THE GUIDING FORCE

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I. THE LAWS OF CIRCULAR MOTION

The laws of circular motion were discovered and formulated by the English mathematician and physicist Isaac Newton (1642 - 1727).

These laws are universal and allow any kind of movement to be described.

Principle of inertia

'*A moving mass on which no force acts, describes a perfectly rectilinear trajectory*.'

The concept of force is deduced from this principle.

Force concept

'*A force refers at any cause capable of deflecting the trajectory of a mass.*'

Principle of reciprocity

'*Any mass on which a force is acting, simultaneously exerts a reciprocal action equal in magnitude, but opposite in direction.*'

How to apply these laws in the case of a land vehicle describing a circular path?

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II. GUIDING FORCE: THE TRUE DEFINITION

In another ADILCA document (‘*centrifugal force*’), we have shown that the centrifugal force was only an imaginary force, the only force to be considered when the car describes a circular path being the guiding force.

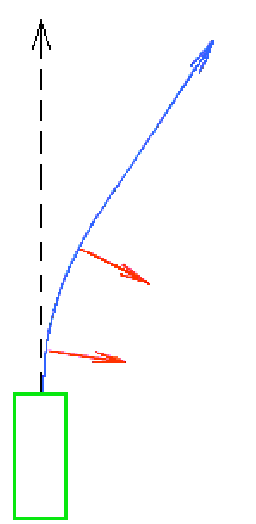
Some specifications are now necessary as new questions arise. For example: what is a force, in the physical sense of the term? How to visualize a transverse force? Where does the guiding force come from and how to represent it? What is the true nature of the guiding force? With what formula can we express it? And what does it change, concretely? These are the questions we shall answer here.

A fundamental principle!

Three centuries ago, a physicist by the name of Isaac Newton decided to reconsider physics and formulated the universal laws of motion.

Among other fundamental laws, the Newton’s *principle of inertia*: ‘*The natural trajectory of a moving mass is rectilinear. To deflect this trajectory there must be a cause, that is to say a force.*’

The precise definition of this term therefore follows from the previous law: ‘*A force is any cause able to deflect the trajectory of a mass.*’



Newton's law: to deflect a mass from its path,
one must apply a transverse force, represented by a red arrow.

How to visualize a force?

Let us observe a child pulling a toy along with a string. The tension of the string and the movement of the toy perfectly illustrate the concept of force.

In this case, it is a drive force, but the reasoning is also true for a circular path because according to Newton's law of motion, such a path results from the action of a transverse force.

To visualize this type of force, one only needs first to imagine the toy moving along a straight path, then to suppose that an invisible hand pulls on the string transversely to deflect the path.

Automotive applications

Does this concept apply to cars? We all know from experience that the normal trajectory of a car is a straight line, it is a practical verification of Newton's law.

Taking a turn is not all that obvious. If the driver wants to steer the car properly, he must apply a transverse force which deflects the initially straight trajectory.

Obviously, there is no invisible hand or string, the driver simply turns the wheel. So what is the phenomenon involved in this operation?

The wheels of the shopping trolley

When the driver operates the wheel, he causes pivoting of the steered wheels, so it is through these that this mysterious force manifests itself. How? A trivial observation will help us understand the principle.

Have you ever noticed how difficult it is to push a shopping trolley if one of the wheels is not perfectly aligned? The erratic path of the trolley is due to the unexpected force the misaligned wheel exercises in contact with the floor.

…and those of the car…

The same principle enables the driver to steer the car. The rotation of the wheel causes pivoting of the steered wheels, and, with it a transverse force exerted by the tire in contact with the road.

This force is called the guiding force. It is through this principle that the driver can deflect the path of the car, there is no other force into play on this occasion. The enigma of the circular path is resolved. We must now identify the characteristics of this force.

How to draw a force?

In order to draw a force, the best solution is to draw an arrow, preferably a red one, because this colour symbolizes well the concept of force. But make sure you isolate the different phenomena. You need to picture the situation mentally.

The speed of the car, for example, is a quantity that is supposed to remain constant throughout the turn, it can only vary with the force of traction or braking, so it had better be forgotten! And most importantly, no mixing of concepts!

Remember that adding two vectors representing quantities of different natures is strictly prohibited! You cannot mix apples and oranges, forces and paths! In other words, on a drawing meant to represent a force, it is not advisable to include anything else, such as a path, for example, except as a dotted line or using a different colour.

In any case, there is no need to add or overload the drawing as only one force is needed to make the car run! Just choose the right one and orientate it correctly.

Make a clean sweep of the past...

That is not all! Brainwashing is essential!

You must throw overboard everything that has been said on the subject for so many years, especially those famous wacky descriptions that clutter our minds and which everyone tries to hang onto out of habit, laziness or ignorance.

You must make a clean sweep of the past. Too bad for the sorcerer's apprentice who juggled forces, concepts and reference frames the way one plays with a grenade without pin.

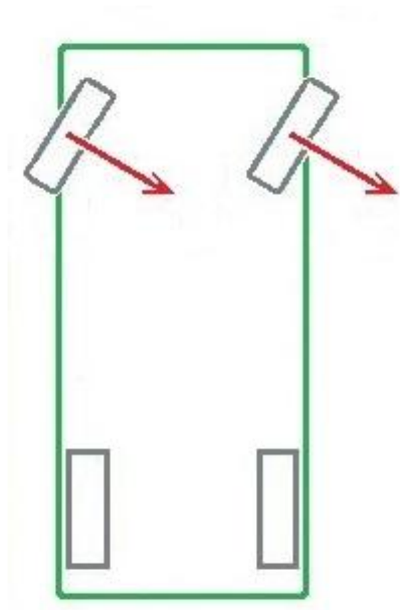
Indeed, if descriptions are not lacking, they all have one thing in common: they conceal the only force that really exists!

Here is the guiding force!

Time for a drawing now!

The force that deflects the trajectory of the car originates at the ground contact point of the two steered wheels. It is represented by an arrow perpendicular to the plane of rotation of the wheels, orientated towards the inside of the bend, i.e. to the side where the car is deflected.

There is nothing else to add, except for the role of the rear wheels: as they prevent the car from turning on itself, they participate in the lateral acceleration of the center of mass. No other force is needed to describe the circular motion of the car.

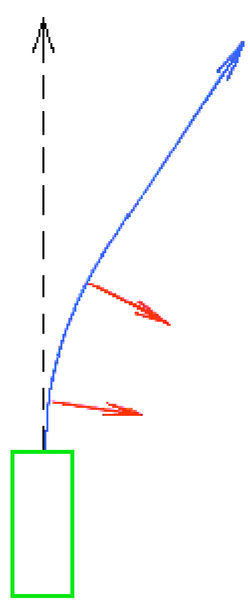


The guiding force originates on the steered wheels upon contact with the ground.

A little tip to make sure...

No real scientific description without verification!

How to check the validity of a drawing? It is very simple, and only requires a little common sense and a stretch of the imagination by replacing mentally the arrow supposed to represent a force with a string on which an invisible hand pulls.



To visualize a force, replace the red arrow with a string on which one pulls!

If the drawing is correct, the imaginary movement reflects a path deflection as we could observe in the field!

And while you are at it, you may also use this tip to test the drawings that pass through your hands. You will be surprised! No need for heavy scientific demonstration, you will tell immediately whether the description makes sense...

Guiding force and centripetal force

One question needs to be answered: what is the true nature of the guiding force? Is it centripetal?

<u>First evidence</u>: centripetal means '*which brings closer to the center*', this center being that of the circle that describes the car. Obviously, the car never takes the path, it never approaches, it is only deviated from a straight path.

<u>Second evidence</u>: the centripetal force acts on a center of mass while the guiding force is exerted on the periphery of the tires. One attracts, the other deviates. Let's remember that it is impossible to exert the slightest force on any center of mass whatsoever.

Logically, only a force acting at a distance on two centers of mass can be described as centripetal, but there are only two that meet this criterion: the electromagnetic force and the gravitational force (see ADILCA file '*centripetal force'*). The guiding force is not the centripetal force!

A contact force

The guiding force is a contact force, of the same kind as that is activated when you take something between your fingers. Just as the pressure on the object, the weight on the wheels is an important factor that determines the intensity of this force, but it is not the only one.

Indeed, contact affinities derived from tiny electrical loads acting at the level of atoms can occur between the tire and the road surface. These affinities allow the tread rubber to exploit the roughness of the road surface.

The so-called 'grip' is the result of this combination of factors. It explains many phenomena that may be a priori incomprehensible: with the same mass on rough ground, wide tires stick better than narrow tires; the grip is better if the wheels roll than if they slide; the braking force can be greater than the weight, etc.

Guiding force: the true definition!

The foregoing leads us to this new and original definition of the guiding force:

'Guiding force refers to any pressing force, contact or friction force able to deflect the trajectory of a vehicle.'

Is it a completely new definition? It is indeed, because we must remember once again that this force, important as it is, activated as it is daily by millions of drivers, is named or described nowhere in the usual works of reference... One would think that physicists did not know that it existed or acted as if it did not!

Guiding force: what correct formula?

How to express the guiding force? Of course, everyone knows the famous formula that is used everywhere, and often indiscriminately:

$$F = M V^2 / R$$

However, not many know that this formula does not express, never expressed and will never express the centrifugal force, but only the guiding force(1)!

Can we demonstrate it mathematically? Yes we can!

And here is how: centrifugal force is a fictitious force which appears only in the context of imaginary descriptions, as is a static description or one which takes the vehicle as a reference frame (see ADILCA documents).

But what characterizes this type of description is the total lack of movement. It is as if nothing moved, as if the mobile was immobile! Under such conditions, the speed is always zero, of course. If you try to apply the formula, the result is surprising:

$$\forall M, \forall R \neq 0, \text{ for } V = 0, F = MV^2/R = 0 / R = 0!...$$

Not to mention the radius of the path which no longer exists either, but is still considered, for want of anything better, as a real non-zero real number! In short, in this kind of description, the formula is strictly inapplicable. Q.E.D.!

In reality, of course, there is no path radius without speed, and speed exists only in the context of an actual description of the movement. Then it works! The formula thus applies if, and only if, one considers a mass (**M**) driven with a speed (**V**) and describing a circular path of radius (**R**).

In other words, the famous formula **F = MV²/R** refers indeed solely to the dynamics, and therefore to the guiding force, but to it alone! Everything is now perfectly clear!

Calculation

Let us now take the example of a car, mass of 3,300 lb (1,500 kg), which describes a circular path of radius 330 ft (100 m) at a speed of 45 mph (20 $m.s^{-1}$).

Let us calculate the intensity of the guiding force that is exerted on the tires of the car in contact with the ground:

$$\mathbf{F = MV^2/R}$$

$$\mathbf{F =} 1{,}500 \times 20^2 / 100 = 6{,}000 \ \mathbf{N}$$

Attention to the units [(2)]!

The limits of the function

Let us study the limits of the function **F = MV²/R** in relation to **R** (radius).

If we consider that a u-turn is a curve with a zero radius, we can, on the basis of the preceding relation, write:

$$\mathbf{F = MV^2/R = MV^2/0 = \infty}$$

We can deduce that a u-turn on the spot is impossible because it would require a guiding force of infinite intensity. Conversely, if we consider that a straight line is a curve of infinite radius, we can, on the basis of the preceding relation, write:

$$\mathbf{F = MV^2/R = MV^2/\infty = 0}$$

We can deduce that the rectilinear trajectory results from a lack of guiding. It is exactly what happens when a car swerves off the road: if the guiding force is insufficient or absent, the car describes or goes back into a straight path.

Let us study now the limits of the function **F = MV²/R** in relation to **V** (speed).

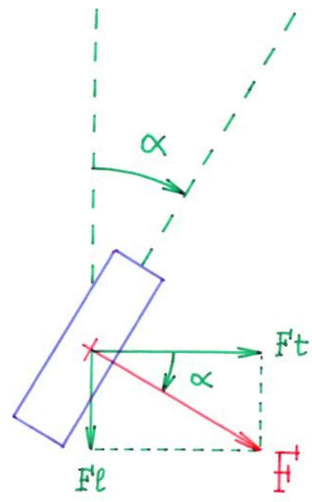
All quantities being equal, we can see that the guiding force must vary in proportion to *the square of the speed*. In other words, the intensity of the guiding force must be doubled when the cornering speed is multiplied only by value $2^{1/2}$ ($2^{1/2} = 1.414$).

The following table summarizes the correlation between the speed of the car and the guiding force necessary to maintain a circular path (the value 1 has been arbitrarily correlated at a speed of 35 mph to serve as a reference):

speed (**mph**)	**35**	**40**	**45**	**50**	**55**
guiding force (**N**)	**1**	**1,3**	**1,7**	**2**	**2,5**

The two components of the guiding force

Because of the pivoting angle of the steered wheels, the guiding force has two components: one is a transverse force, the other is a front-to-back force [(3)].



The components of the guiding force F.
α: pivoting angle of the steered wheels.
F*t*: transverse component.
Fℓ: front-to-back component.

The transverse component makes the car change course [4]. The front-to-back component brakes the car.

The reactions of the car

The guiding force has two components. These two components do not act exactly on the center of mass of the car, but on the tires of the steered wheels in contact with the ground.

The height and the distance between the ground and the center of mass of the car acts as a lever arm, the two components act as a torque.

Thus, when the driver operates the steering control, the mass of the car reacts by a rotational motion around its center of mass [5]:

- Rotation in a horizontal plane, this is the *yaw.* The turn makes the car change course.

- Rotation in a transverse plane, this is the *roll*. During the turn, the car weighs on the side wheels.

- Rotation in a longitudinal plane, this is the *pitch*. During the turn, the car weighs on the outer front wheel more than on the rear one.

The concept of guiding force responds to the questions that had haunted automotive specialists for ages and had as yet not been answered satisfactorily, among which are the following ones:

- How to explain the rotation of the car in a horizontal plane when the driver makes a turn to change course?

- Where does the induced braking process come from?

- Why is the pivoting angle of the steered wheels limited to 45°?

- What is the role of the rear wheels?

- What are the consequences of acceleration or braking in a turn?

- How to account for the action of the ESP (Electronic Stability Program)? Etc.

It is clear and final: the guiding force is definitely the only force to be considered in the study of circular motion.

The reciprocal action

Newton's third law goes: *'Any mass on which a force is acting, simultaneously exerts a reciprocal action equal in magnitude, but opposite in direction'*[(6)].

Does this law apply to the guiding force? Of course it does, because the guiding force is a real force!

Let us resume our reasoning. As pointed out above, the guiding force is acting on the tires in contact with the ground. The reciprocal action also occurs at ground level. Indeed, when a driver activates the guiding force, the car performs a thrust against the Earth, and this thrust should logically affect its rotational movement[(7)].

Fortunately, this effect is purely theoretical because the mass of the car is considerably lower than that of the Earth, so that the car can only slide or register obediently on a circular path[(8)]!

Let us note that the divergent trajectories of the large number of vehicles in circulation would negate this effect, should it be noticeable.

Warning ! The reciprocal action is often confused with the centrifugal force:

- The centrifugal force is supposed to act on the center of mass of the car, while the reciprocal action acts by contact with the ground.

- The centrifugal force being an imaginary force, it does not result from an interaction and can not generate any (see ADILCA file ''*centrifugal force*'').

The passenger's feeling...

The Newton's third law also concerns passengers and it is easy to check it during an ordinary car trip.

Let us detail the mechanism of the circular movement: the guiding force is exerted on the tires in contact with the ground, it is transmitted to the passengers by means of the wheels, the frame, the bodywork and the seats.

The principle of reciprocity applies: since the passengers are driven by the guiding force, they exert a reciprocal action on the seats and the bodywork, of equal intensity but of opposite direction.

The passengers feel perfectly this reciprocal action that they confuse with the centrifugal force, wrongly. Logically, it is impossible to feel the effects of an imaginary force.

Conclusion

Physics is a noble science which admits only one truth. The natural path of a vehicle is straight. To deflect this path, one needs to apply a transverse force called guiding force.

The guiding force is a contact force exerted on the tires of the steered wheels in contact with the ground when the driver activates the steering control.

This force is expressed by the formula $\mathbf{F = MV^2/R}$. Its intensity is inversely proportional to the radius of the path, it depends on the mass of the car and the square of its speed. There is no other force acting on the car.

The car reacts by a triple rotational movement that are the *pitch*, the *roll* and the *yaw*.

The passengers of the car feel perfectly the guiding force acting, and the reciprocal action that they exert on the seats and the bodywork.

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Additional remarks

(1) *It is more precisely the net force causing the lateral acceleration of the center of mass of the car, which must be distinguished from the yaw moment exerted by the steering axle.*

(2) *According to the International System of Units (symbol:* ***SI****) – compulsory in most countries around the world, e.g. in United states since 1964, in United Kingdom since 2004 – the mass is expressed in kilograms (symbol* ***kg)****, the speed is expressed in meters/second (symbol* $\mathbf{m.s^{-1}}$*) and the radius of a trajectory is expressed in meters (symbol* ***m****). The dimension obtained is kilogram-meter per square second (symbol* $\mathbf{kg.m.s^{-2}}$***)*** *which characterizes the force unit, the* newton *(symbol* ***N).*** *This quantity is named in tribute to the work of Sir Isaac Newton, English physicist and mathematician (1642-1727), one of the forerunners of modern science.*

(3) *The pivoting angle of the steered wheels can vary from 0 to* ± 45 *degrees. The transverse component is a function of the* cosine*, it decreases with the angle, while the longitudinal component, function of the* sine*, increases. The two components are equal when the pivot angle reaches 45 °.*

(4) *The course is defined as the direction in which the front of the car is pointing: heading north, east, south or west, with all possible variants. One could perfectly conceive a transverse acceleration without change of course, which would happen if the car were provided with four steered wheels pivoting of the same angular value.*

(5) *Beware of misinterpretations: the reaction of the car around its center of mass is the result of a torque, it has nothing to do with the principle of reciprocity. But it is however one of the usual confusions related to the abusive use of the concept of centrifugal force.*

(6) *This law does not apply to fictitious forces.*

(7) *The reciprocal action can 'work' the coating, as can be seen for example on car racing circuits, where drivers operate a transverse acceleration.*

(8) *The guiding force exerts on the car, the reciprocal action exerts on the terrestrial globe. They are two equal forces but their effect is inversely proportional to the mass on which they are exerted, it is the fundamental principle of the dynamics (or second principle of Newton: [F = M Y] or [Y = F / M]). If one compares a car that weighs 2 metric tons and Earth (*6×10^{24} *kg), the mass ratio is 1 to* 3×10^{21}*, that is 1 to 3,000 trillion!*

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III. GUIDING FORCE: THE CALCULATION MODE

1. Transverse acceleration

$$Y = V^2 / R$$

Y: transverse acceleration expressed in **$m.s^{-2}$**
V: speed, expressed in **$m.s^{-1}$**
R: radius of trajectory, expressed in **m**
consistency of the units: **Y** = $(m^{+1}.s^{-1})^2 . m^{-1} = m^{+2}.s^{-2} . m^{-1} = \mathbf{m.s^{-2}}$

Example: calculate the transverse acceleration of a car describing a circular path of radius 100 m at a speed of 20 $m.s^{-1}$:

$$\mathbf{Y} = 20^2 / 100 = 400 / 100 = 4\ \mathbf{m.s^{-2}}$$

Passengers properly seated on board as well as securely stowed luggage undergo transverse acceleration of the same intensity.

2. Grip coefficient

$$\mu = Y / g$$

μ: grip coefficient, dimensionless quantity;
Y: transverse acceleration in **$m.s^{-2}$**
g: reference acceleration, expressed in **$m.s^{-2}$**
(Earth's gravitational acceleration **g** = 9.8 $m.s^{-2}$)
consistency of the units: **μ** = $(m^{+1}\ s^{-2}) . (m^{-1}.s^{+2})$ = dimensionless quantity.

Example: calculate the grip coefficient enabling a transverse acceleration of 4 $m.s^{-2}$:

$$\mu = 4 / 9.8 = 0.4$$

3. Guiding force

$$F = M . V^2 / R$$

F: guiding force, expressed in **N**
M: mass, expressed in **kg**
V: speed, expressed in **$m.s^{-1}$**
R: radius of path, expressed in **m**
consistency of the units: **F** = $kg . (m.s^{-1})^2 . m^{-1} = kg . m^{+2}.s^{-2} . m^{-1} = kg . m.s^{-2}$ = **N**

Example 1: calculate the guiding force capable of maintaining a 1,500 kg (around 3,300 lb) car mass over a circular path of radius 100 m at a speed of 20 $m.s^{-1}$ (45 mph):

$$\mathbf{F} = 1{,}500 \times 20^2 / 100 = 1{,}500 \times 400 / 100 = 6{,}000 \ \mathbf{N}$$

This force is exerted in the ground contact surface of the tires.

By virtue of Isaac Newton's principle of reciprocity, the tires of the car exert a reciprocal action on the ground, of the same intensity as the guiding force, but in the opposite direction. The earth globe remains insensitive to this action because of its mass.

Example 2: calculate the guiding force exerted on a passenger weighing 80 kg (around 175 lb) when the car describes a circular trajectory of 100 meters radius at a speed of 20 $m.s^{-1}$ (45 mph):

$$\mathbf{F} = 80 \times 20^2 / 100 = 80 \times 400 / 100 = 320 \ \mathbf{N}$$

This force comes from the tires of the car. It is transmitted to the passenger via the wheels, frame, bodywork and seat.

By virtue of the principle of reciprocity stated by Isaac Newton, the passenger exerts a reciprocal action on the seat and bodywork, of the same intensity as the guiding force, but in the opposite direction.

The passenger perfectly feels this action that gives him the impression of weighing on the edge of the seat and the bodywork. The frame and bodywork must be sufficiently rigid and the seat sufficiently secure to resist.

4. Center of mass

$$\mathbf{d = L \,.\, M2 / (M1 + M2)}$$

d: distance between the center of mass and the steering axle, expressed in m
L: wheelbase, expressed in **m**
M1: mass on the front axle, expressed in **kg**
M2: mass on the rear , expressed in **kg**
consistency of the units: $\mathbf{d} = m \,.\, kg \,.\, kg^{-1} = \mathbf{m}$

Example: calculate the distance between the center of mass and the steering axle of a car with the following characteristics: wheelbase 2.5 m, 840 kg weight on the front wheels, 660 kg on the rear wheels:

$$\mathbf{d} = 2.5 \times 660 / (840 + 660) = 1{,}650 / 1{,}500 = 1.1 \ \mathbf{m}$$

5. Front wheel guidance

$$F = M \cdot Y \cdot (L - d) / L$$

F: guidance of front wheels, expressed in **N**
M: mass, expressed in **kg**
Y: transverse acceleration, expressed in $m.s^{-2}$
L: wheelbase, expressed in **m**
d: distance between center of mass and steering axle, expressed in **m**
consistency of the units: **F** = $kg.\ m^{+1}.s^{-2}\ .\ m^{+1}\ .\ m^{-1} = kg.m.s^{-2}$ = **N**

Example: calculate the guiding force exerted by the front wheels of a car of mass 1,500 kg (wheelbase 2.5 m, distance between the center of mass and steering axle 1.1 m) for a transverse acceleration of 4 $m.s^{-2}$:

F = 1,500 x 4 x (2.5 – 1.1) / 2.5 = 6,000 x 1.4 / 2.5 = 3,360 **N**

6. Transverse Component

$$F_t = F \cdot \text{cosinus}\ \alpha$$

Ft: transverse component, expressed in **N**
F: front wheel guidance, expressed in **N**
α: pivoting angle of the steered wheels, expressed in degrees.
consistency of the units : **F** = **N**
[*Trigonometric values are dimensionless quantities which do not affect the units with which they combine*]

Example: calculate the transverse component of the steered wheels when a guiding force of 3,360 N is exerted on the steering axle, the pivot angle of the steered wheels being equal to 15° (cosine 15° = 0.96):

Ft = 3 360 x 0,96 = 3 226 **N**

7. Rear wheels guidance

$$F = M \cdot Y \cdot d / L$$

F: guidance of rear wheels, expressed in **N**
M: mass, expressed in **kg**
Y: transverse acceleration, expressed in $m.s^{-2}$
d: distance between center of mass and steering axle, expressed in **m**
L: wheelbase, expressed in **m**
consistency of the units: **F** = $kg.\ m^{+1}.s^{-2}\ .\ m^{+1}\ .\ m^{-1} = kg.m.s^{-2}$ = **N**

Example: calculate the guiding force exerted by the rear wheels of a 1,500 kg car mass (distance between the center of mass and steering axle 1.1 m, wheelbase 2.5 m) for a transverse acceleration of 4 $m.s^{-2}$:

F = 1,500 x 4 x 1.1 / 2.5 = 6,000 x 1.1 / 2.5 = 2,640 **N**

8. Roll motion

R = M. Y. H / L

R: roll motion, expressed in **N**
M: mass, expressed in **kg**
Y: transverse acceleration, expressed in $\mathbf{m.s^{-2}}$
H: height of the center of mass, expressed in **m**
L: width between wheels, expressed in **m**
coherence of units: **R** = $kg.\ m^{+1}.s^{-2}.\ m^{+1}.\ m^{-1} = kg.m.s^{-2}$ = **N**

Example: Let's calculate the roll reaction of a car driven by a transverse acceleration of 4 $m.s^{-2}$ (mass 1,500 kg, center of mass height 0.5 m, width 1.5 m):

R = 1,500 x 4 x 0.5 / 1.5 = 2,000 **N**

This phenomenon is improperly called mass transfer (masses that constitute any solid are not transferred separately except in the case of collision or disintegration).

It is actually a transfer of the load on the tires when the car is driven by a transverse acceleration, because of the distance between the ground and the center of mass. This distance acts as a lever arm.

If the guiding force exerted directly on the center of mass, this phenomenon would not occur.

The result means that the outer wheels of the track receive an additional weight of 2,000 N, while the inner wheels are relieved accordingly. The total weight of the car remains obviously unchanged (15,000 N for "**g**" = 10 $m.s^{-2}$).

The roll is distributed on the front and rear wheels in the same proportions as the static weight, if the road is horizontal and without banking, and if we neglect the pitch related to the front-to-back component of the guiding force.

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