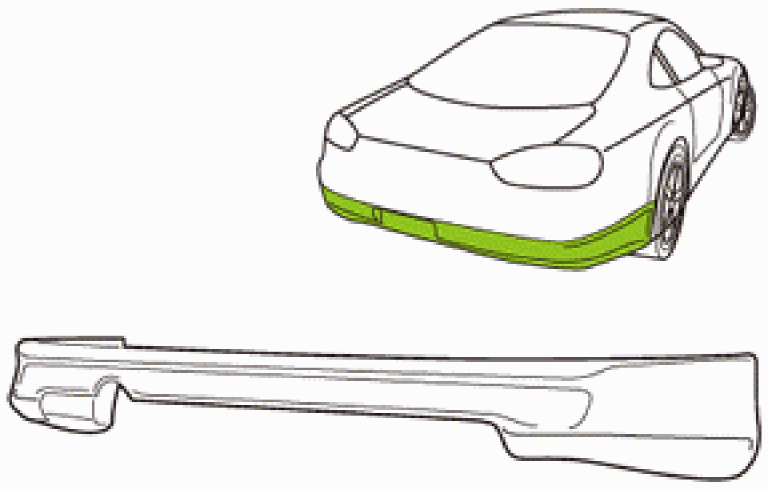
Designed to curb the flow of air underneath the car, thus reducing lift. However, in some rare cases, poorly shaped parts fitted on a car lowered to the ground can make pressurized air flow underneath the narrow space between the car and the ground, and become a cause of lift instead of suppressing it. In the worst cases, this can lead to complete loss of control.



©GTA

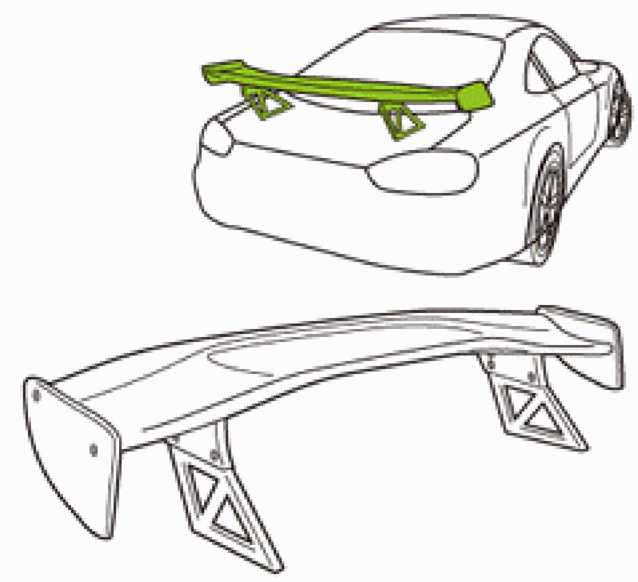
Rear Bumper Spoiler

Designed to optimize the shape of the rear bumper, preventing air turbulence behind the car and ensuring smooth airflow. The rear bumper and the rear bumper spoiler can be manufactured as one part, or the spoiler can be installed as a separate part that attaches to the bottom of the bumper. The former is called a rear bumper spoiler, and the latter is called a rear under spoiler or rear skirt.



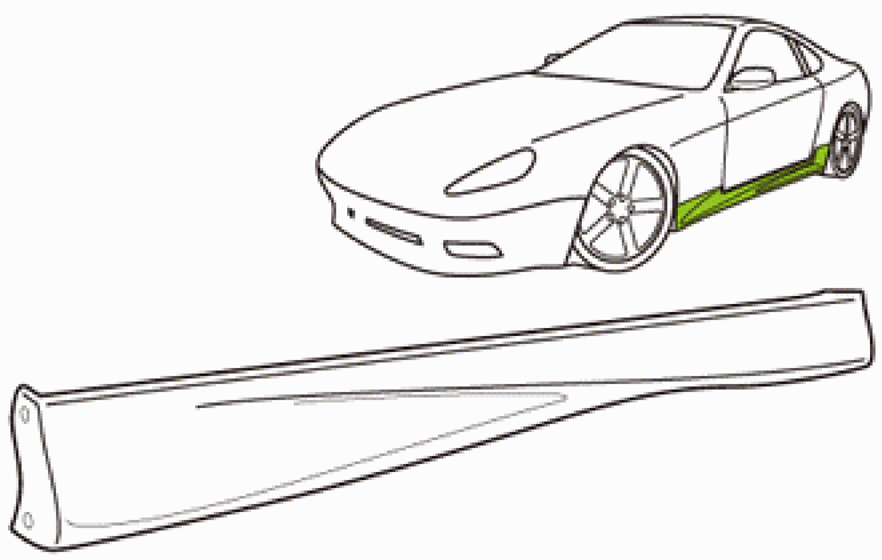
Rear Wing

Mounted on the upper part of the rear of the body, rear wing spoilers ensure that airflow is smooth around the car, and prevents air turbulence. The shape of the spoiler is also designed to counter lift. The greater the size, the more downforce generated, and the more grip is increased on the rear tires.



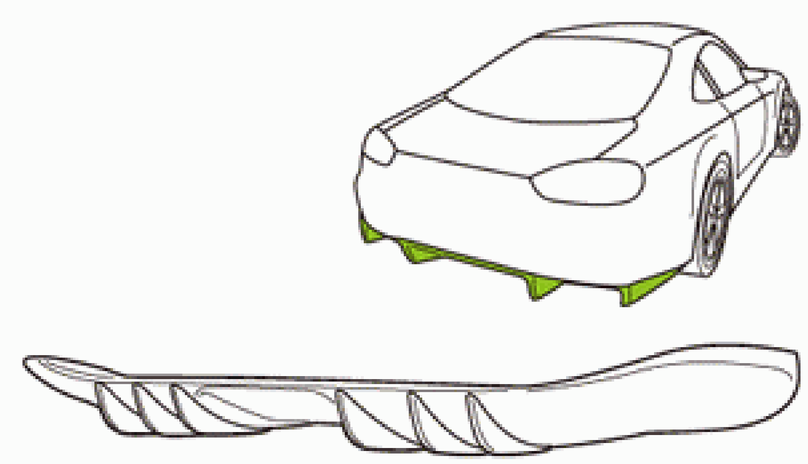
Side Spoiler

Also called side skirts or side steps, these are mounted on the left and right side sills of body. They reduce air resistance that occurs along the side of the car.



Rear Diffuser

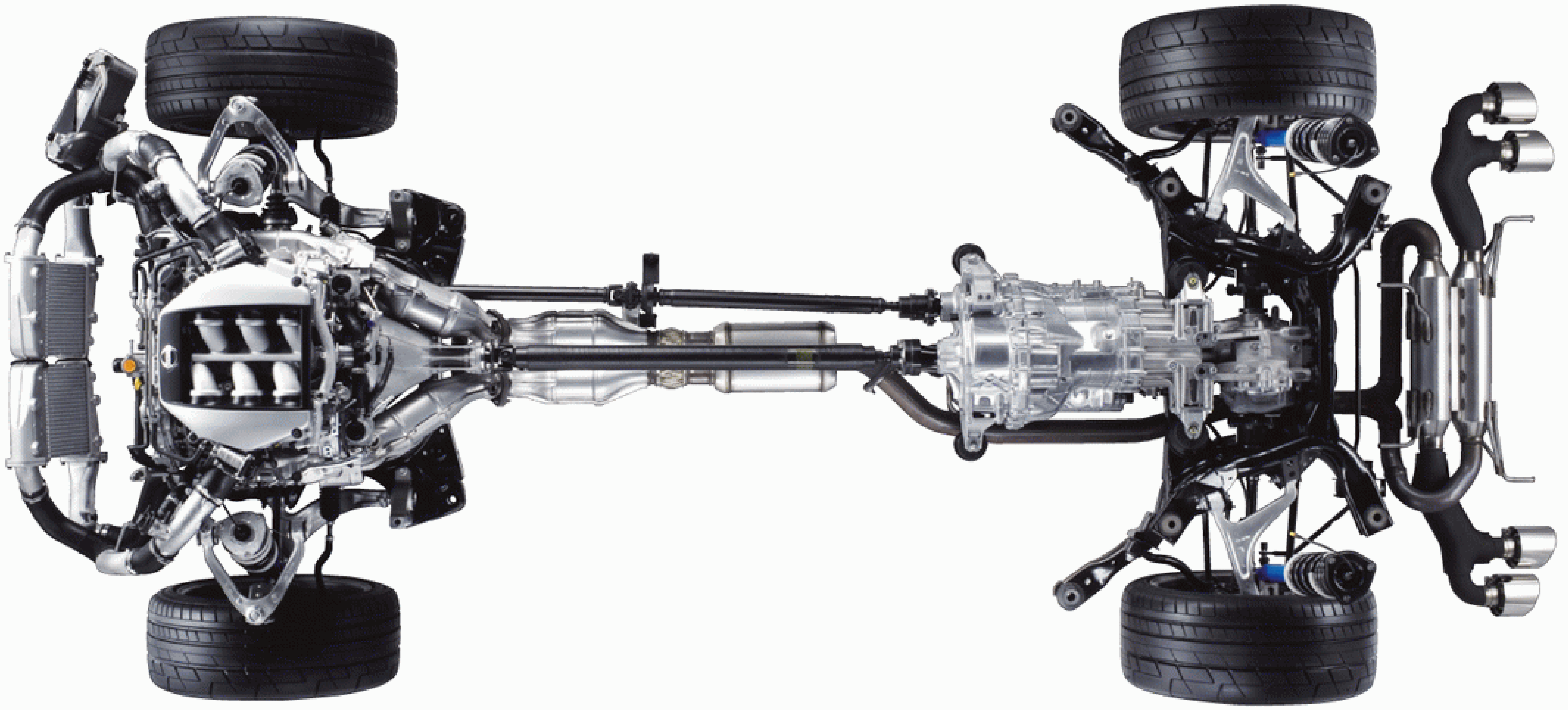
Rear diffusers are fitted beneath the rear bumper, and create negative pressure by efficiently drawing out the air from the underside of the car, thus increasing downforce. They are often used in racing cars, and the smaller the gap between the diffuser and the road, the greater its effect.



CHARACTERISTICS

Changing Settings According to Car Characteristics

The possible settings when tuning a car are as varied as the cars themselves. Among the differences between cars, drivetrain layout can have one of the biggest effects on handling and vehicle behavior. It is important to understand how the different layouts behave before making any adjustments.



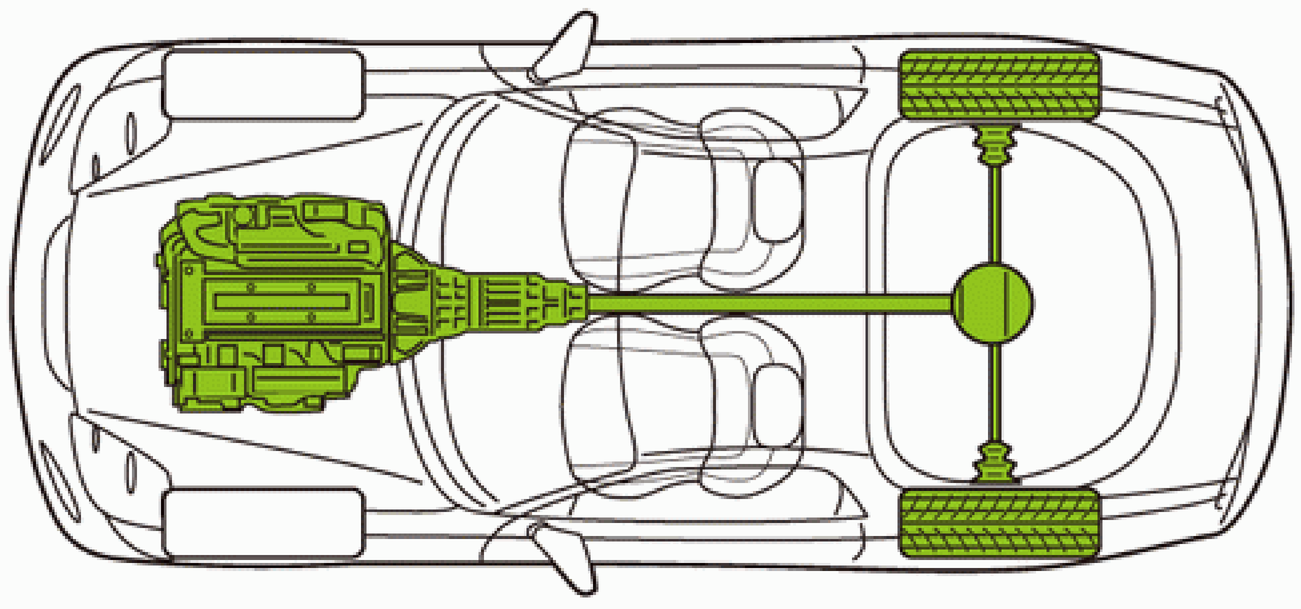
Drivetrain Layout

The drivetrain layout refers to the location of the engine - the heaviest part of the car - and the wheels to which that engine delivers its power. Different drivetrain layouts have different benefits and disadvantages, and even in highly tuned sports cars, drivetrain type remains a huge factor as it has a direct effect on how the car handles and behaves. Changing drivetrain layout is difficult, but it is possible instead to tweak a particular layout to bring out the good points while suppressing the bad. A set-up that cleverly exploits and improves upon existing drivetrain layout, suspension and aerodynamics characteristics can create handling that is in a different class than the norm.

FR

If given a good weight distribution, an FR car offers superb cornering and stability.

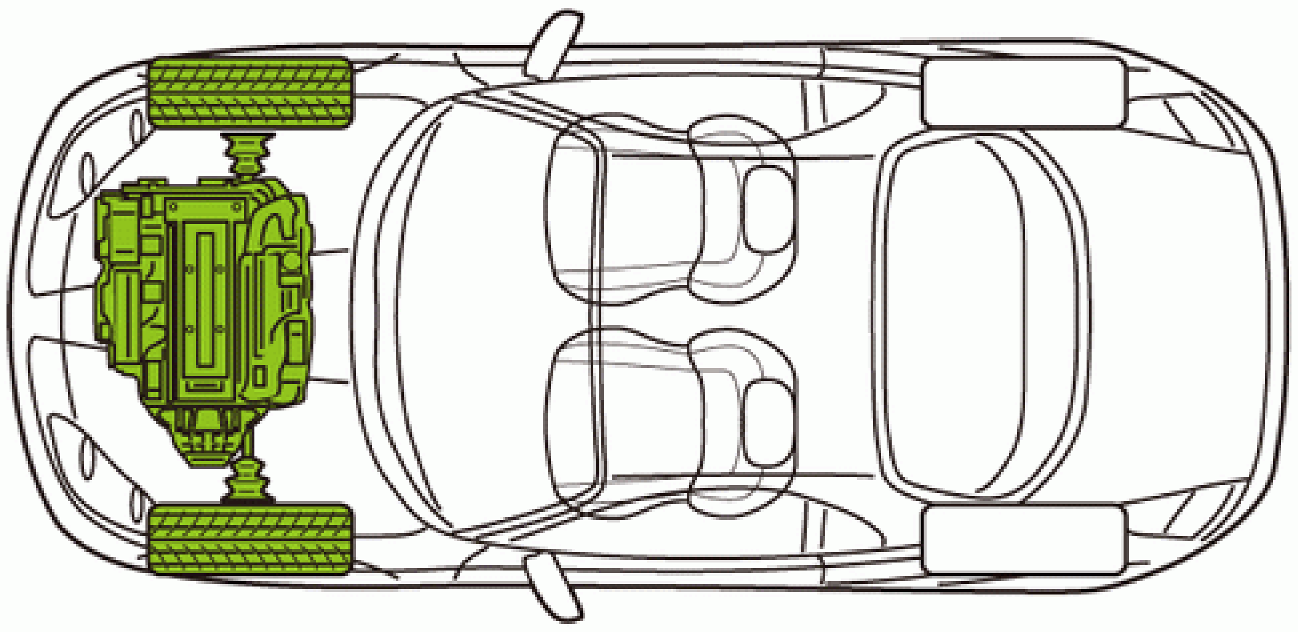
If you want to go faster, it is a good idea to tune it for increased traction at the rear wheels so that the tail does not slide out during acceleration. The front on the other hand should be tuned so that it is not prone to a "pushing Understeer" condition that will prevent you from tracing the desired driving line, again when the load from the front is reduced during acceleration.



Compensate for Weak Points, Improve Strong Points

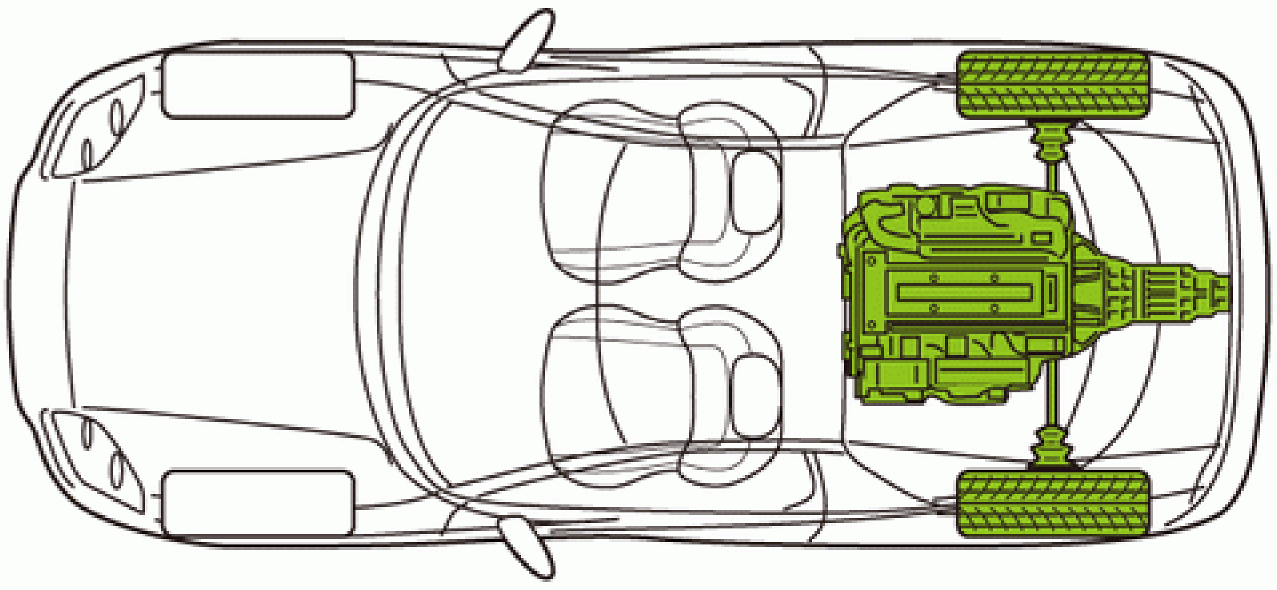
FF

In a FF the front tires which are both steering and drive wheels tends to attract all the attention, but you must not forget about the rear. On a high speed course, the rear should be set for more stability, while on a course with many turns, the focus should instead be placed on allowing the rear to slide out easier when letting off the pedal, enabling sharper cornering. FF cars normally use 1-way type LSDs that only activates when accelerating.



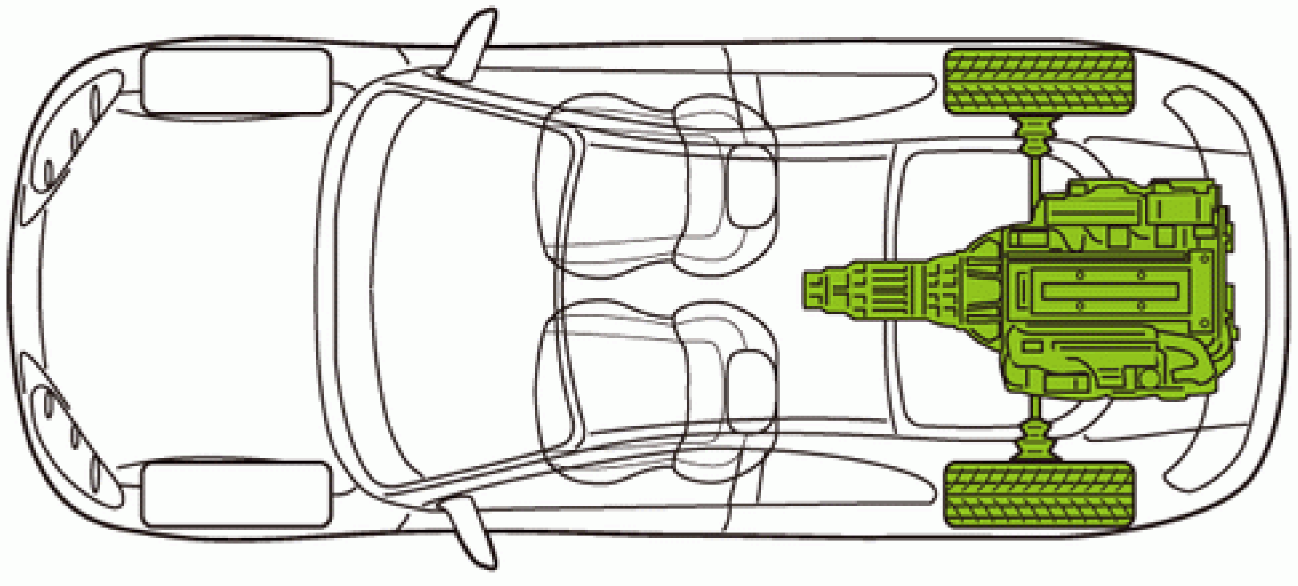
MR

Positioning the engine towards the center of the car enables good acceleration and deceleration. Turning is also sharp but when pushed to the limit, the smaller load in the front end can lead to understeer. The speed at which the rear end slides is also very quick and trickier to control. When tuning, attention should be paid to first securing its turning performance at the entry of corners, then the traction when accelerating out of a corner. Front and rear downforce should also be carefully balanced.



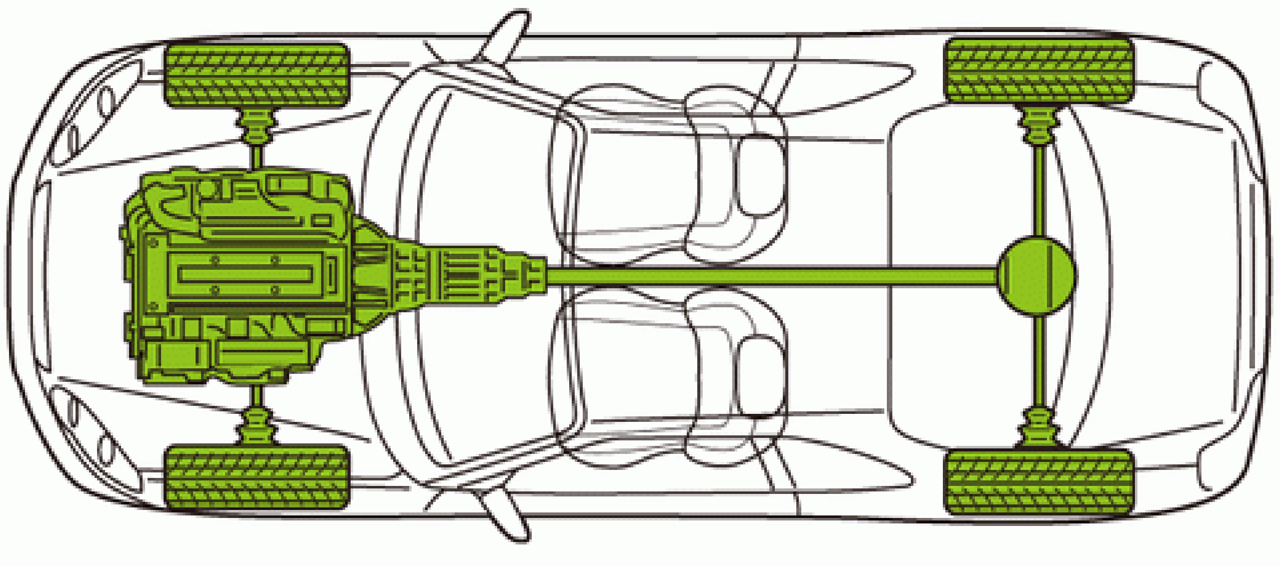
RR

A combination of the rear mounted engine and rear wheel drive gives great acceleration and deceleration, but there is even less weight on the front end than a MR layout, making understeer during cornering even more pronounced. Also, when pushed to the limit through a corner, the heavy rear end will act like a pendulum, swinging sharply around and causing sudden oversteer. Tuning this drivetrain layout is usually a case of improving the initial turning ability upon entry into a corner.



4WD

Depending on the drivetrain layout on which the 4WD is based, the car will behave differently, but generally speaking, turning in a 4WD vehicle is more difficult due to its extremely high stability. Stability during acceleration out of a corner is extremely good to begin with, so the settings should focus on its turning ability upon the initial entry into a corner. The LSDs used on these cars are usually 1 way in the front and 2 way in the rear.



Basic Settings Part-by-Part

Just installing high performance parts will not make your car faster. Performing settings in consideration for the total balance of the car is the only way to draw out the full potential of each component and to increase a vehicle's overall performance.

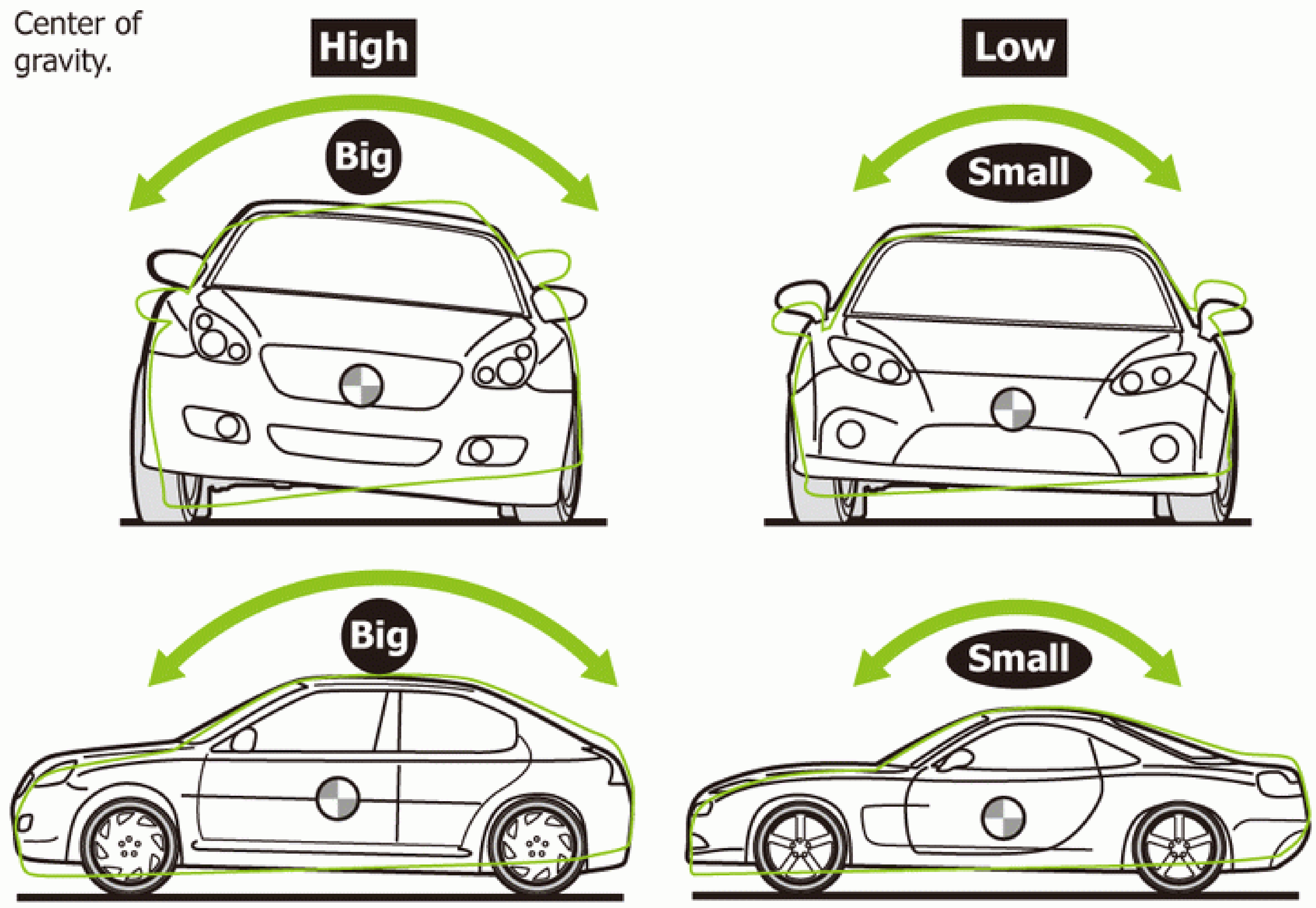
Suspension
[Ride Height/Spring Rate]

Changing Your Car's Behavior

If road conditions are good and the surface is flat, the lower the ride height of a car is set, the lower the center of gravity. This will reduce the pitching during acceleration and deceleration, and roll during cornering, thereby improving overall performance. The car's behavior can also be fine-tuned by setting the front and rear suspension to different heights. For example, making the front suspension lower than the rear will push the front wheels against the road harder when entering a corner, and the car will turn in more smoothly. In FF cars, this can also be used to counteract the tendency of the front of the car to rise up when accelerating.

Spring rate also has a large impact on how a car moves. It is often thought that the harder the springs, the better, but this is not always the case. Harder springs can reduce unfavorable driving movements such as pitch, yaw and roll in the same way that reducing ride height can, but if they are too hard, kickback from the road surface will be increased to the point where it is difficult for the tires to remain in contact with the ground, and traction will be lost. For this reason, spring rate should be carefully calibrated in order not to be too tight or too loose for your needs.

Spring rate also has a big impact on handling. Increasing the rate at the front can lead to understeer, and increasing the rate at the rear can increase oversteer, but this can be compensated for somewhat by adjusting the damping force of the shock absorbers so they must be set in pairs.



Getting the Front and Rear Suspension Balance Right

Suspension [Damping Force]

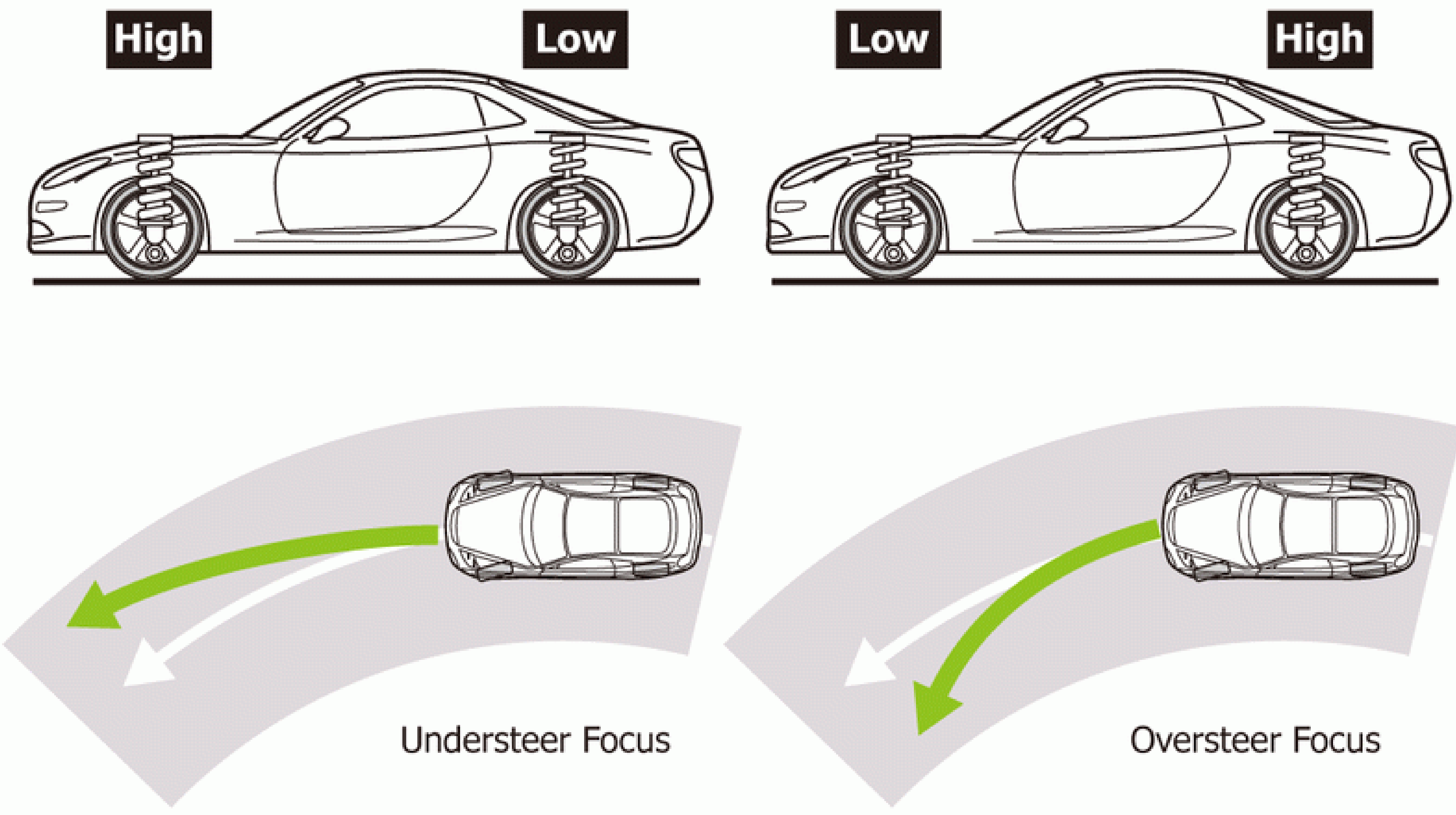
Controlling Spring Compression and Extension

Shock absorbers control the speed at which suspension springs expand and contract when load is placed on them, and the force they exert is known as "damping force." Damping force is generated by the resistance created in oil or gas sealed inside the shock absorber's piston when it moves up and down. The higher the damping force, the more quickly the springs' movement will be suppressed, and the lower it is, the longer it will take for the movement of the springs to subside.

Damping force settings for compression and extension can be changed independently, allowing the car's behavior and handling to be controlled more precisely. If damping force is increased for spring compression, the speed of nosedive during braking, roll when cornering and other body movements will be reduced, but the increased stiffness of the undercarriage will make the wheels more likely to leave the road under bumpy conditions, and will make it more difficult to use load transfer effectively. On the other hand, increasing the damping force for spring extension helps subside major movement changes. For example, the lifting of the front of the car when accelerating out of a corner will be suppressed by preventing the front suspension from extending immediately, maintaining the contact of the front tires to the ground.

Handling characteristics can also be adjusted by changing the damping force for spring compression/extension between front and rear wheels. If damping force is reduced for spring compression at the front of the car, more load of the car will tip towards the front in a turn thus improving grip in the front, countering understeer. Reducing damping force for spring extension in the rear will increase oversteer, and increasing it will increase understeer. As a rule of thumb, the damping force for spring compression should be set before the damping force for spring extension.

Front and Rear Damping Force (For Spring Compression).



Suspension
[Wheel Alignment: Camber Angle]

The Positive Effect of Negative Camber

The most commonly altered wheel alignment setting is the camber angle. A negative camber is when the bottom of the wheels are spread wider apart than the tops of the wheels when viewed from the front, and a positive camber is when bottom of the wheels are pointed in towards the center of the car.

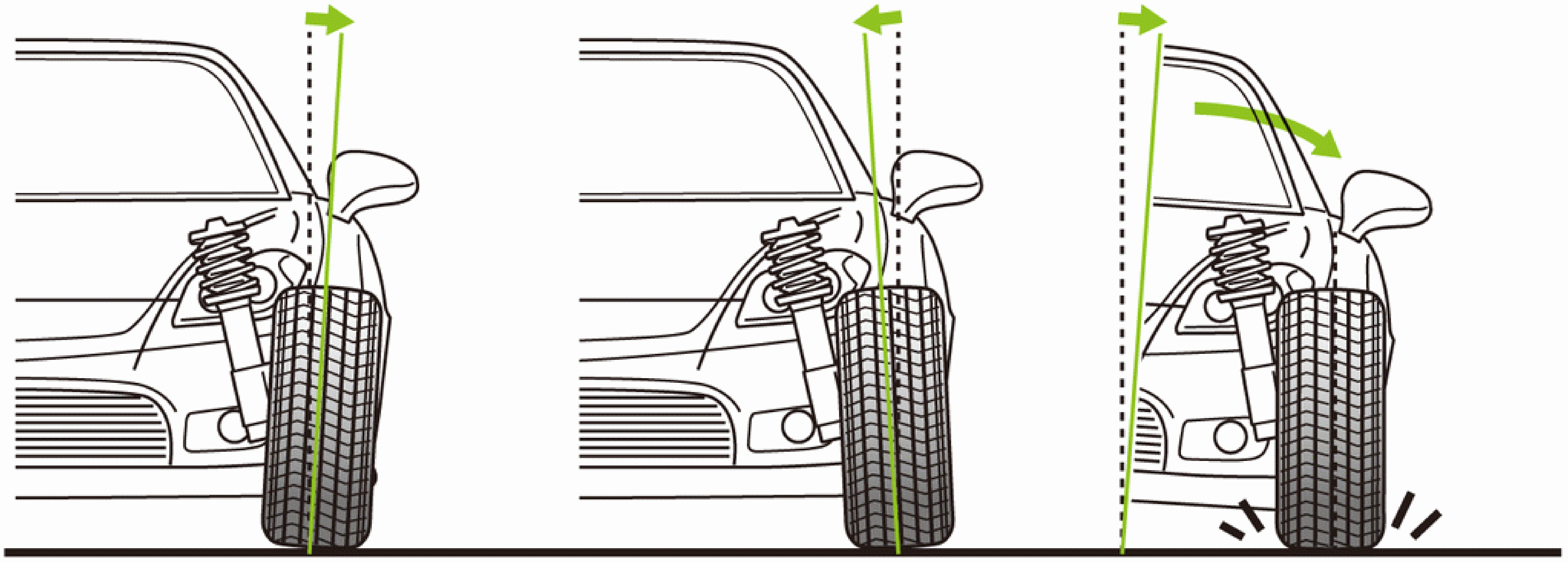
When cornering, centrifugal force will cause the car to lean towards the outside of the turn. If the wheels are given a negative camber in anticipation of this, more of the tire surface will be in contact with the surface when turning, and better traction can be achieved. "Increasing camber angle" usually refers to increasing negative camber.

However, a negative camber has disadvantages when travelling in a straight line. The tires are not upright on the road, so steering can be more easily disrupted by ruts or unevenness in the road surface, and it can be more difficult to gain traction. The angle of the wheels will also increase resistance, which will impede acceleration performance, and the reduced amount of tire surface in contact with the ground will also lengthen braking distances. The more severe the negative camber, the more severe the negative effects when on the straight, so it is important to think very carefully before making any drastic changes.

When applying negative camber, it is important to consider the effect of weight balance between the front and rear wheels when cornering. If there is a lot of load on the front of the car, the negative camber of the front wheels should be larger, and that of the rear wheels should be smaller. This will reduce the risk of understeer.

A positive camber is almost never used, as it reduces tire grip, and makes movements of the car oversensitive.

Positive Camber **Negative Camber** **Roll While Cornering**
Negative Camber Increases Grip When Cornering.



Achieving Optimum Grip

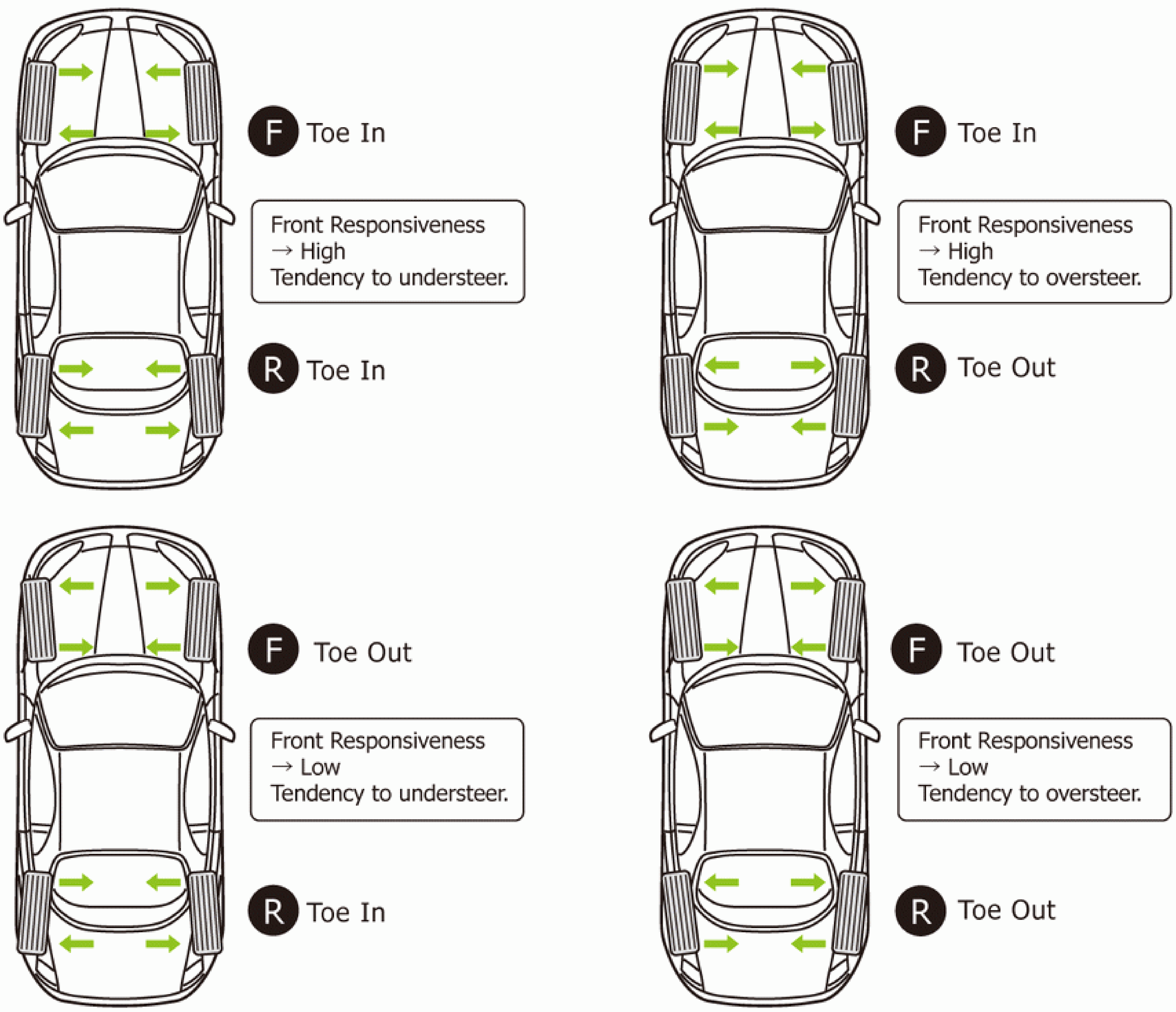
Suspension
[Wheel Alignment/Toe Angle]

A Shallow Angle With a Deep Effect on Stability

The toe angle is the angle of the wheels when the car is looked at from above. It plays an important role in maintaining stability when weight balance between the left and right sides shifts dramatically. For example, when load moves to the outside wheel when cornering, the angle of that wheel has a huge effect on how the car behaves. The toe angle setting dictates this angle, and as such, plays an important role in maintaining stability.

"Toe-in" is when the front of the wheels face inwards. "Toe-out" is when the front of the wheels face outwards. In terms of handling, setting the front wheels to toe-in and the rear wheels to toe-out will cause a greater tendency to oversteer, while the opposite setting will cause a tendency to understeer. The front wheels are also sometimes set to toe-out in order to make them move less erratically when cornering.

Toe angle is intricately related to wheelbase, track width, camber angle and engine power. It is often the last of these to be adjusted, and only then in order to correct slight peculiarities caused by the other factors, or to subtly tweak handling characteristics. A steep toe angle will cause a lot of resistance, so adjustments are always very small. Changes to the toe angle of the rear wheels in particular can have a large impact on drive performance and handling, so the angle of the front wheels are usually set first, and only very minor adjustments made to the rear.



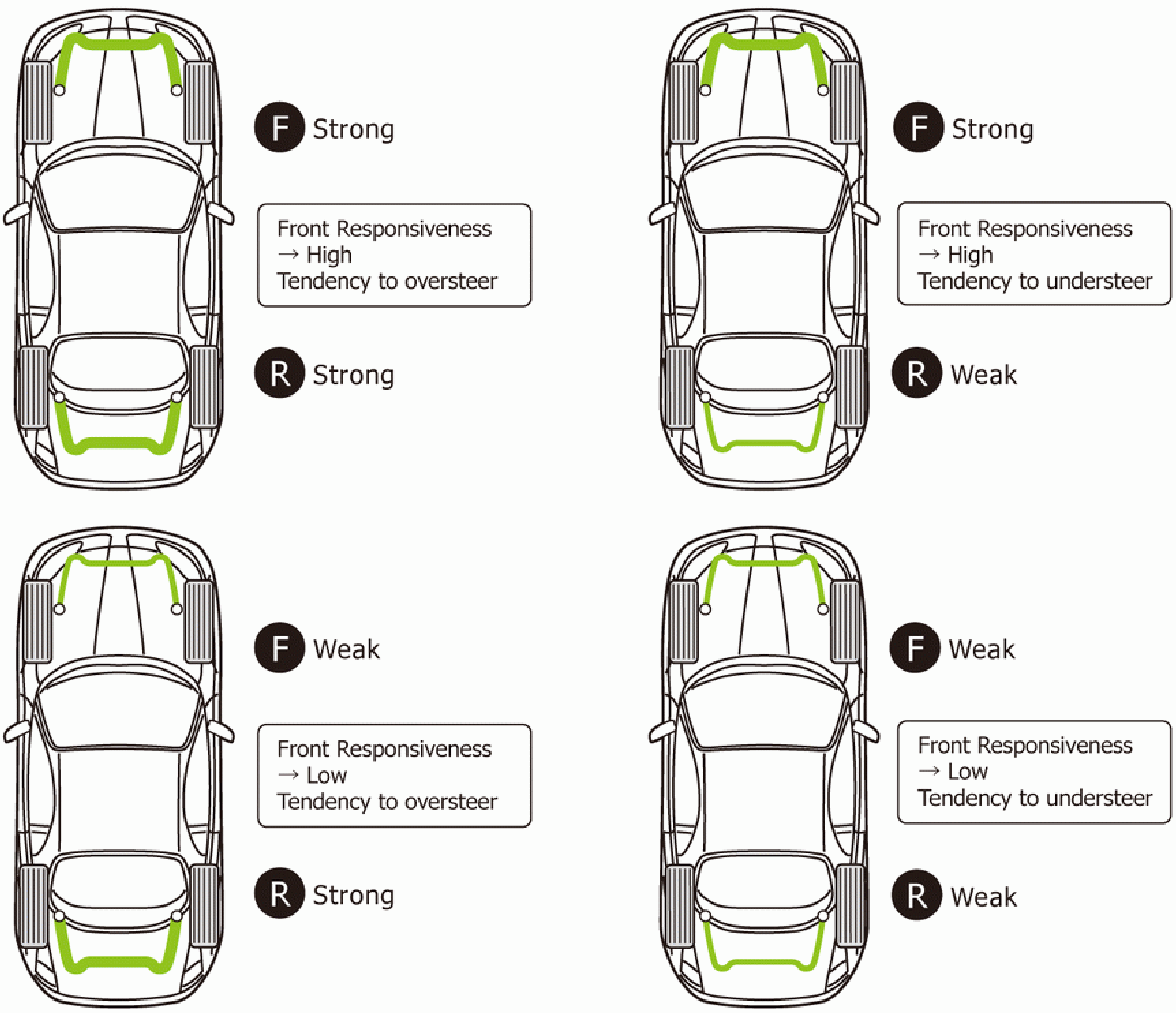
Suspension
[Anti-Sway Bar/Stabilizer Stiffness]

A Final Tweak

An anti-sway bar is a torsion bar spring that connects the lower arms of the left and right suspension. A torsion bar spring is a metal bar that utilizes the resistance of twisting force placed upon it. When the suspension on one side moves during cornering, the resistance of the suspension on the other side counteracts that movement, reducing roll, and thereby keeping more of the tire surface in contact with the ground. The stiffness of this bar is represented by a spring rate similar to that of a suspension spring, and increasing the stiffness of the front anti-sway bar will improve steering response.

When adjusting an anti-sway bar, it is important to not set the spring rate higher than that of the suspension spring. If the anti-sway bar is stronger, the suspension spring will be too weak to overcome it, and when weight moves to the outside wheel, the inside suspension will lift up with the anti-sway bar, causing the inside wheel to lift off the track, and traction to be lost.

It is also possible to adjust handling by altering the spring rates of the front and rear anti-sway bar, but these kinds of adjustments should usually be made by just changing the spring rate of the suspension springs and the damping force of the shock absorbers. Adding anti-sway bar stiffness to the equation overcomplicates things, and makes it very difficult to achieve the desired result. Anti-sway bar stiffness adjustments should be seen as a final tweak rather than a tuning method in themselves.



Drivetrain
[LSD]

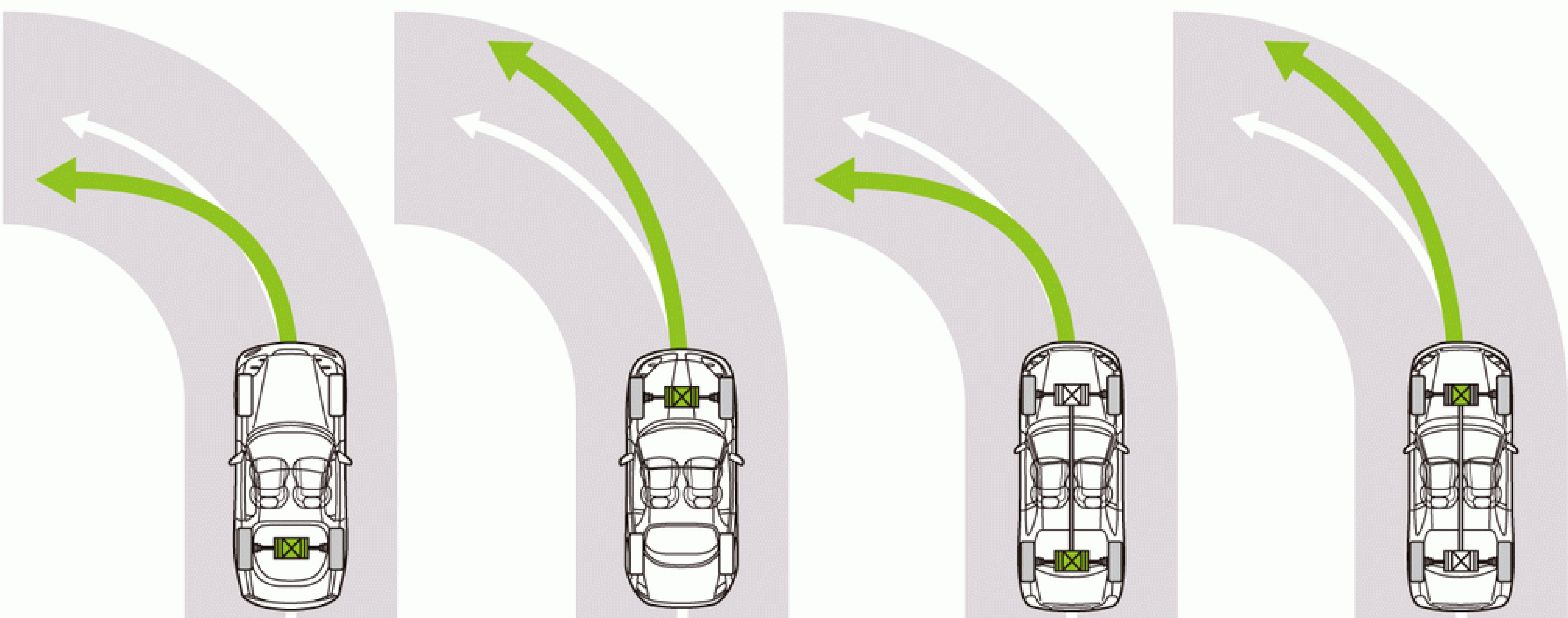
Changing the Limit Changes Maneuverability

Initial torque decides the point at which the LSD kicks in. The higher it is, the more easily the LSD will lock, and the more responsive acceleration will be. The lower the initial torque, the more slowly the LSD will take effect.

Generally speaking, increasing the initial torque will accentuate the handling peculiarities of a vehicle's drivetrain layout. Therefore, oversteer will be increased in rear-wheel drive cars, and understeer will be increased in cars with front-wheel drive. Although this improves traction in both cases, it will make turning more difficult. As such, initial torque adjustments should be made with the desired handling requirements in mind.

Another setting that can be adjusted is how the LSD behaves during acceleration and deceleration. The acceleration setting governs the effectiveness of the LSD when stepping on the accelerator, and the stronger it is, the more drive power is transmitted to the wheels, and the more quickly the car will be able to clear corners. However, this will also accentuate any handling peculiarities, and getting the car to point in the direction needed to exit the corner may require some skill.

The deceleration setting governs the effectiveness of the LSD when the accelerator is released. The stronger it is, the more stable it will be upon entry into a corner while braking. This allows you to go into the turn very fast, because you can keep braking longer than you would otherwise. However this makes turning more difficult, and is only recommended for advanced drivers who are skilled at compensating for initial understeer.



FR／MR／RR
Tendency to oversteer.

FF
Tendency to understeer.

4WD Rear
Tendency to oversteer.

4WD Front
Tendency to understeer.

Adjusting Cornering Behavior

Drivetrain
[Gear Ratio]

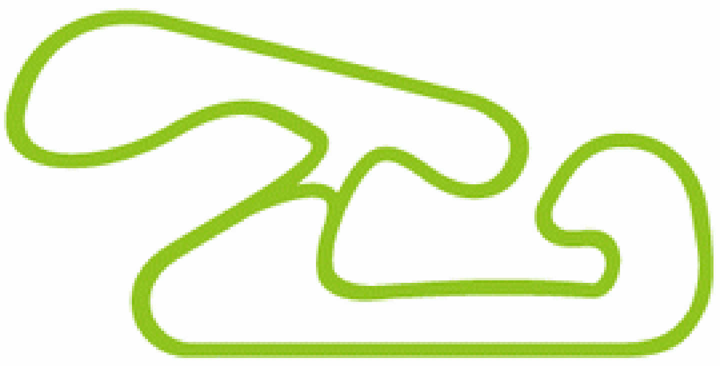
Maintaining Power with a Close Ratio

Racecars have to drive on all kinds of circuits, from winding tracks with many corners to tracks that feature long, high-speed straights. In order to get the best out of your engine on a particular course, it is often necessary to change the gear ratio of your drivetrain. This usually involves changing both the final gear and the gears of the transmission itself.

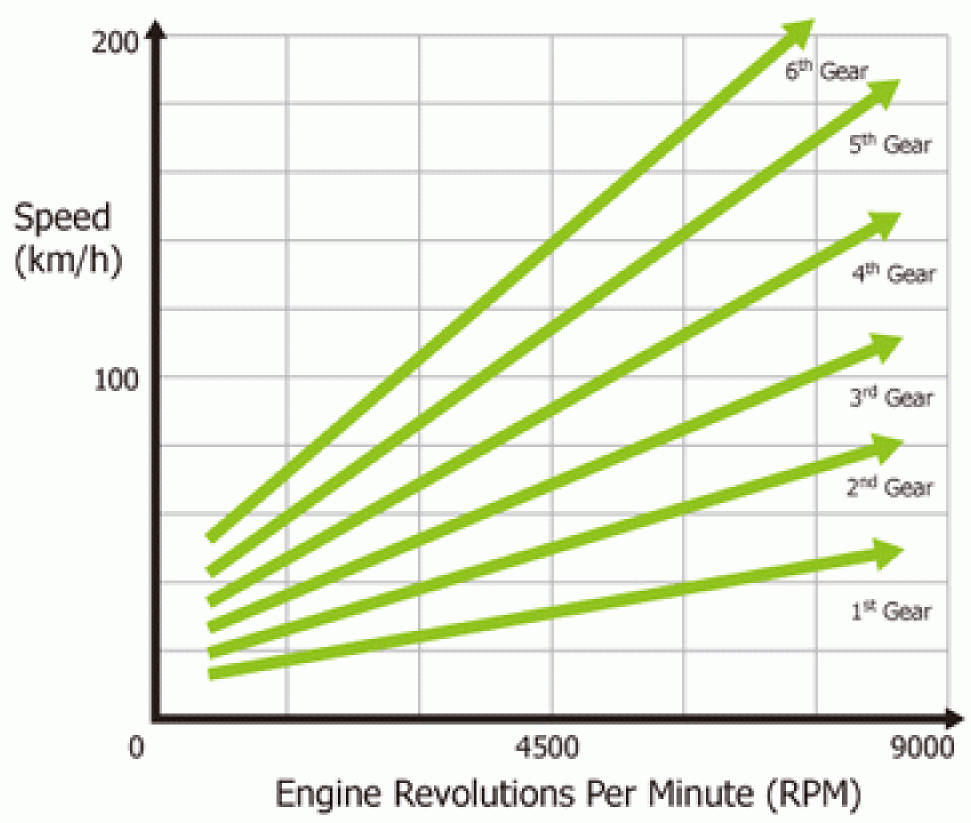
When driving on a track with lots of low and mid speed corners, your focus will need to be on accelerating out of the corners rather than achieving high speeds. At times like these, a transmission consisting of gears of similar ratios will allow you to stay more easily within the powerband. This kind of gear setup is known as a "close ratio."

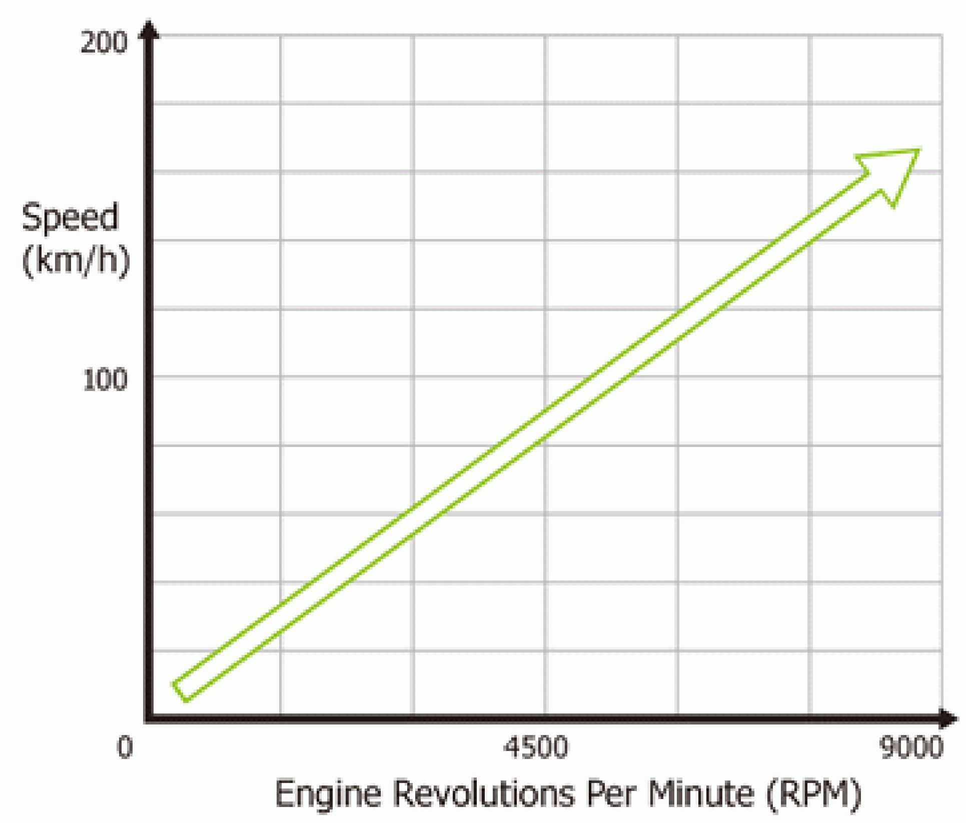
On the other hand, on a course featuring lots of long straights that emphasize high speed, you will want a setup that increases top speed by using smaller ratios for 5th and 6th gear. This kind of gear setup is known as a "wide ratio."

The gear ratio of the final gear affects how the transmission as a whole behaves. If the final gear is made smaller with the same set of transmission gears, acceleration will be improved, but top speed will be reduced, whereas a larger final gear will increase top speed at the expense of acceleration. When you first start adjusting gears, you should just change the final gear for an easy adjustment. You want to set the gear so that the engine will reach the rev limit in the last gear of the transmission, just by the end of the straightaway on the track.

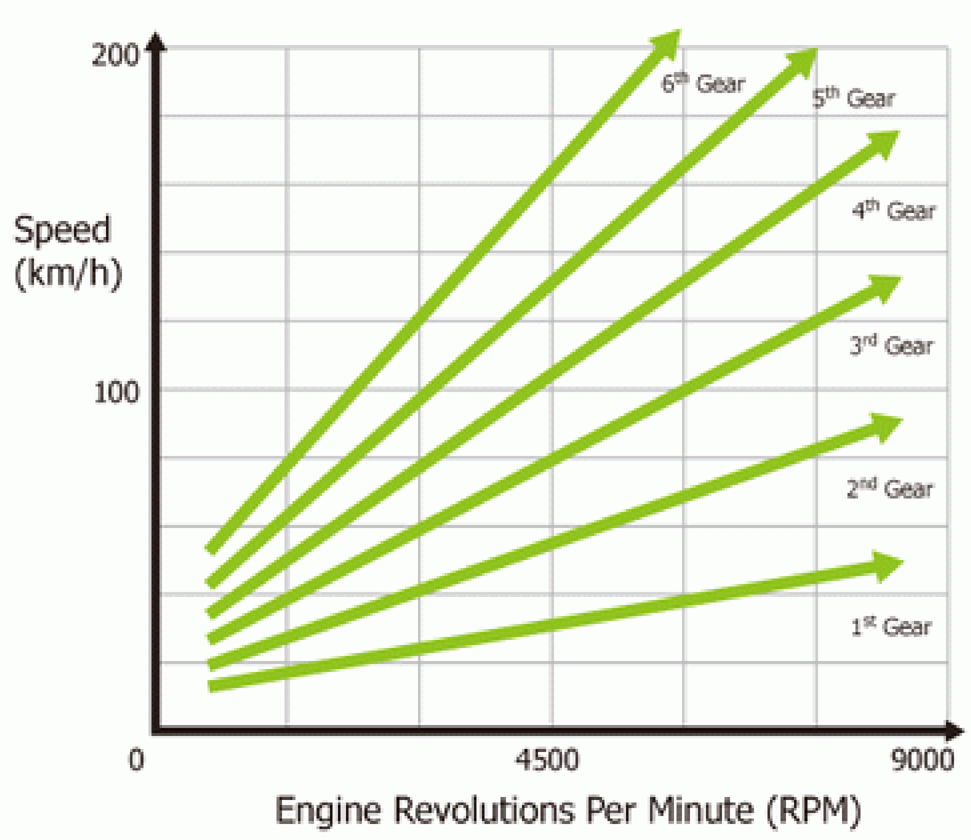


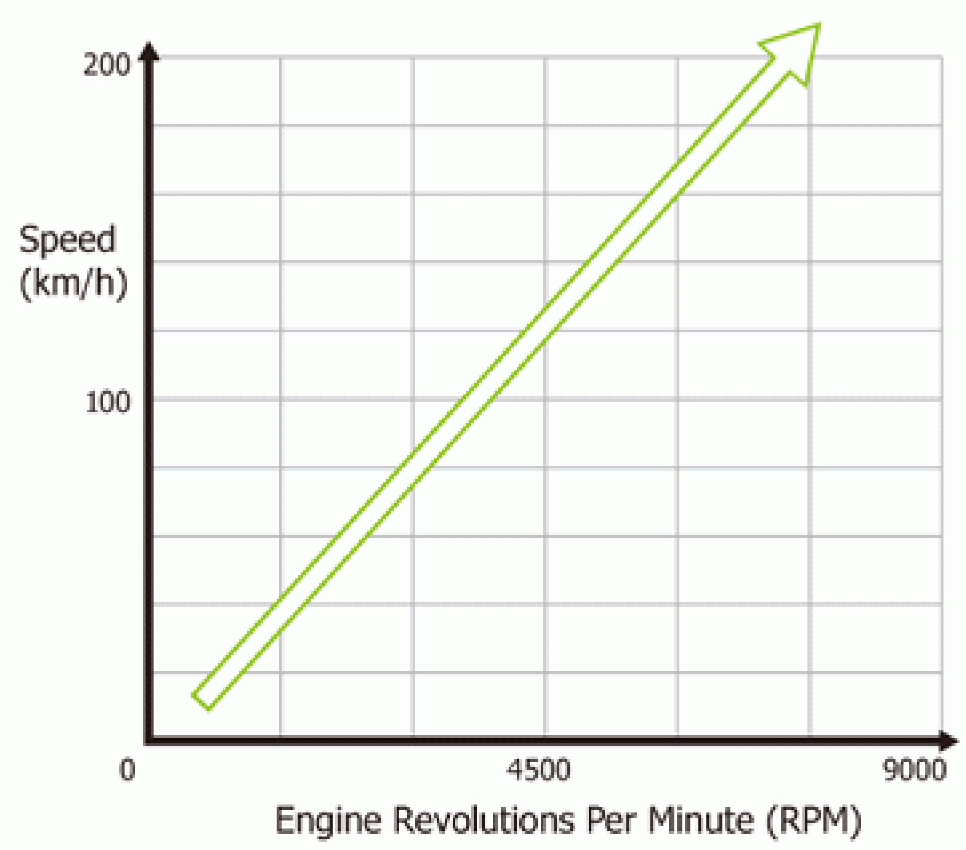
On a course with lots of corners, bringing the ratios of all the gears closer together puts the focus on acceleration performance.





On high-speed circuits with long straights, increasing gear ratios will put the focus on increasing top speed.





Aerodynamics

[Downforce]

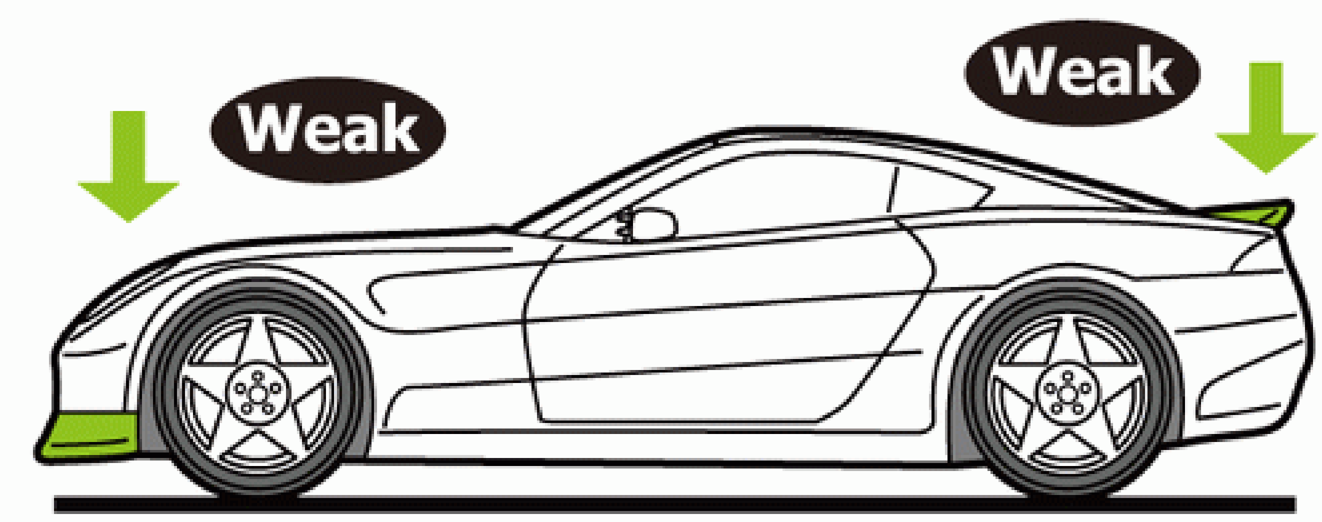
Improving High-Speed Performance

It is impossible to ignore the effects of air when driving at high speed. These effects can broadly be divided into two categories: air resistance, which limits top speed, and lift, where the movement of air picks the car up off the ground. These two factors are closely related: reducing air resistance increases lift, and reducing lift increases air resistance. Therefore, a careful balance needs to be struck between the two.

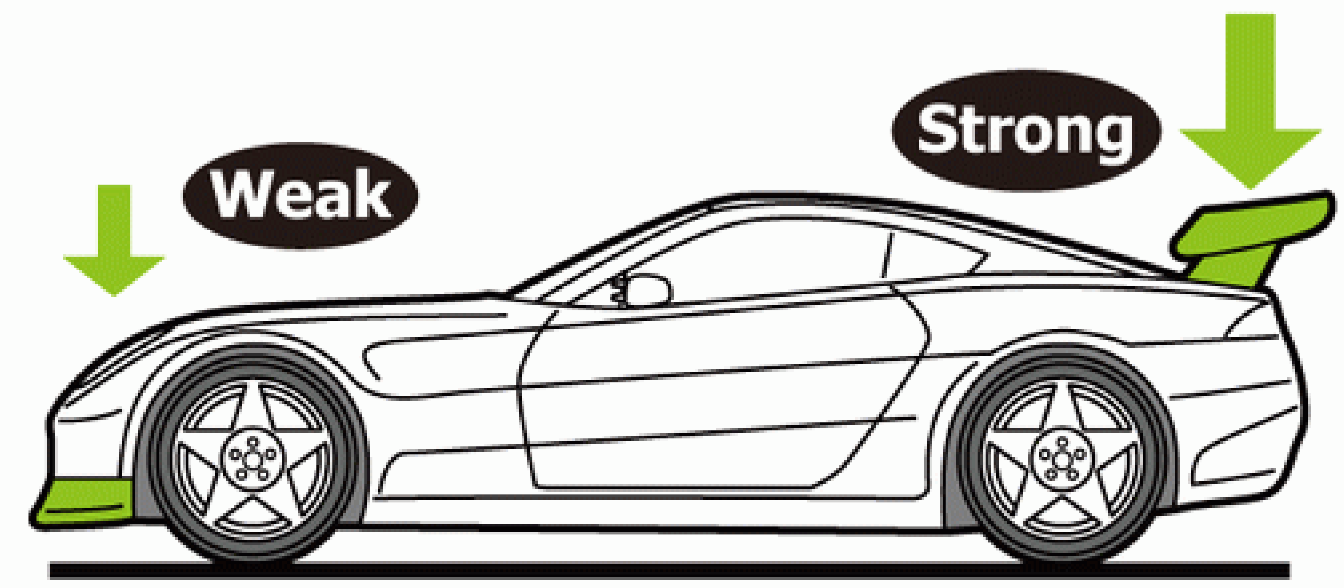
A key concern when tuning to deal with air movement at high speed is how best to exploit downforce. Downforce is the force exerted when air resistance pushes down on the car, improving contact with the road. An increase in downforce will reduce top speed, but will increase stability when cornering, and improve cornering speed, especially on high-speed corners. Reducing downforce, on the other hand, will reduce cornering speed, but will allow the car to move more quickly on the straight.

The amount of downforce needed is dictated by the nature of the course, and although it might seem so, having strong downforce from the start will not produce a good setting. The ideal way to set a car is to perform various settings with the minimum downforce, then gradually increase it according to the importance of the high-speed corners. For small displacement cars, the best approach is usually to maximize top speed by reducing downforce to zero.

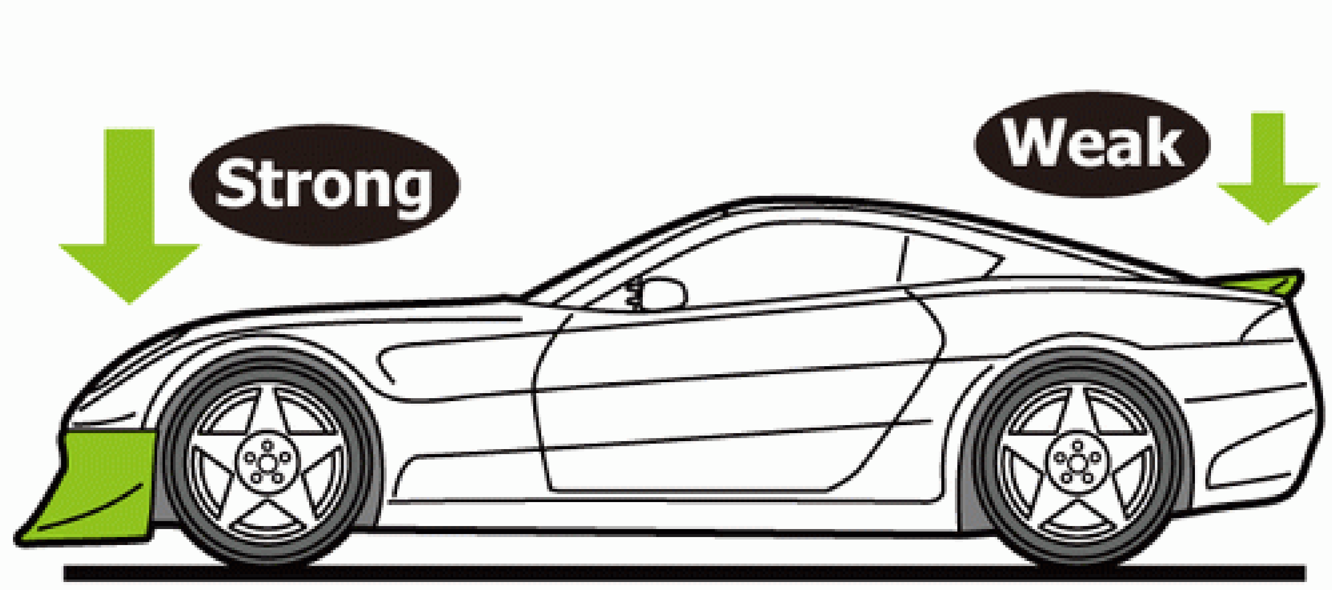
Variations in front and rear downforce can also be used to alter handling characteristics when negotiating high-speed corners. Increasing downforce on the front end will increase grip on the front wheels, increasing oversteer, whereas stronger downforce on the rear will have the opposite effect, increasing understeer. Adjustments of this type can make all the difference on high-speed circuits.



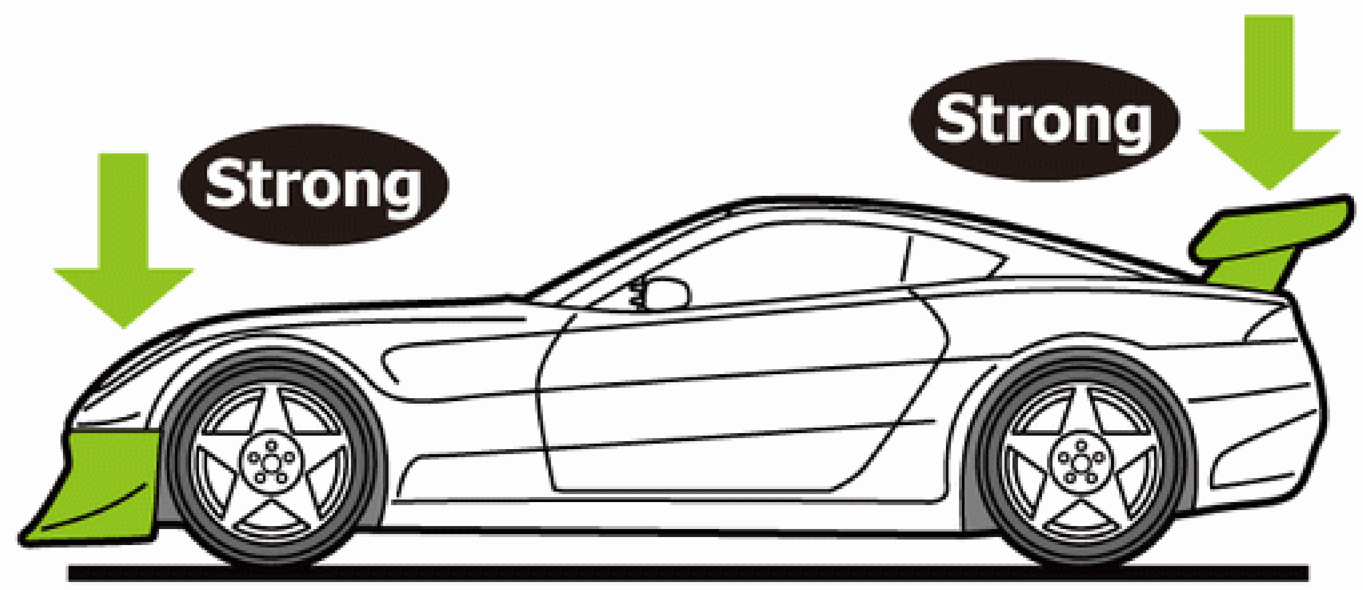
Top Speed → Increases
Control → Decreases



Top Speed → Decreases Slightly
Tendency to Understeer



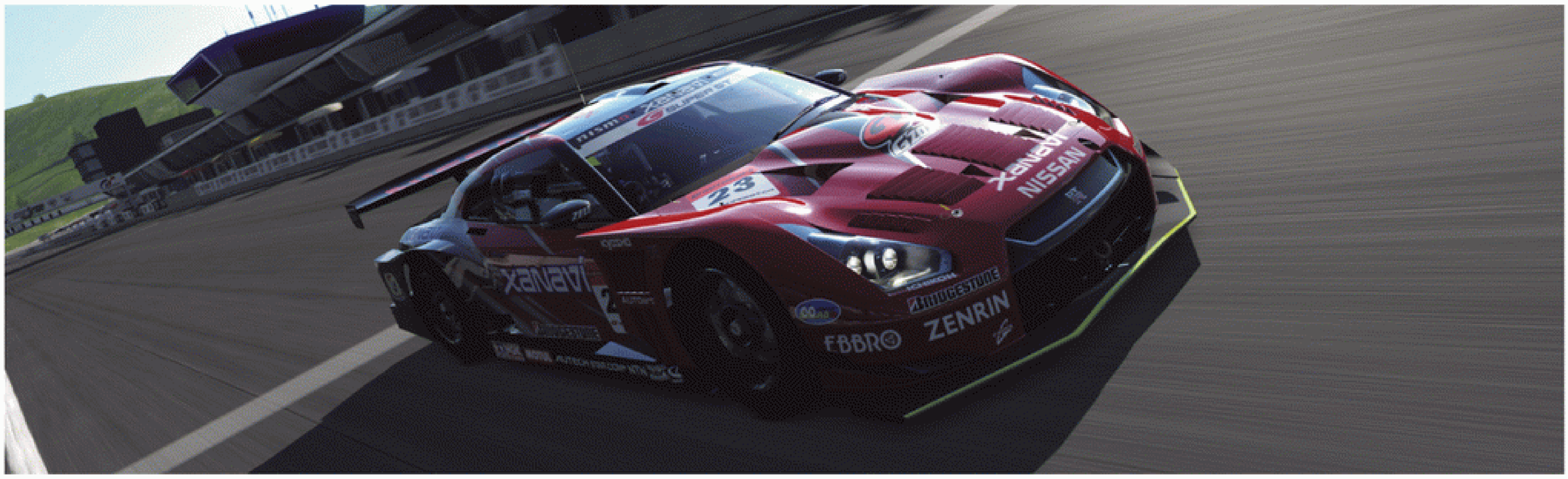
Top Speed → Increases Slightly
Tendency to Oversteer



Top Speed → Decreases
Control → Increases

Settings for Specific Situations

One very important reason for adjusting your car's settings is to deal with a specific course or specific conditions. A few quick suspension and drivetrain tweaks can make a surprising difference to how your car handles a particular track.



High-Speed Circuits

Improving Top Speed

The ideal settings for a high-speed circuit are those that allow the car to take high-speed corners as fast as possible. The suspension and shock absorbers should be stiff, and the ride height low. However, if the ride height is so low that the springs cannot move sufficiently, the suspension will be too hard to absorb the impact of bumps and undulations in the road, cancelling out any beneficial effects. If you use stiffer suspension springs, reducing the stiffness of the anti-sway bars will create a little roll that will keep the wheels in better contact with the road. If, on the other hand, you soften the springs a little in order to deal with an uneven road surface, stiffening the anti-sway bars will help combat excessive roll. Basically, the idea is to have your anti-sway bars compensate for the shortcomings of your springs.

Wheel alignment is also important. Increasing the rear toe-in angle is a good way of improving stability. The camber should be at least slightly negative, but you also want as much of the tire as possible to be in contact with the track when driving fast on the straight and when braking hard, so it's best not to go overboard.

As far as gear ratios are concerned, the aim is the same as always: to keep the car within the powerband as much as possible. The final gear should be set to a ratio that allows the top gear to just reach redline by the end of long straights. As for downforce, the minimum possible amount should be used in order to maximize speed on the straight, but you want to make sure that stability is not lost when cornering and braking.

Suggested Suspension Settings

		FRONT	REAR
Ride Height		Low	Low
Shock Absorbers	Extension	Strong	Strong
	Compression	Strong	Strong
Spring Rate		Hard	Hard
Wheel Alignment	Toe Angle	0	In
	Camber Angle	Negative	0
Anti-Sway Bar		Hard	Hard

※ Depending on the car, these settings may not be possible.

Getting the Best Performance

Technical Courses

Efficiently Transfering Power to the Road

For a technical course with a lot of tight corners, the goal is to set up a car that can turn quickly and has the ability to accelerate out of corners with a minimum loss of power. The first thing to do is set the ride height to an appropriate level for the course, which should be as low as can be achieved without causing problems.

The front springs should be softened and the rear springs stiffened (only moderately in rear-wheel drive cars) in order to enable better turning, and the shock absorbers set with the same aim in mind. Alignment-wise, the front wheels should be set with a slight toe-in angle if the driver wishes to prioritize initial responsiveness when cornering, but with less toe-in if the emphasis is more on drive feel at and beyond the clipping point. Negative camber should be used in moderation, as traction needs to be maintained when braking and cornering.

The transmission gearing should be set with a close ratio to maintain revs rather than prioritizing top speed, and the final gear ratio should be low to allow quick acceleration.

If full-scale engine tuning is possible, the focus should be on achieving maximum torque at low and medium speeds in order to boost acceleration out of corners rather than on achieving maximum power at high revs. Downforce on both front and rear should be as high as possible, as the aerodynamics of the car should support stability during cornering rather than improving top speed.

Suggested Suspension Settings

		FRONT	REAR
Ride Height		Low	High
Shock Abosrber	Extension	Strong	Weak
	Compression	Strong	Weak
Spring Rate		Hard	Weak
Wheel Alignment	Toe Angle	0	In
	Camber Angle	0	0
Anti-Sway Bar		-	-

※ Depending on the car, these settings may not be possible.

Countering Understeer

Understanding Where the Car Refuses to Turn

Start by identifying when understeer occurs, whether it is on entry to a corner, near the clipping point, or when accelerating away.

If understeer occurs on entry to a corner, the grip of the front tires needs to be increased as much as possible. This can be achieved by softening the front suspension springs and increasing the extension side of the shock absorber, while reducing it for spring compression in order to encourage load to move forward.

As well as suspension-related factors, an over-sensitive LSD can also cause understeer at this stage of a corner, and lowering the LSD's lock rate and initial torque can go some way to rectifying this. If you are using a 2-way LSD (one which takes effect whether the accelerator is pressed down or not) in a rear-wheel drive car, try changing it for a 1-way system that does not take effect when decelerating. On courses with high-speed corners, increasing front-end downforce to improve the grip of the front wheels can also be effective.

If understeer is occurring when approaching the clipping point, negative camber should be increased in order to ensure that more of the tire is in contact with the ground. Reducing rear-wheel toe-in can also help to balance grip, and if possible, increasing track width at the front end can also be effective.

If understeer occurs in rear-wheel drive cars when accelerating out of corners, it can be counteracted by decreasing ride height at the front, increasing the damping force for extension on the front shock absorbers, and increasing it for compression on the rear. If it occurs in an FF car, it can be combated by increasing the effect of the LSD.

Suggested Suspension Settings

		FRONT	REAR
Ride Height		Low	High
Shock Absorber	Extension	Strong	Strong
	Compression	Weak	Strong
Spring Rate		Weak	Hard
Wheel Alignment	Toe Angle	In	0
	Camber Angle	Negative	0
Anti-Sway Bar		Weak	Hard

※ Depending on the car, these settings may not be possible.

Countering Oversteer

The Trouble With Rear-Wheel Drives

FF and 4WD cars rarely suffer from oversteer. This problem almost exclusively affects rear-wheel drive cars.

If you are aiming simply to have maximum control of oversteer, e.g. for a drift event, then both the front and rear suspension should be stiffened in order to improve control over how much the rear end slips out. However, in a time trial or similar track racing event, you will need to take measures to maintain traction in order to keep the car moving forward.

The main reason for unwanted oversteer is the loss of rear-wheel traction when the accelerator is applied, which causes drive power to be wasted on moving sideways rather than accelerating.

Spring rate and damping force can be tuned to counter this effect. The rear springs should be softened, and the damping rate of the shock absorbers decreased for compression, and increased for extension. It can also be beneficial to reduce the stiffness of the rear anti-sway bar in order to increase load movement onto the inside wheel. If possible, rear track width should also be increased. If the front suspension is too soft, weight from the rear can shift forward too easily, so the front suspension should be stiffened in order to improve grip at the rear.

If there is a rear spoiler, the angle should be increased in order to increase downforce. However, this will mean a slight loss of top speed.

Suggested Suspension Settings

		FRONT	REAR
Ride Height		High	Low
Shock Abosrber	Extension	Strong	Strong
	Contraction	Strong	Weak
Spring Rate		Hard	Weak
Wheel Alignment	Toe Angle	-	In
	Camber Angle	-	Negative
Anti-Sway Bar		-	Weak

※ Depending on the car, these settings may not be possible.

Wet Conditions

Get the Best Out of Your Tires

As you might expect, when it rains, the friction coefficient (μ) of the road surface is reduced, and grip along with it. Let's look at some settings that can be tweaked in order to deal better with wet conditions.

Spring rate, damping force and anti sway bar stiffness should all be set lower than they would be in dry conditions, and in some cases, the rear anti sway bar can be removed entirely. Stiff suspension will make it harder for the wheels to remain in contact with the ground, and may cause the car to slide out suddenly. Hard suspension improves grip when the grip of the road is good, but in wet conditions, where grip is poor, the softer the better. The camber angle should be decreased slightly more than in dry conditions to ensure that more of the tires maintain contact with the ground during acceleration and deceleration. In cars where aerodynamic adjustments are possible, front and rear downforce should be increased in order to maximize grip.

One of the simplest wet weather tweaks is to adjust your tire pressure. In heavy rain, increasing tire pressure will put less of the tire surface in contact with the ground, increasing load on the part of the tire that is touching the ground, and thereby preventing hydroplaning. Conversely, in light rain, reducing tire pressure can improve performance. Altering the air pressure of the front and rear tires is a quick and easy way to fine-tune the amount of grip they achieve, and is usually one of the first adjustments made.

If full-scale engine tuning is possible, the emphasis should be placed on low- and mid-range torque rather than top-end power. Relying more heavily on electronic control devices can also improve wet-weather performance, and it can be surprising to see how much difference an electronic braking-control system can make.

Suggested Suspension Settings

		FRONT	REAR
Ride Height		Low	Low
Shock Absorber	Extension	Weak	Weak
	Compression	Weak	Weak
Spring Rate		Weak	Weak
Wheel Alignment	Toe Angle	In	In
	Camber Angle	Negative	Negative
Anti-Sway Bar		Weak	Weak

※ Depending on the car, these settings may not be possible.

Gravel

Improving Control

The most important thing when setting a car up for gravel driving is to allow for flexible control. The condition of unpaved surfaces is often unpredictable, and altering your driving line even slightly can take you over areas whose friction coefficient is completely different. Cars will also kick up sand, dust and gravel as they drive, completely changing the nature of the road surface for those that follow them. If a car is tuned solely to push the limits of its performance, as it would be on a surfaced track, it won't have the flexibility to deal with sudden changes in the road surface.

One way of tuning for road surfaces of this kind is to aim for a set-up that will cause the front of the car to turn in when the driver's foot is taken off the accelerator, but will have neutral steering (i.e., no oversteer or understeer) when the accelerator is applied. This is what might be called an "oversteer" set-up, which allows turning to be controlled to some degree by acceleration. It can be achieved by using a 2-way LSD, and adjusting the balance of braking power between the front and rear.

Understeer and oversteer countermeasures can be approached in the same way on gravel as on paved roads. Ride height depends entirely on the road surface - lower is still better, but bumps, rocks and other obstructions mean a higher risk of damaging the car. On courses with jumps, the aerodynamics should be balanced so that the car maintains a good position when airborne. Engines should be tuned for maximum response rather than maximum power.

Generally speaking, achieving good speed on gravel uses the same set of driving techniques as on the track.

Suggested Suspension Settings

		FRONT	REAR
Ride Height		High	High
Shock Absorber	Extension	Strong	Strong
	Compression	Strong	Strong
Spring Rate		Stiff	Stiff
Wheel Alignment	Toe Angle	In	0
	Camber Angle	Negative	Negative
Anti-Sway Bar		Weak	Stiff

※ Depending on the car, these settings may not be possible.

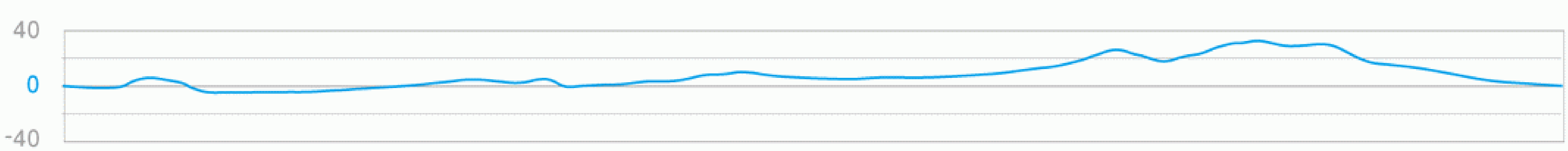
NEXT P194➡


TOYOTA
TOYOTA
TOYOTA
TOYOTA
WILLOW
TOYOTA
GOODYEAR

Ascari Full Track | Spain

Attention has been taken to preserve the natural landscape, even on the track. The curbs are natural in color, instead of the customary red and white.

Overall Length : 5425m	Elevation change : 38.56m	Longest straight : 470m	Number of corners : 26



Ascari Full Track

Spain's longest racetrack with a variety of challenging corners

The track was named after the legendary former F1 champion, Alberto Ascari. It's the center point of "Ascari Race Resort," a full scale automotive enthusiast facility located 10 minutes from the center of Ronda, a historic town in southern Spain made famous by its bullfighting arena. Its 26 corners are divided into 13 right handers and 13 left handers, so the layout is very balanced and quite technical in nature. The track design offers corners similar to "Eau Rouge" from Spa and "Copse" from Silverstone.

info An "automotive resort," catering to those who love enthusiast cars

As the name "Race Resort" denotes, the concept of this facility sets itself apart from other circuits. In order to keep the landscape pure, there are no high buildings, such as a control tower. Currently no championship races are held here, and only club members are permitted to enter the premises. This type of exclusivity invites testing and media events by car makers.

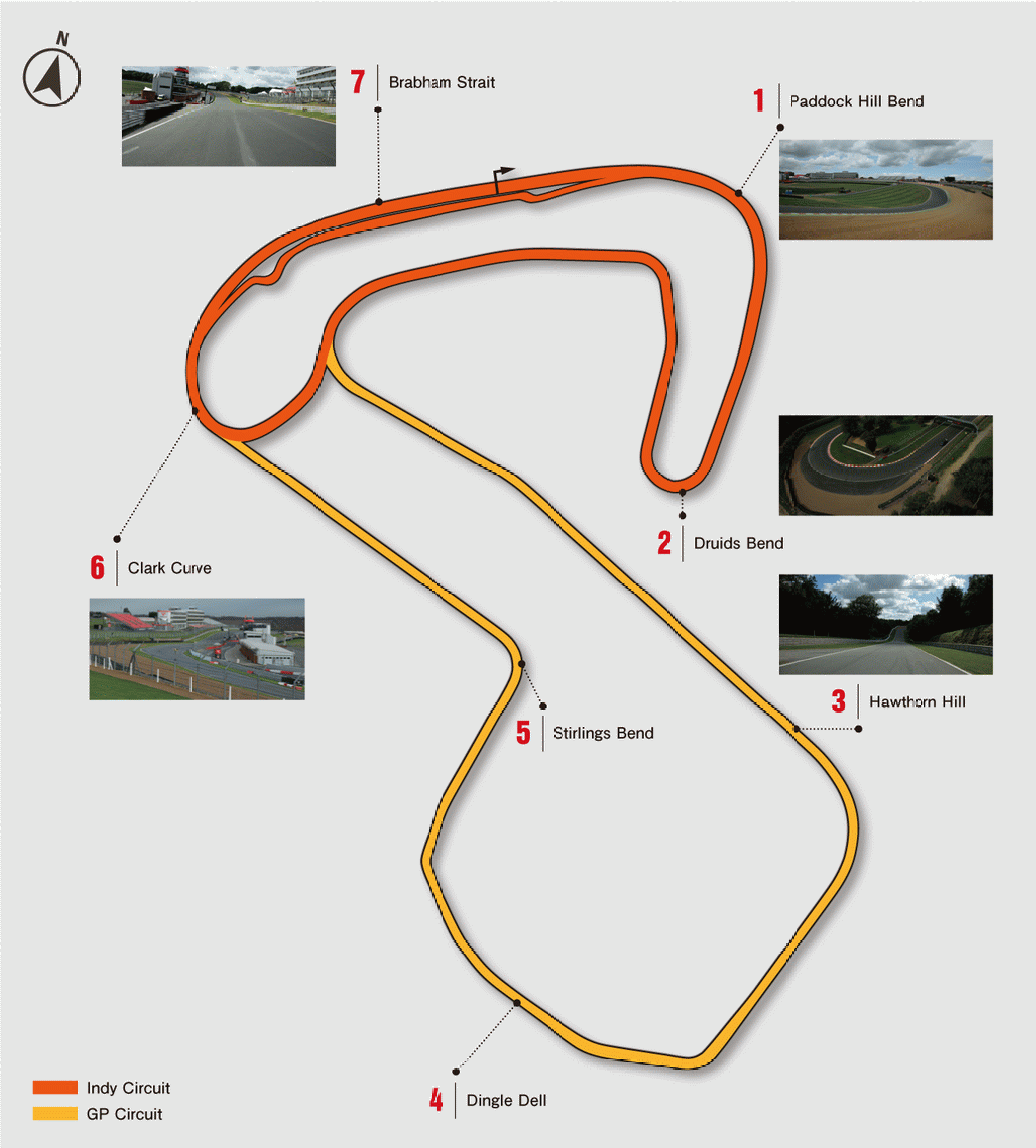
Typical of a South European resort, the outer walls of the buildings within the facility are all white. Next to the restaurant is a pool with an entire view of the track. Here you are able to experience an automotive getaway that no other circuit can provide.

From Seville Airport, drive through Seville and head south on A-376, then A-375, A-384 and A367 until arriving at Ronda. The track is 10 minutes from Ronda with a total travel time of about 1.5 hrs. It is also possible to access the track from Gibraltar airport.

Corresponding list

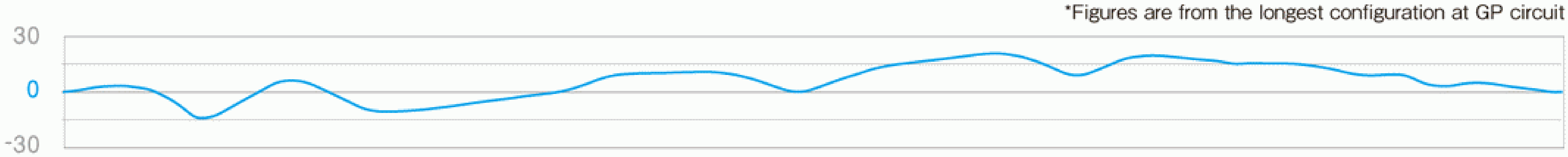
1	Strating Straight	The straightaway that sets up the racing line. This straight ends with a chicane.
2	Cops Corner Silverstone	This section is named after the famous corner from Silverstone. Although it's not an exact duplicate, the high-speed characteristic of this corner is identical.
3	Eau Rouge Spa	A rhythmic series of corners with ups and downs. This section closely resembles the "Eau Rouge" at Spa.
4	Daytona Banking 17° Daytona	This high-speed section is inspired by the banked sweeper at Daytona, characterized by its insane 17-degree embankment.

Brands Hatch | United Kingdom



Overall Length : 3916m	Elevation change : 35m	Longest straight : 475m	Number of corners : 9

*Figures are from the longest configuration at GP circuit



Brands Hatch

A technical course with deep-rooted history and lots of undulations.

Located in Kent, about 30km southeast of London, Brands Hatch is surrounded by the luscious green English countryside. Brands Hatch has been holding auto racing events since 1950. It's a challenging high-speed course, with tricky mid- to high-speed corners, lots of up-and-downs and a narrow track width. There are two configurations: the GP Circuit that runs through the deep forest; and the Indy Circuit that takes a shortcut from Turn 4 called "Surtees" to the last corner, dubbed "Clark Curve."

info For British race enthusiasts, this is where the "heart" of British racing resides.

Each section of Brand Hatch pays homage to legendary British race drivers...an appropriate dedication as this track has played a vital role in the history of British motorsports. Many famous battles have been fought on this track and many racers still call this place their home track.

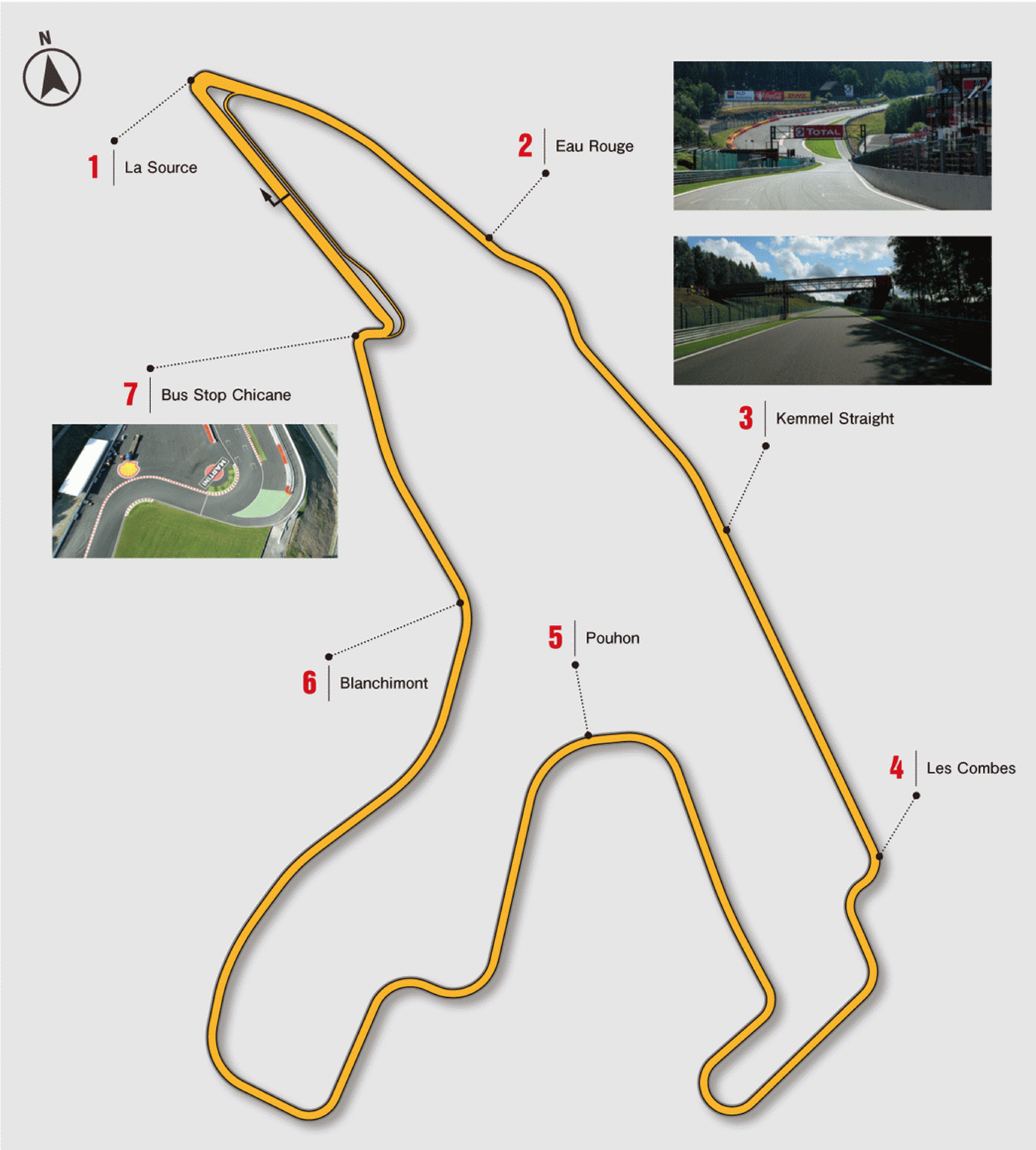
Paddock Hill Bend is full of hospitality events during race week, but when there is no event, it's usually filled with local racers, young and old--a testament to the notion that car enthusiasm knows no age limits and is truly universal.

The commute from Victoria Station in London to Swanley Station is approximately 1 hour. The distance from the Swanley city center to the race track is 8km and easily reached via bus or taxi.

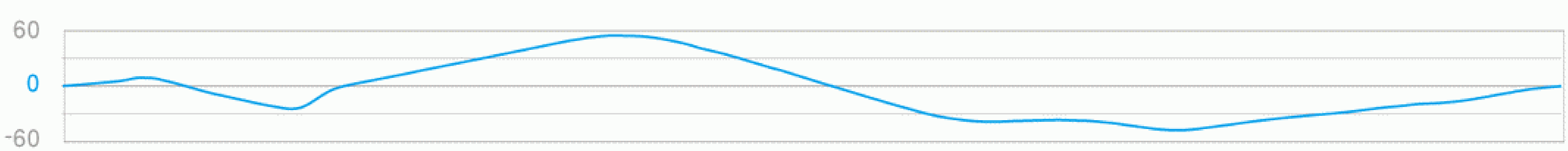
Corresponding list

1	Paddock Hill Bend	The Brabham Straight that climbs up and then falls downhill into the first turn. The section requires skills and courage.
2	Druids Bend	This hairpin corner comes after descending the hill and climbing up again after the first turn. It is a completely blind corner that results in many crashes.
3	Hawthorn Hill	This downhill straight stretches through the forest and is the best overtaking spot on the course.
4	Dingle Dell	This is a very high-speed corner. Mastering this section is a challenge as the exit is blind and hitting the apex is extremely difficult.
5	Stirlings Bend	This section is named after the legendary driver, Stirling Moss. After passing here, the exit to the forest becomes visible.
6	Clark Curve	This last corner bends big to the right. Since the entrance and exit elevation varies, gear selection becomes the key to success here.
7	Brabham Strait	The front straight. A unique characteristic that it is banked towards the pits.

Circuit de Spa-Francorchamps | Belgium



Overall Length : 7004m	Elevation change : 104m	Longest straight : 751.8m	Number of corners : 21



Circuit de Spa-Francorchamps

A world class high-speed technical circuit with dynamic elevation changes.

Spa-Francorchamps is a world class high-speed technical circuit located in the Ardennes, Belgium, near the German border. The circuit is famous for its long full-throttle straights and mid- to high-speed corners that dissect the hilly terrain with elevations changes of up to 104m. The famous Eau Rouge is a steep hill that defines Spa. The dramatic elevation difference creates unstable weather conditions, which resulted in the term, “Spa Weather.” In order to win at Spa, you not only need skill, but luck is also usually required.

info Take advantage of the surrounding nature when visiting this track.

One of the appeals of Spa-Francorchamps is the backdrop, a scenic mountain terrain. As the name implies, there are many natural spas located in the nearby towns, making it a popular destination for European vacationers. By driving just 15 minutes from the track, you're treated to a wondrous view of the High Fens, which is completely different than that of the forest of Ardennes.

The wetlands of High Fens (French: Hautes Fegnes) were created by ancient glaciers. The area is a nature reserve park with the highest point of Belgium located within its borders. Depending on the weather, you can see Germany or Holland from here.

Spa is located one-and-a half hours by train from Brussels Station, or via a bus from Verviers Central Station. Taking a drive while enjoying the Belgium scenery is also recommended, and since the track is close to the German border, access from Frankfurt is also possible.

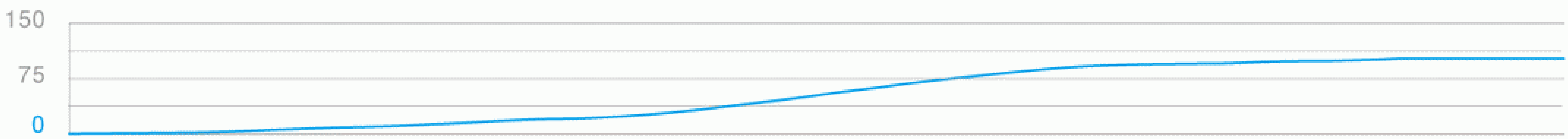
Corresponding list

1	La Source	The first hurdle is this sharp hairpin corner. This sudden braking zone immediately after the start can result in position changes.
2	Eau Rouge	Spa's famous high-speed left-right-left turns with plenty of Gs that leads to a steep uphill drive.
3	Kemmel Straight	This is the longest straight on this track. The top speed here is determined at how well you negotiate Eau Rouge.
4	Les Combes	Here is where the highest point of this circuit is located. After passing this point, you are met by mid- to high-speed downhill sections.
5	Pouhon	A high-speed curve followed by the downhill section. It is important to determine the clipping points as it's a combination of sweepers.
6	Blanchimont	This high-speed section starts from the exit of the Paul Frère curves, which tests the drivers' courage like the Eau Rouge.
7	Bus Stop Chicane	The chicane that requires slowing down the car, even more than at La Source. Braking battles are common and is a famous overtaking point.

Goodwood Hillclimb | United Kingdom

An escape zone after the gate…it doesn't exist. You need skill and guts to get through this section.

Overall Length : 1867m	Elevation change : 92.7m	Longest straight : 360m	Number of corners : 9



Goodwood Hillclimb

The most glamorous time trial stage in the world.

Every July, England plays host to a grand motor racing festival called the Goodwood Festival of Speed. The primary event is a famous hillclimb that takes place on the property of the Earl of March. The 1.16-mile (approximately 1.9km) course is lined with old fashion straw barriers and runs through the property's garden and out to a spacious pasture. Despite its simple layout, the difficulty level is high as the course is extremely narrow. The time of 41.6 seconds set in 1999 by Nick Heidfeld in a McLaren MP4-13 is the course record.

info This is a motorsports festival for all ages

Many think that this festival is only for special people, but in truth, anyone can visit the Goodwood Festival of Speed by just purchasing a ticket. Many bring their families, packing a picnic basket and folding chairs to enjoy the day. And because many race drivers casually walk around the grounds, meeting your favorite driver is entirely possible.

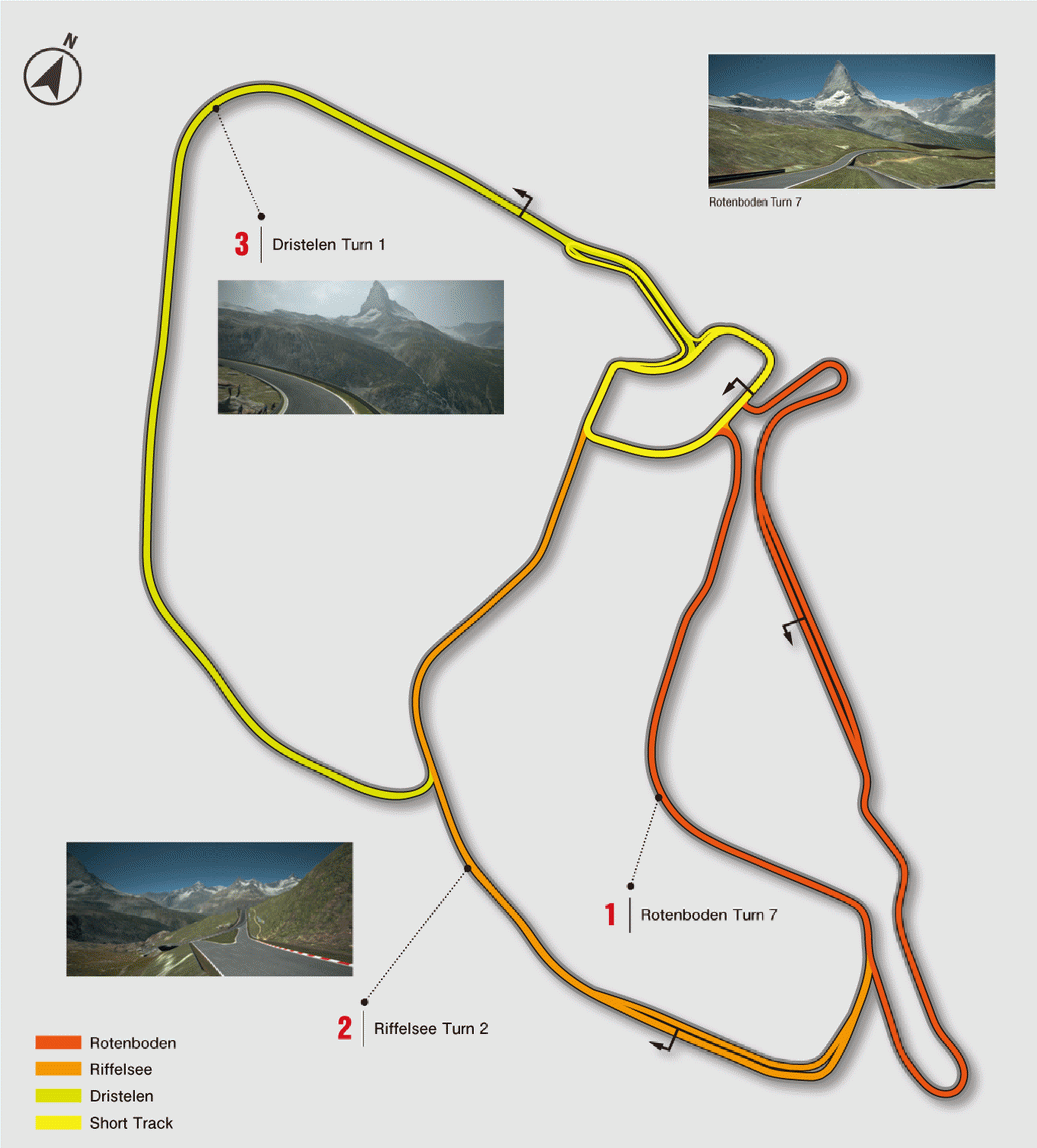
Car makers display their latest models and most historic cars, but at times, there some oddities like this one. It looks like a bed, but it is a registered automobile that's legal to drive on public roads.

From Victoria Station in London to Chichester Station is a 90 minute-ride with one transfer. During events, there are shuttle buses from the station to the Goodwood grounds. It is only few minutes by foot from the shuttle drop off point to the track.

Corresponding list

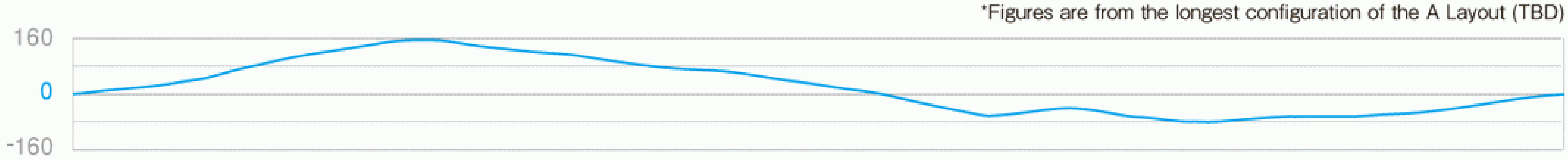
1	Park Straight	The Goodwood House is visible from the start line, underneath the trees to the open air straightaway.
2	Molecomb Corner	This left-hand turn after the straight is gradual, but the road is narrow with virtually no escape zone. The driver's courage is tested.
3	The Flint Wall	This section involves left to right corners like a chicane, with an auspiciously placed brick wall that makes it a completely blind corner.

Matterhorn | Switzerland



Overall length : 3577.8m	Elevation change : 236m	Longest straight : 415m	Number of corners : 15

*Figures are from the longest configuration of the A Layout (TBD)



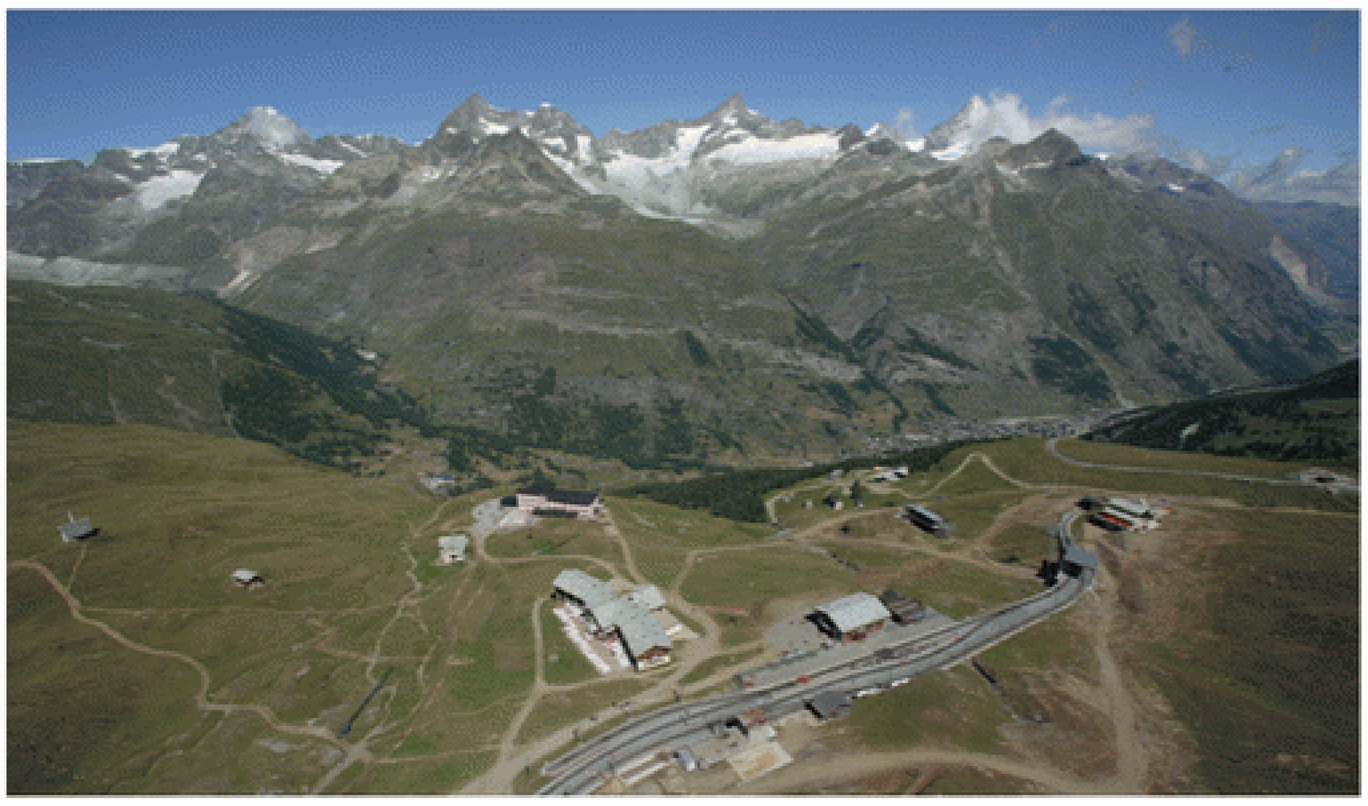
Matterhorn

A course challenging the majestic 4000m mountain range

The majestic Swiss Alps and the daunting 3000m peak of the Matterhorn serve as the backdrop for this original course, located near the famous Gornergrat station. The course is comprised of a long full-throttle section and high-speed corners making it very technical in character. The transitions from its high-speed section and mid- to low-speed corners are noteworthy. The course itself is wide, but because this is a mountainous course, there are plenty of blind corners and steep slopes. It's a different animal than a customary road course with plenty of unique challenges.

info A majestic view of the world beyond the forest limits.

The course is located in the Riffelberg and Rotenborden area, which is well over 2500m above sea level. It is also a central location for travelers enjoying the Alps' great outdoors. Ski is a way of life in the Alps, but if you would like to enjoy the various high mountain foliage such as those found in the Edelweiss, wild animals, and the majestic view from the high elevations, it is recommended to travel during the spring and summer hiking seasons.



The Gornergrat Bahn starting at Zermatt and ending at Gornergrat takes about 30 minutes during which it spans across elevations peaking at 1400m. A majestic view granted by the high elevations of the surrounding area can be seen out of the forest prior to reaching Riffelberg.

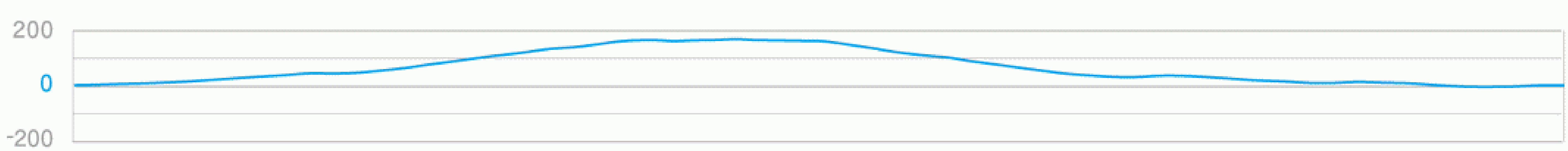
It takes about 4 hours from Geneva Cointrin International Airport or Zurich Airport to get to Zermatt station, the starting station of Gornergrat Bahn. From there it takes about 20 minutes to Riffelberg. Note that Zermatt restricts entry of vehicles with internal-combustion engines.

Corresponding list

1	Rotenboden Turn 7	This downhill section comes from around the Rotenboden Station. There are plenty of tight corners, with a high-speed sweeper mixed in to keep you on your toes.
2	Riffelsee Turn 2	The end of the downhill section is met with a rollercoaster-like rise towards Riffelberg.
3	Dristelen Turn 1	This high-speed corner heads towards the Matterhorn. The key here is to use the bank. Don't let the beauty of the landscape distract you.

Mount Panorama Motor Racing Circuit | Australia

Overall length : 6213m	Elevation change : 174m	Longest straight : 1916m	Number of corners : 23



Mount Panorama Motor Racing Circuit

A famous racing track in Australia which uses public roads

In Bathurst, located in New South Wales, Australia, lies the Mount Panorama Motor Racing Circuit track, known for the “Bathurst 1000” and other popular major events. A unique feature is that it uses public roads, with the track situated over the hills. Although there’s a long full throttle section in the early and latter part of the course, the other sections have extreme up-downs and repeated blind corners. It can be said that the tricky features distinct to this course serves as its greatest appeal.

info Enjoy the best scenery in Bathurst.

As the name states, the views from the mountainous landscape is part of its charm. It is normally used as a public road and regularly used a walking/jogging spot by both young and older residents. If you happen to drive through here, watch your speed as the normal speed limit here is 60 km/h, and the police are always looking to bust anyone exceeding the posted limit.

The area around Brock’s Skyline is a famous spot for the locals where one can enjoy the marvelous views of Bathurst city. Many locals visit the area throughout the day, but of note are the night views here. Many drive and gather here to enjoy the evening vistas.

Located 200km west from Sydney, travel on Barrier Highway (Route A-32) for about 3 hours to arrive at Bathurst. If going by air, use the regular flight service provided by Regional Express at Sydney for access to the site in about 50 minutes.

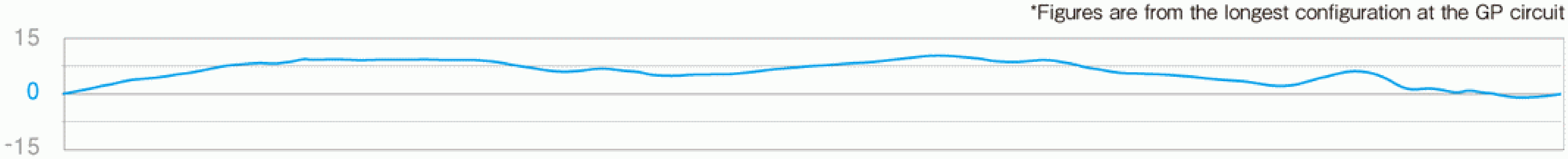
Corresponding list

1	Hell Corner	This left-hand corner appears immediately after start. The sharp corner is a feature that's akin to a turn on a public road, where the course has its foundation.
2	Mountain Straight	This long full-throttle straight appears in the early part of the course. As its name states, it is a straight heading towards the side of the mountain.
3	Brock's Skyline	A section named after the legendary driver, Peter Brock. The expansive view on the right is a highlight in itself.
4	The Dipper	This is the most difficult section of the course. Repeated blind corners with its narrow roads resemble that of the Nürburgring.
5	Forrest's Elbow	The end of the hilled section of the course features a corner named after the crash by the motorcycle racer, Jack Forrest.
6	Conrod Straight	This long straight undulates after coming down a steep hill. Maximum speed can easily surpass 300 km/h.
7	The Chase	This chicane built for the 1987 World Touring Car Championship drops vehicle speed drastically, as racers head towards the final corner.

Silverstone Circuit | United Kingdom

Overall length : 5891m	Elevation change : 11.34m	Longest straight : 789m	Number of corners : 18

*Figures are from the longest configuration at the GP circuit



Silverstone Circuit

A traditional racing track with more than 65 years of history.

Silverstone Circuit was opened in 1948 on the site of a Royal Air Force airfield. In 1950, the first F1 Grand Prix, the British GP, was held here. Since then, the racing course has been historically noted as being the birthplace of motor sports. Recently, despite the course going through improvements, which has made it more technical, its reputation and characteristic as a high-speed track remains intact. Three different layouts are used in the game: the National Circuit using the northern section, the International Circuit using the southern section, and both sections combined as the Grand Prix Circuit.

info Silverstone, the origin connecting virtual with reality

Since the start of the GT Academy program, Silverstone has served as the stage for the final selection where the top player of Gran Turismo is given a chance to become a professional race driver. It has been six years since first competition in 2008, and Silverstone has since become sacred ground for race racers and Gran Turismo players alike.

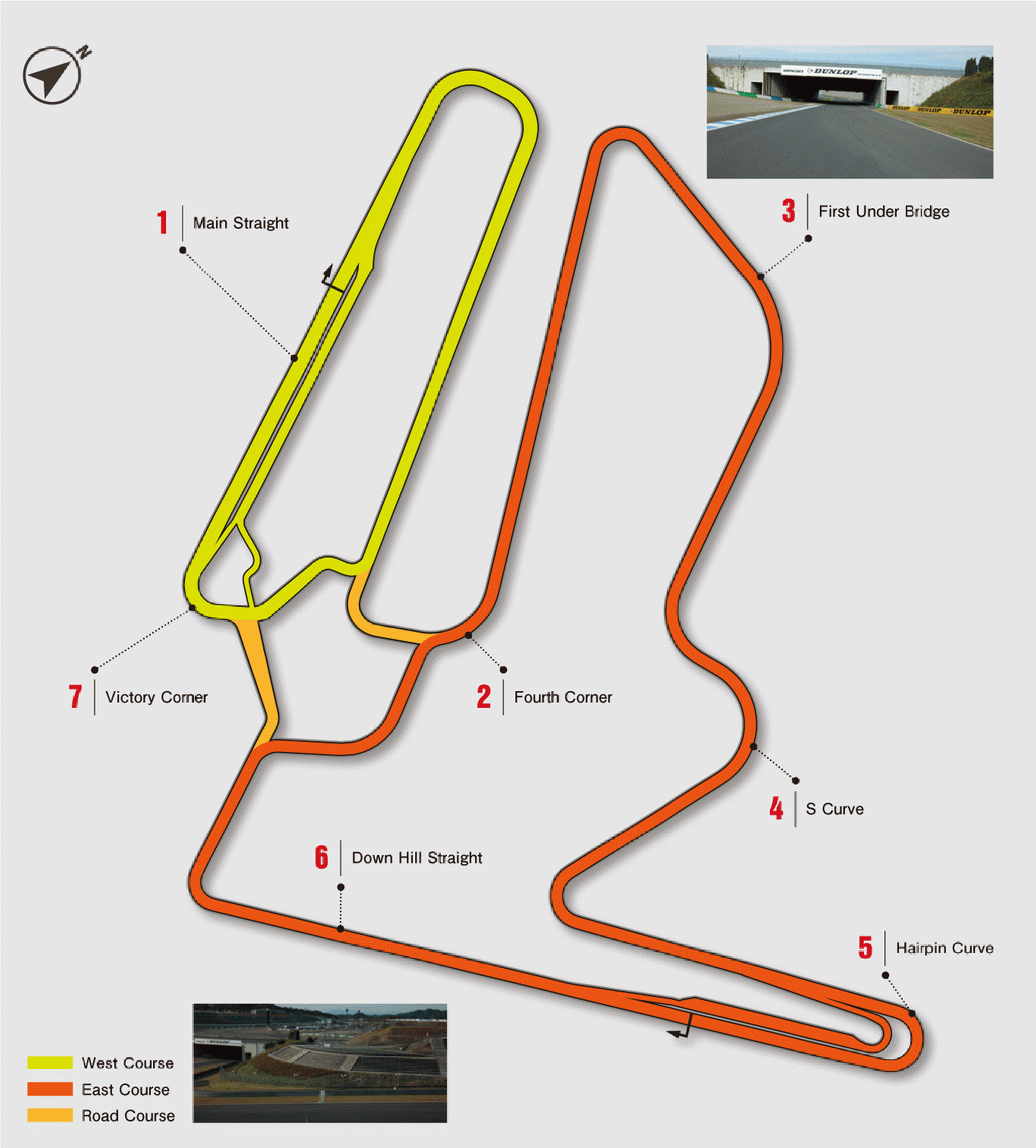
The scene at Silverstone for the Finals of the GT Academy. Aside from driving techniques, various aspects of the racers' potential are measured, including their physical fitness, leadership qualities, communication capabilities and, of course, driving ability.

Take the train from Euston Station to Northampton Station, which takes about an hour. Then, it's about another 30 minutes by taxi. Note that during race week, the traffic around Silverstone is congested, so it is recommended to have ample time for access.

Corresponding list

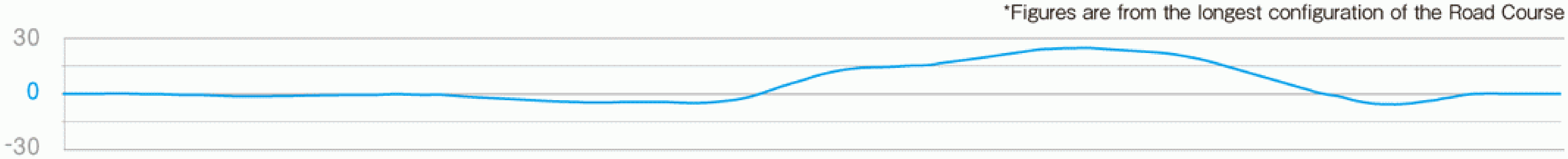
1	International Pits Straight	After improvements have been made, this has become the front straight. In view is the newest hospitality paddock, "The Silverstone Wing."
2	Wellington Straight	This new straight was the product from the improvements made to the track. At the end is a sharp curve that's an ideal spot for overtaking.
3	Copse Corner	With the change in the racing line, this super high-speed corner now has an even greater entry speed. Racers will be tasked to clear the corner at full wick.
4	Maggotts - Becketts - Chapel Curve	The consecutive S-curves are said to hold the key to victory at the Silverstone Circuit. The difficulty level here is perhaps tops in the world.
5	Hanger Straight	The longest straight of the Silverstone Circuit stretches about 800m. The course is also wide, allowing for aggressive passing maneuvers.
6	Stowe	Similar to Copse Corner, there is a long straight after the corner, but braking is necessary. Getting through the apex takes patience, making it a difficult corner to master.
7	Club	This blind corner has a gentle reverse bank. After the renovations to the track were made, this has become the final turn.

Twin Ring Motegi Road Course | Japan



Overall length : 4801m	Elevation change : 30.4m	Longest straight : 762m	Number of corners : 14

*Figures are from the longest configuration of the Road Course



Twin Ring Motegi Road Course

The second international race course for Honda

Twin Ring Motegi Road Course is an international standard racing course created by Honda in 1997. The European-style road course utilizes a stop-and-go speed control layout and has a very different track personality in comparison to Honda's Suzuka Circuit course. By using the short cuts, there are 3 course layouts: the East Course, West Course, and the longest of them all, the Road Course. The highlight of the course is the downhill straight coming down the steep slope heading towards the angled 90 degree corner. The braking techniques displayed here are fierce.

info A message from motor sports to those affected by the Great Northeast Japan earthquake.

The Great Northeast Earthquake is still fresh in everyone's minds. Of all of Japan's major international race tracks, this course is located closest to the disaster site and was severely damaged from the tremor. But, within the same year, the track was repaired. With the slogan, "Let's Go! Japan", Motegi was back in business again. Thereafter, recovery events are held continuously, and the location has become a symbol of the recovery efforts from the earthquake within Japan's motorsports.

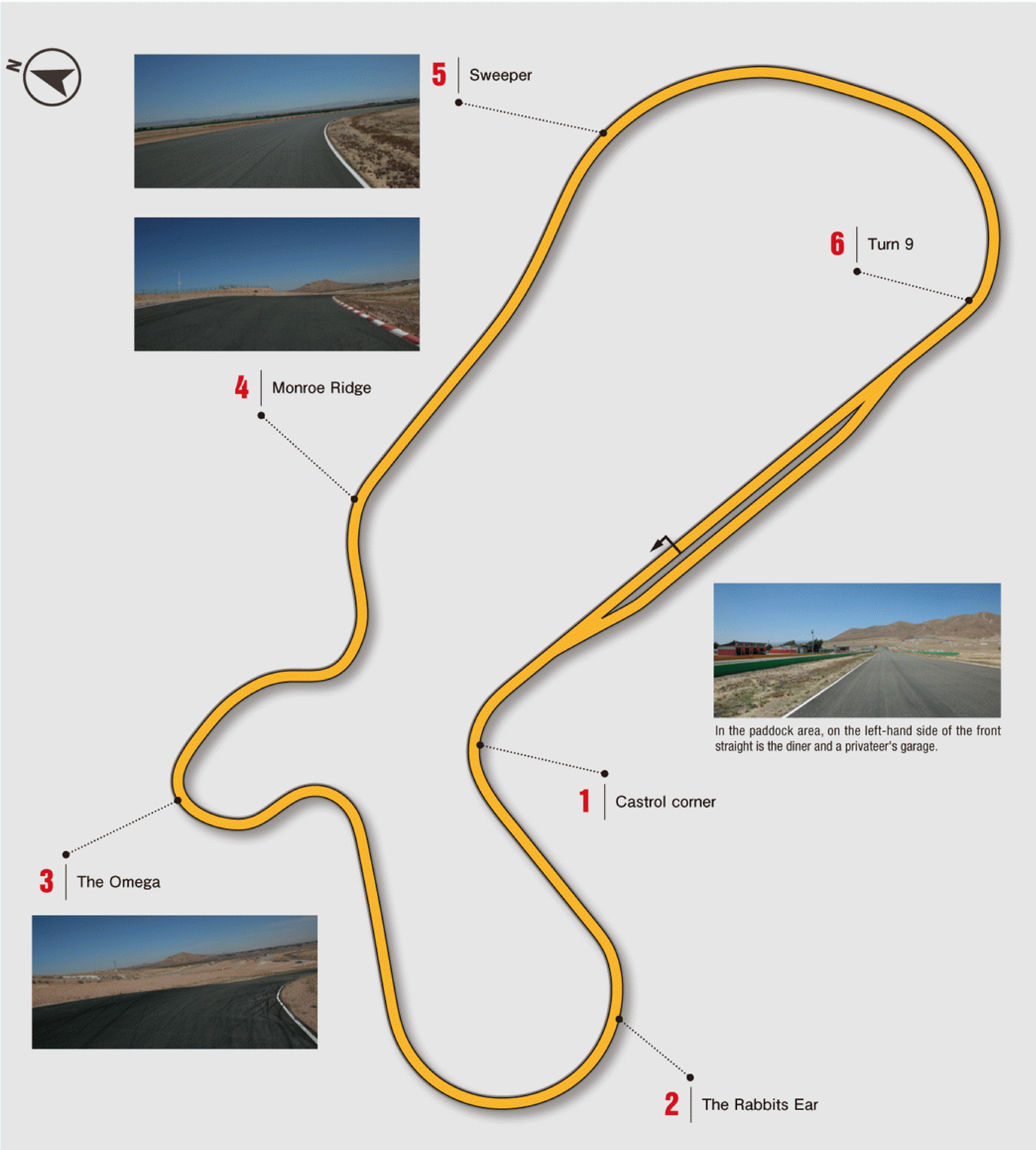
A slogan found hanging on the control line of the road course reads がんばろう!日本, which means "Let's go! Japan," in reference to the Great Northeast Earthquake. With the circuit located close to the source of the disaster site, these words provided courage and hope to all motorsports fans in Japan.

If starting in Tokyo, the most convenient way to get to Motegi is to take the bullet train to Utsunomiya, about a 50-minute ride. From there, it will be another 90 minutes by bus. It could be faster using a taxi, the fee will be much more expensive. Also, it gets quite congested during race events, so give yourself ample time to get there.

Corresponding list

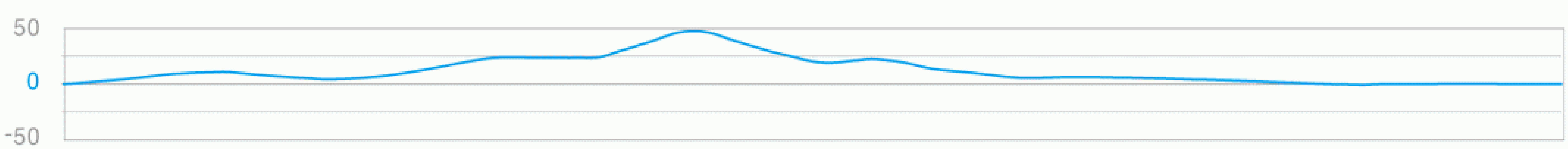
1	Main Straight	The front straight is the prominent feature of the circuit. Towards the back is a challenging section that's comprised of two consecutive corners.
2	Fourth Corner	The combination of turns here is made up of corners 3 and 4. But, the R is much stronger.
3	First Under Bridge	Near the tight 5th corner of the road course is where the two tracks at Motegi come together. As you enter the turn, the Super Speedway is directly overhead.
4	S Curve	This S-shaped corner has a strong left-right transition; therefore, instead of going in at full speed, finding the shortest distance through the section is the key to going fast.
5	Hairpin Curve	Because this corner is located at the top of the ascent, braking is not very difficult. Make sure to carefully clip the apex to get good speed onto the straight that follows.
6	Down Hill Straight	The longest straight of the course descends as it leads into a right hand corner. Thus, it makes for an ideal overtaking point.
7	Victory Corner	This chicane-like final corner is composed of two consecutive left corners with one right corner.

Willow Springs International Raceway Big Willow | USA



In the paddock area, on the left-hand side of the front straight is the diner and a privateer's garage.

Overall length : 3951m	Elevation change : 50m	Longest straight : 756m	Number of corners : 10



Willow Springs International Raceway -Big Willow

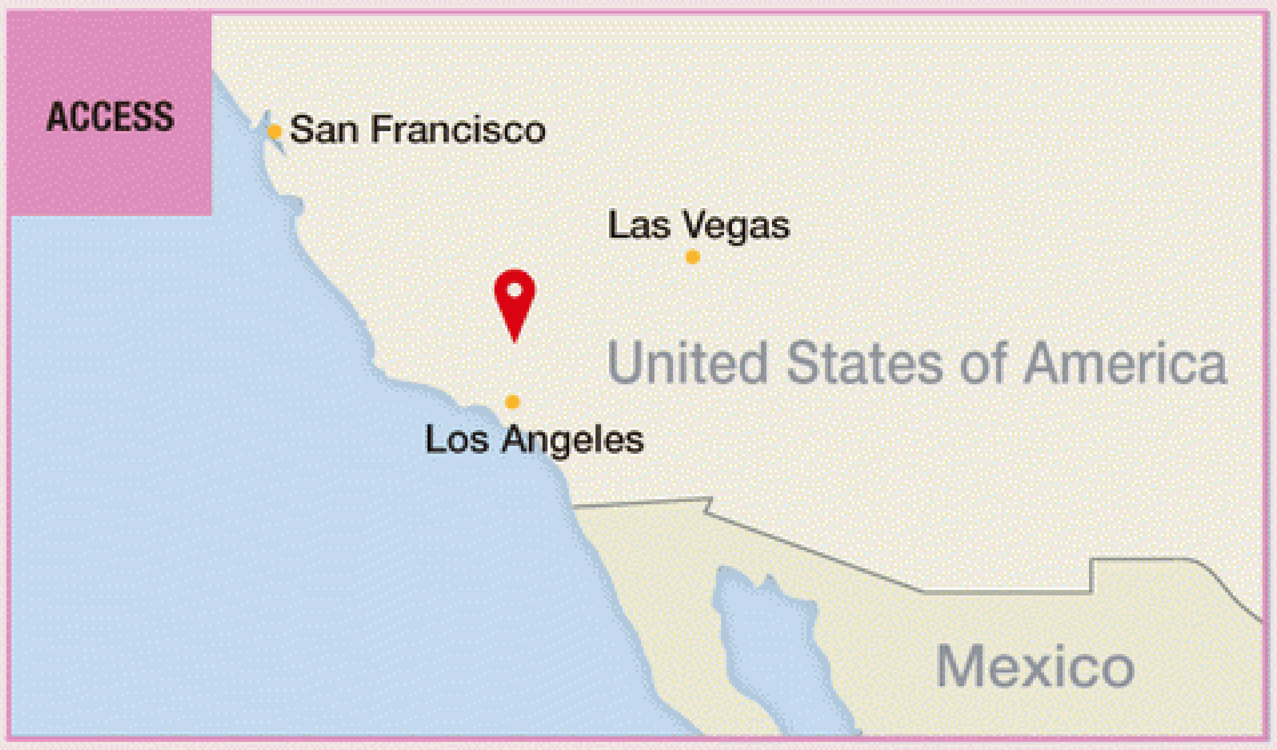
A high speed course utilizing the surrounding environment to create extreme undulations and high-speed corners.

Founded in 1953, the nostalgic race track Willow Springs International Raceway sits in the desert near Los Angeles. Among the various courses found here is the main course dubbed Big Willow, a 2.5-mile (approximately 4 km) high-speed road course characterized by mid- and high-speed corners. At first glance the course seems simple, but with many long sweepers, maintaining precise speed control proves quite difficult. Add to the formula severe elevation changes, and you have a track that maybe is the scariest of any in the country. Keeping the car in full control at high speed is the key to mastering this track.

info The sacred grounds of U.S. grassroots racing

Family owned and managed, Willow Springs has an idyllic and serene ambiance. Although the staff is small, everyone is very friendly and helpful. There are a number of privateers with garages within the premises who have a habit of conversing with the visitors here. Talking about their pet car project is a subject of conversation and enjoyment.

The air-conditioned paddock and diner is a hidden gem of the course and a great place to avoid the scorching heat. The food here is typical American fare: a hearty, delicious meal that won't break the budget.



The most convenient access is by car. From Los Angeles International Airport, go north on I-405 and connect to I-5 and then to State Route to arrive in Rosamond in about 90 minutes. Another 5 km and you will arrive at the circuit.

Corresponding list

1	Castrol corner	The left-hander that follows the front straight represents the highly technical aspect of the race track.
2	The Rabbits Ear	As its name states, this section resembles the shape of a rabbit's ear. The long sweeping nature of this corner makes determining the proper clipping point vital.
3	The Omega	The part represents the mid-point of the technical section and is also the primary feature of the course. The vast scenery which unfolds from the downhill turn is spectacular.
4	Monroe Ridge	The view is partially obstructed by the undulations, but taking the proper racing line through this important corner will translate to speed on the high speed section.
5	Sweeper	A very high-speed corner that holds the key to mastering this tricky track. Go fast here, and you might become a local legend among the locals.
6	Turn 9	The final corner, at first glance looks simple, but due to the tight nature of the exit, taking and staying on the proper racing line here is difficult.

Willow Springs International Raceway; Streets of Willow | USA

Overall length : 2675m	Elevation change : 20m	Longest straight : 395m	Number of corners : 14

Willow Springs International Raceway -Streets of Willow

A technical track with all types of corners

This is a short course, measuring 1.6 miles (roughly 2.6 km) located on the north side of Big Willow. It often sees use as a test course and plays host to a variety of "track day" events—few competitive races are run here. The layout is very technical, and with the exception of two short straights where you can go flat out, most of the track consists of low- to medium-speed corners coming one after another. It's short in overall length, but it's nonetheless quite challenging, highlighted by a range of different turns, from simple sweepers to difficult combination corners. With all the variety of corners, it's an ideal place to hone your driving skills.

info A sandstorm in the Mohave Desert, featured in many Hollywood movies.

Regardless of the season, the strong wind and severe sunlight of the desert reminds you of how brutal Mother Nature can be. At this race track, you can get a sample of these harsh elements. There are sandstorms here too—and seeing great clouds of sand approaching from afar is a frightening sight indeed. But a few times a year, Mohave gets a bit of rain, and during years when there has been a significant amount of rainfall, the hills surrounding the track become vibrant with a green hue, making the scenery very different.

Willow Spring Raceway is located in the middle of the Mohave Desert, which has served as the set for the movie Baghdad Café. As you drive to the race track, the view from the freeway makes it feel like you're in the middle of a giant movie set.

Getting to this track is basically the same as "Big Willow," mentioned in the previous page. That said, you can take an alternate route by going straight up I-5 North until you pass the mountains, and then take side roads along State Route 138. This way, you'll be able to enjoy the great American countryside on your commute.

Corresponding list

1	Turn 2	There is at least a 10-meter elevation change in the first few corners, making the up-and-down nature of the track quite severe. After the road shown here is a tricky downhill left-hander.
2	Turn 4	This part of the track is highlighted by a sharp uphill hairpin turn. The rough driving surface here makes it difficult to keep the car stable.
3	The Bowl	Dubbed the "bowl," this famous sweeper features a 20-degree banking.
4	Turn 11	For this quick left-hander that follows a long straight, be sure to demonstrate steady brake control after the gradual S curves.
5	Turn 14	This turn is characterized by its expanse nature, looking and acting like a giant skidpad. For races, cones are placed to make it act like a "normal" corner.

The Gran Turismo Magazine
Beyond the Apex

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Graphic Design
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Technical Illustration
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Pictures
HKS CO., LTD.
GTA Co., Ltd.
Software Cradle Co., Ltd.
Toyota Motor Corporation
Nissan Motor Co., Ltd
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