KINETICS OF AUTOMOBILE IN FRONTAL CRASH

M. K. Chopra*1, C. M. Agrawal and R. M. Sarviya2

1. Department of Mechanical Engineering, RKDF Institute of Science and Technology, Bhopal, (INDIA)
2. Department of Mechanical Engineering, MANIT, Bhopal, (INDIA)

Received December 14, 2009 Accepted August 04, 2010

ABSTRACT

In this study, a attempt has been made to simplify the role of tractive effort in applying driving force to overcome the resistances to motion of the automobile. Further, energy is stored in the automobile by virtue of its motion, which is termed Kinetic Energy. An analysis has been made on forces on car in a frontal crash. A comparison of forces on driver in a frontal crash (with or without non-stretching seat belt and with stretching seat belt) has been made. It has been concluded that there is reduction in fatalities if a driver wore a stretchable seat belt. Further, the occupant of the less massive vehicle is more at risk when a collision occurs1-2

Key Words : Seat belt, Tractive Effort, Automobile, Fatality, Fixed barrier, Passive safety, Resistances, Crash

INTRODUCTION

India is a developing country. Its remarkable advances in various fields is having an impact on the world. The growth in automobile market is one of the highest in the world. The increase in accident rate is also alarming. The need of the hour is to reduce the injury to the driver and hence the fatality. The steps taken in this direction involves creating awareness among the occupants of the automobile supplemented by technical advances in safety features.3-6

* Author for correspondence
frontal crash with fixed barrier (fixed barrier being one which does not get deformed i.e. no work done is done on the barrier) equals the product of force of impact on car and the extent of deformation of front portion of car. The analytical calculation of the deceleration helps to come to a conclusion as far as fatality of driver is concerned. In the event of an automobile frontal crash, passive safety features like seat belt play an important role in minimizing injury to the occupants.7-10

MATERIAL AND METHODS

Resistances to motion of an automobile

In order to move the automobile from rest, the forces to be overcome are characterized as below11:

- Air resistance
- Gradient resistance
- Rolling resistance

Air resistance

The air offers a resistance to the passage of bodies through it. This depends on the size and shape of the body and upon its speed through the air. However the effect of the shape and size of an automobile on its air resistance need not be considered here, because for any given vehicle the shape and size are fixed quantities. The effect of speed on air resistance must however be considered, as illustrated in Fig.1, which is a graph of air resistance plotted against speed. It is seen that when the speed is zero the resistance is zero and that as the speed increases so does the air resistance, the rise being at an increasing rate as the speed gets higher. In practice, the air resistance is taken to vary as the square of the speed, so that if the speed is doubled the resistance is increased four times. It should be clear from the graph that for slow-speed vehicles such as lorries, the air resistance will be very small and may be neglected, but with high-speed vehicles it become important. In racing cars, it is of paramount importance.

Since it is the speed of the vehicle through the air that determines the air resistance, the latter may be considerable even for lorries if a strong head wind prevails.

Gradient resistance

Fig.2. shows an automobile standing on a gradient and it will be seen that the weight of the car, \( W \), which acts vertically downwards, can be resolved into two components \( W \sin \theta \) and \( W \cos \theta \). The component \( W \cos \theta \) is perpendicular to the road surface and \( W \sin \theta \) is parallel to the road surface. If the automobile is to be propelled up the gradient, part of the driving force goes to neutralize the force \( W \sin \theta \). This forces an additional resistance to the motion of car and may be called ‘Gradient resistance’. It depends simply on the steepness of the gradient and weight of an automobile. It is not affected by
the speed of the automobile up the gradient.

Rolling resistance
The rolling resistance is due to the deformation of the road and tyre and to the dissipation of energy through impact. It depends mainly on the nature of road surface, the nature of tyres with which the automobile is fitted and the total weight of the vehicle and load. It is generally taken to be directly proportional to the weight of automobile and load. On soft, muddy and sandy roads, rolling resistance is greater than on hard dry macadam or wood paving; it is less with pneumatic than with solid rubber or steel tyres.

The part of rolling resistance which is due to impact undoubtedly depends also on the speed and springing of the automobile. However, on roads having a hard dry surface free from large bumps and holes, the impact losses are small and independent of speed.

Total resistance
The total resistance to the motion of vehicle is the sum of the above three resistances. A curve of total resistances against speed is therefore obtained by shifting the curve of Fig. 1 up vertically by the amount of the rolling and gradient resistances as is shown in Fig. 3.

Thus, when the speed is 0.5 km/hr., the total resistance SP is composed of the rolling resistance SR, the gradient resistance RQ and the air resistance QP. If either the gradient or the rolling resistance increases or decreases, then the curve would simply shift up or down by the amount of the increase or decrease.

Total resistance Vs tractive effort (driving force on the automobile)

Tractive effort
We have seen that an automobile at rest requires to overcome the total resistance in order to move. The resistance is overcome by a force acting on the automobile in the forward direction. The source of this force is the engine, which turns the clutch shaft with a torque T. This torque is transmitted to the gear box. The torque acting on the road wheel is given as

\[ T_1 = n \times m \times T \]

By applying the principle of conservation of energy, the product of the engine torque and the speed of the clutch shaft equals the torque acting on the road wheel and the road wheel speed (the two wheels considered as
single wheel); neglecting frictional losses and energy storage.
The way in which torque $T_1$ produces a driving force to propel the car along the road is shown in Fig. 4.

If the wheel shown in Fig. 4 is regarded as being in equilibrium, then the forces that act upon it must be in equilibrium and the couples also. Now, at every instant, the wheel can be considered as a lever fulcrumed at the point of contact of the wheel and the ground.

Under the action of the torque $T_1$, the lever will tend to rotate about the point of contact with the ground and the centre of the wheel will tend to go forward and to take the axis and the vehicle with it. At its centre, therefore, the wheel is pressing forward on the axle casing with a force which is designated as $P_1$. The reaction $P_2$ of this force $P_1$ acts backward on the wheel. Since the wheel is in equilibrium, there must be an equal and opposite force $P_3$ acting on it. This is the adhesive force between the wheel and the road. The forces $P_2$ and $P_3$ constitute a couple tending to turn the wheel in the clockwise direction and since the wheel is in equilibrium, and the couples acting on it are therefore also in equilibrium, the couple $P_2 P_3$ must equal the torque $T_1$ applied to the wheel by the driving shaft. Now the magnitude of the couple $P_2 P_3$ is $P_3 x R$ where $R$ is the distance between the forces $P_2$ and $P_3$, i.e., the radius of the wheel in present case.

Hence, $T_1 = P_3 x R$ and since

$$T_1 = n \times m \times T,$$

we have

$$P_3 x R = n \times m \times T,$$

or

$$P_3 = n \times m \times \frac{T}{R} = K \times T$$

where $K$ is a constant for any particular gear box with gear ratio $n$, final drive ratio $m$ and wheel radius $R$.

Thus,

$$K = \frac{n \times m}{R}$$

The tractive effort is given by the equation

$$P = K \times T$$

We have seen that the tractive effort $P$, varies with engine torque $T$. Also the engine torque, $T$ varies with the engine speed as shown in Fig. 5. Thus the tractive effort $P$, varies with vehicle speed, $V$. This has been exhibited in Fig. 6. The shape of the curve is similar in both Fig. 5 and Fig. 6. The Fig. 6 shows a tractive effort $P$ Vs. Vehicle speed, $V$ curve for a given gear box ratio, a given final drive ratio and a given road wheel radius. If the gear box ratio is altered, we shall get another curve of tractive effort. Thus, if the gear box ratio is altered so that the total gear ratio between the engine and the back wheels is double of what it originally was, then the curve MN will become the curve OP. For a given engine speed, $N$, doubling the total gear ratio will
halve the vehicle speed but will double the tractive effort.

\[ \text{Kinetic Energy} = \frac{1}{2} MV^2 \]

Now imagine the automobile to crash against a fixed barrier; fixed barrier being one which does not get deformed (i.e. no work is done on the barrier). In effect the automobile collapses to a distance of \( S_1 \) metres and then stops. Let \( F \) be the force which is exerted on the automobile to stop it.\(^{20-23}\) Thus we have the relation

\[ \text{Change in Kinetic Energy} = \text{Work required to stop the automobile} \]

or

\[ 0 - \frac{1}{2} MV^2 = F \times S_1 \]

or

\[ F = \frac{-\frac{1}{2} MV^2}{S_1} \text{ Newton} \]

and Deceleration = \(-\frac{F}{M}\) m/sec\(^2\)\(^{-}\) (ve sign indicates deceleration)

Please refer to Fig. 7. regarding above Case Study I

Mass of Driver, \( M_1 = 80 \text{ Kg} \)

Velocity of automobile, \( V = 50 \text{ Km/hr} \)

\[ = 14 \text{ m/sec} \]

Distance of collapse of automobile, \( S_1 = 0.3 \text{ m} \)

Amount of stretch of seat belt, \( S_2 = 0.2 \text{ m} \)

Total distance traversed by driver during crash,

\[ S_3 = S_1 + S_2 \]

\[ = 0.3 + 0.2 \]

\[ = 0.5 \text{ metres} \]

Impact force on driver,

\[ F_1 = -\frac{1}{2} M_1 V^2 \times 1 / S_3 \]

\[ = -\frac{1}{2} (80 \times 14 \times 14) \times 1 / 0.5 \]

\[ = -15680 \text{ N} \]

\[ = -15.68 \text{ KN} \]

Deceleration,

\[ a = \frac{F_1}{M_1} \]

\[ = -196 \text{ m/sec}^2 \]

Please refer to Fig. 8.1, Fig. 8.2 and Fig. 8.3 to clarify on forces on driver in a frontal crash.\(^{24-28}\)
RESULTS AND DISCUSSION
It is observed that the impact force experienced by the driver of car in the event of frontal crash vary depending upon the constraints. Further, the deceleration experienced by the driver vary accordingly. In the present comparison, the weight of the automobile is taken as 1600 kg and the

Table 1: Forces on driver in a frontal crash

<table>
<thead>
<tr>
<th>CONSTRAINTS VARIABLES</th>
<th>With non stretching seat belt</th>
<th>With stretching seat belt</th>
<th>Without seat belt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of driver, M₁ (kg)</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Velocity of automobile, V (km/hr)</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Amount of collapse of automobile on crash, S₁ (mtr)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Amount of stretch of seat belt, S₂ (mtr)</td>
<td>0.</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>Stopping distance of driver, S₃ (mtr)</td>
<td>0.3</td>
<td>0.3 + 0.2 = 0.5</td>
<td>1/5th of 0.3 = 0.06</td>
</tr>
<tr>
<td>Impact Force on driver, F₁ (kN)</td>
<td>26.1</td>
<td>15.68</td>
<td>130.7</td>
</tr>
<tr>
<td>Deceleration , a (m/sec²)</td>
<td>-327</td>
<td>-196</td>
<td>-1633.75</td>
</tr>
</tbody>
</table>

Fig. 7: Forces on a car in frontal crash
Fig. 8.1: Car crash scenario with car stopping after collapsing 0.3 m upon impact with fixed barrier, from a speed of 50 km/hr.

In the case of usage of non-stretching seat belt, driver stops with car in a distance of 0.3 m. Force on 80 Kg. driver is 26.1 kN and deceleration is 327 m/sec².

Fig. 8.2: Car crash scenario with car stopping after collapsing 0.3 m upon impact with fixed barrier, from a speed of 50 km/hr and the seat belt stretching a distance of 0.2 m.

In the case of usage of stretching seat belt, stopping distance of car is 0.3 m and stopping distance of driver is 0.5 m. (0.2 m. being stretch of seat belt) Force on 80 Kg. driver is 15680 N; deceleration is 196 m/

Fig. 8.3: Car crash scenario with car stopping after collapsing 0.3 m upon impact with fixed barrier, from a speed of 50 km/hr and driver is without seat belt.

In absence of seat belt, stopping distance of driver by impact after flying free while car stops is 0.06 m. (u 0.2 x 0.3 = 0.06m) Force on 80 kg driver is 130700N; deceleration is 1633.75 m/sec².
weight of the driver is taken as 80 kg. The velocity of car before frontal crash with a fixed barrier (i.e. fixed barrier is one which does not get deformed on being impacted by an automobile) is taken as 50 km/ hr. The extent of deformation of car in frontal crash till it stops is assumed to be 0.3m. The above given values are representative of most acceptable condition for the purpose of generalization in the calculation of forces and deceleration experienced by the car and driver. The maximum stretch of seat belt holding the driver in a frontal crash is taken as 0.2 m

CONCLUSION
A summary of results obtained is as below:
(a) Forces on a car in a frontal crash with a fixed barrier: The impact force on a car is 523 kN and the deceleration equals 327 m/sec².
(b) Forces on a driver held by non stretching seat belt in a frontal crash with a fixed barrier: The impact force exerted by a seat belt on the driver is 26.1 kN and the deceleration equals 327 m/sec².
(c) Forces on driver held by stretching seat belt in a frontal crash with fixed barrier: The impact force exerted by the seat belt on the driver is 15.68 kN and the deceleration equals 196 m/sec².
(d) Forces on driver do not held by seat belt in a frontal crash with fixed barrier: The impact force on the driver equals 130.7 kN and the deceleration equals 1633.75 m/sec². It has been observed that usage of stretchable seat belt by the drivers reduces the force exerted on the driver from 26.1kN to 15.68 kN and the deceleration from 327 m/sec² to 196 m/sec² when compared to usage of non stretchable seat belt. However, in the absence of seat belt, the force on the driver is as high as 130.7kN and the deceleration of 1633.75 m/sec². The driver fly free until stopped suddenly by impact on the steering column, windshield etc.

It is concluded that reduction in the intensity of injury and fatalities occur if all drivers wear seat belt.

NOMENCLATURE / NOTATIONS
a Uniform acceleration of automobile
S₁ Extent of deformation of car till it stops
F Force on automobile in frontal crash with fixed barrier
S₂ Maximum stretch of seat belt holding the driver
F₁ Impact force exerted by seat belt on the driver
S₃ Total distance traversed by driver during crash
K Constant
t Time taken for change of velocity from V₁ to V₂
m Final drive ratio
T Engine Torque
M Mass of the automobile
T₁ Torque acting on road wheels
M₁ Mass of driver
V Speed of the automobile
n Gear box ratio
V₁ Initial velocity of automobile
N Engine speed
V₂ Final velocity of automobile
P Tractive effort
W Weight of automobile
R Radius of the wheel
θ Angle in degrees
S Distance moved in time t

REFERENCES


