Some Aspects of Vehicle Active Safety

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Three selected aspects of vehicle active safety are presented in this article: (a) modeling the driver and the driver-vehicle environment system, (b) the dynamic aspects of vehicle rollover, and (c) an analysis of the process of passing. Sample solutions and results show the need for further research in the field of vehicle safety in order to lower the probability of drivers, passengers, and other road users being involved in road accidents.

1. INTRODUCTION

Vehicle safety is part of a wider field of transport safety. Generally speaking, vehicle safety should be regarded as the prevention of road accidents.

Road traffic is one of the most dangerous areas of everyday human activities. The human toll taken by road traffic is vast: More than 300,000 people a year are killed in road accidents all over the world and 10 million people a year are injured (Rumar, 1991). However, if one takes into account that every year more than 30 million vehicles are produced and sold around the world, and about 1 out of every 10 vehicles is involved in an accident in which people are injured (Hagg et al., 1992), the large number of accidents is easier to understand.

There are several ways of rating vehicle safety. In general, three phases can be distinguished:

1. Active safety systems (before collision) strongly associated with driver response and perception and vehicle dynamics.
2. Passive safety systems (at the time of collision) in which (a) energy absorption technology (body, bumpers, steering mechanism, safety windows), (b) passenger restraint devices (safety belts, air bags), and (c) pedestrian safety (elimination of body edges, prevention of dragging) are usually analyzed.
3. Postcrash safety in which (a) occupant rescue (accessibility through doors or windows) and (b) fire prevention items are considered.

In this article, some aspects and results of vehicle active safety are presented.

2. DRIVER-VEHICLE ENVIRONMENT SYSTEM

To reconstruct an accident is to provide a complete history of the circumstances and the course of the accident using all the available data. An analysis based only on an advanced dynamic vehicle model is not satisfactory. When attention is focused on accident reconstruction, the concept of a driver-vehicle system control plays a key role. Traffic safety problems that involve an interaction between the driver and the vehicle should also take into consideration the road environment. Thus, the following three elements: (a) road-vehicle kinematics, (b) vehicle dynamics, and (c) driver response and perception, should be taken into account (Figure 1).
The road–vehicle kinematics component generates a vehicle path within a specified road environment.

Vehicle motion is the result of the driver's steering actions. The vehicle dynamic model can also be used to compute performance characteristics. For example, vehicle lane deviations can be determined as a result of road disturbances or gusts of wind. Random influences and statistical properties should usually be analyzed using mean square or covariance propagation techniques.

The driver component generates steering responses from a combined perception of a desired path in the road environment as compared with the path and motion of the vehicle.

3. DRIVER MODELING

Statistical data indicate that 70% of accidents are caused by the driver's mistakes. Therefore, a description of driver characteristics is essential for accident reconstruction. A driver model can be described at various levels. Anthropometric descriptions of the size and shape of the driver are useful for determining the indoor size of a vehicle, the position of control instruments, mirror and window design, and so forth. The control response of a driver model, coordinated with visual stimuli and related to the dynamic vehicle control model, can make a correct simulation of an accident reconstruction possible. However, the problem of an adequate mathematical description of the behavior of the driver/controller is very complex. The input–output relation cannot be described as purely linear, nonlinear, time variable, or random only: It is actually a combination of all those characteristics. In addition, drivers are highly adaptive controllers who learn from experience, who can be subjected to a biological adaptation (e.g., they are capable of adapting certain situations to optimize their sphere of activity), and so forth.

Psychological aspects should also be taken into account. The driver's behavior can be divided into three categories (Kobayashi, 1990) as shown in Figure 2.

Logical behavior reduces the risk involved in driving. Illogical behavior governed by mood can also take place while driving (e.g., thinking of something other than driving a vehicle, listening to the radio, etc.). The driver's impulsive and unpredictable reactions to other users of the road constitute examples of common irrational behavior.

Steering cues for the driver come from road markings, other road features, and obstacles in the road environment. The driver's neuromuscular limb system affects the ability to generate desired steering actions. A driver model should take into account the driver's short- and long-term adaptation to changes in the vehicle and environment characteristics. Various impairments like fatigue, alcohol, drugs, and so forth cause deterioration of the driver's behavior. A comprehensive model must realistically take into account current driver characteristics. However, full mathematical description of these requirements is still rather impossible. A quality analysis of this type of behavior can be performed on the basis of some diagrams.

As an example, let us consider a very simple parameter, such as the perception reaction time (RT) of the driver while braking. In the case of the driver applying brakes, the perception RT
is the time necessary to perceive the situation on the road plus the brake RT. Traffic situations
are often complex. The driver must take into account a number of simultaneous events and
select the one that requires a response. Studies conducted in the past 30 years have shown that
for most people, the total brake RT equals 0.5 to 0.7 s. In tests of over 1,400 volunteers (Traffic
Engineering Handbook, 1965), the average brake RT was 0.497 s. However, the brake RT
varied with relative accelerator and brake locations. The relation of the driver's age to brake
RT is very significant. It changes from 0.437 s in the 20- to 24-year-old age group to 0.522 s in
the 65- to 69-year-old age group. The perception RT also depends on other factors, for example,
the driver's experience, the kind of driving (long-distance monotonous driving causes an
elongation of the perception RT), noise, vibrations, and inappropriate ergonomic conditions.
However, under varying road conditions the perception RT can range widely: It can change
from 0.24 to 1.65 s. A pure mathematical description of all those characteristics is not possible,
but Figure 3, which illustrates the relation of the various time periods during the stopping
maneuver, makes understanding the braking process easier.

Figure 3. Relation of the various time periods during the stopping maneuver.
4. DRIVER AS A HUMAN CONTROLLER

For a computer simulation of the steering ability and the directional stability of vehicles, different driver activity patterns are used:

- The driver holds the steering wheel in a constant position (fixed control); this pattern is used to investigate the steady state turning of the vehicle or the influence of disturbances (e.g., side wind) on the vehicle.
- The driver turns the steering wheel in a desired way (open-loop control); the pattern is used to investigate the transient responses of the vehicle on a step, sinusoidal, or random steering input.
- The driver controls the vehicle using the steering wheel to keep the vehicle as close to the desired path as possible (closed-loop control); the pattern is used to investigate the whole driver-vehicle system.

In the first two cases (fixed and open-loop control), a vehicle model is adequate for a computer simulation and only vehicle data have to be added. However, for a computer simulation of closed-loop maneuvers, the vehicle model should be extended by a driver model that maintains the vehicle position according to the desired path and provides control with a feedback of position error.

The driver model—in the sense of a human controller—can be reduced to several conceptually simple parameters for closed-loop compensatory vehicle control. The distance down the road to the desired aim point, that is, aim point distance, is one of them (see Figure 4).

Another criterion is called aim point error. The driver derives an error signal between the desired path and the current path of the vehicle. The control law assumed here is that the driver moves the steering wheel at an angular velocity proportional to the curvature error. This control law is required in order to establish a stable control loop around the vehicle dynamics and properly minimize curvature errors.

A simple driver model has been elaborated in the Institute of Vehicles at Warsaw Technological University (Ręsski, 1991; Ręski & Wicher, 1992). The driver's steering control law, used in this model, is defined as follows: The driver observes an aim point that is situated on the desired path at a distance \( L_a \) ("look-ahead distance") down the road. The driver sees this point at an angle \( \phi \) to the longitudinal axle of the vehicle. This angle is equal to

\[
\phi(t) = \frac{y_d(x + L_a) - y(x) - \Theta(x)}{L_a}
\]

in which \( x = vt \) represents longitudinal position, distance covered by the vehicle; \( v \) represents constant speed of the vehicle; \( y \) represents lateral position of the vehicle; \( y_d \) represents desired path deviation from the road axis; and \( \Theta \) represents heading angle.

![Figure 4. Desired aim point concept.](image-url)
The steering angle $\beta$ controlled by the driver is proportional to the $\xi$ angle (steering angle gain: $W$). The driver’s response delay between position perception and steering response is $T_k$. Then,

$$\beta(t) = W \varphi (t - T_k).$$

Finally,

$$\beta(t) = \frac{W}{L_a} y_d \left( t + \frac{L_a}{v} - T_k \right) - \frac{W}{L_a} y(t - T_k) - W\Theta(t - T_k).$$

Thus, the driver model is characterized by three parameters: (a) the look-ahead distance $L_a$, (b) the response delay $T_k$, and (c) the steering angle gain $W$. The model has been used for computer simulations of the dual lane-change maneuver.

For $10 \text{ m} < L_a < 30 \text{ m}$, $0.1 \text{ s} < T_k < 0.2 \text{ s}$, and $0.3 < W < 0.6$, it has been found that the shapes of curves from the computer simulations and from the road tests are similar. The calculations have been done for velocity $v = 80 \text{ km/h}$. Lateral position $y$ of the vehicle and heading angle $\Theta$ have been estimated using three degrees of freedom vehicle models with parameters typical for light cars. The results depend on vehicle and driver models. The driver model requires many road tests realized with a considerable number of drivers of different genders, age’s, and skills.

5. VEHICLE ROLLOVER

As previously mentioned, vehicle active safety is associated with driver modeling and with the dynamic characteristics of a vehicle. Many aspects need to be considered. Two of them are particularly significant: vehicle rollover and the process of passing.

Recently, many studies have been devoted to vehicle rollover accidents. One of the reasons for this concern is the nearly double fatality rate in accidents with a vehicle rollover compared with those without. Rollover accidents are among the most hazardous according to both the frequency of occurrence and the severity of occupant injuries.

In general, two distinct types of vehicle rollovers can be distinguished: (a) a tripped rollover and (b) a maneuver-induced rollover.

A tripped rollover occurs when a vehicle rolls over after striking a “tripping” device such as a rigid obstacle (curb), soft soil, or other terrain features. A maneuver-induced rollover occurs when a vehicle abruptly moves, and there are excessive driver inputs, or both. A substantial majority of single rollover accidents are classified as tripped rollovers.

The static analysis of a vehicle rollover is based on the Static Rollover Stability factor, defined as the ratio of half track width to the height of the center of gravity. It can be used for comparing the rollover tendencies of various vehicles. Increasing the Static Rollover Stability factor will decrease the rollover propensity of a vehicle. However, the determination of the rollover propensity of a vehicle should not be based solely on static analysis. It cannot determine the direct and indirect effect of all the vehicle design characteristics on a rollover. Dynamic couplings between motions and inertia forces, as well as the vehicle subsystem behavior (suspensions, tires, etc.), can all have a significant influence on the system response during rollovers.

The concept of an energy function for the prediction of vehicle rollovers, based on the Energy factor (EF), has been defined as (Nalecz, 1989):

$$EF = EP - EK$$

in which $EP$ represents potential energy of the critical point (point of an unstable equilibrium of the vehicle body), and $EK$ represents energy of the rotational motion around the axis passing through the contact point of the vehicle wheel with terrain.
However, some problems have been associated with this concept. Determining the portion of energy that contributes to a vehicle rollover is one of the more difficult problems in the development of a rollover predictor function.

Another problem is connected with dissipative energy. From the principles of work and energy for isolated systems, it is known that although energy can be exchanged between various system components, total system energy must always decrease due to the dissipative forces which act on the system.

Another method used for rollover analysis has been based on the velocity reserve concept (Wicher & Łukaszewski, 1991). Velocity reserve has been defined as:

\[ VR_v = v_{cr} - v. \]  

(5)

A percentage velocity reserve factor has also been used:

\[ VR_{\%} = (1 - v/v_{cr}) \]

(6)
in which \( v_{cr} \) represents critical velocity of the vehicle gravity center that causes a rollover and \( v \) represents current velocity of the vehicle gravity center.

Critical velocity \( v_{cr} \) can be estimated from the angular momentum and energy equations.

Cases of side and oblique impact have been studied in Wicher and Łukaszewski (1991). It had been assumed that a vehicle rolls around the tire-ground contact line. Observations of the experimental results of tripped rollovers indicate that during impact situations in which the vehicle skids sideways striking a curb at an oblique angle, the vehicle tends to roll around the curb and not the tire-ground contact line. Bearing this in mind, the assumption that the vehicle rolls around the curb during both side and oblique impact can be utilized.

Critical velocity \( v_{cr} \) of the vehicle gravity center, which causes a rollover, has been obtained using the principle of conservation of energy and the principle of impulse and momentum for the vehicle body. Assuming that kinetic energy of the rotating vehicle roll axis transforms into potential energy of the critical position, the critical velocity \( v_{cr} \) has been obtained. Vehicles reach the critical position when the potential energy is maximum and vehicles do not lose contact with the ground. For the case when the velocity vector of a vehicle’s center of gravity lies in the plane perpendicular to the roll axis and the vehicle strikes a curb at an oblique angle, the formulae for critical velocity has the form:

\[ v_{cr} = \left[ \frac{2gH_{CG} \xi}{mH_{CG}} \right]^{\frac{1}{2}} + \frac{x}{v} \xi \]

(7)

\[ \Theta = \left[ \xi^2 + 1 \right]^{\frac{1}{2}} - 1 \]

(8)

\[ \xi = \frac{a}{H_{CG}} \cos \beta_1 + \frac{T_{me}}{2H_{CG}} \sin \beta_1 \]

(9)

\[ \cos \beta_1 = \frac{x}{v}, \quad \sin \beta_1 = \frac{\dot{y}}{v} \]

(10)
in which \( a \) represents the distance from the vehicle mass center of gravity to the roll axis; \( g \) represents the acceleration of gravity; \( m \) represents the total mass of the vehicle; \( H_{CG} \) represents the distance between the center of gravity and the curb; \( I_c \) represents moment of inertia of vehicle total mass with respect to the roll axis; and \( \dot{x}, \dot{y}, \dot{z} \) represents longitudinal, lateral, and vertical components of the velocity of the vehicle.
6. THE PROCESS OF PASSING VEHICLES

The necessity to reduce the number of accidents on narrow roads is the main reason for considering the process of passing when designing vehicles. For safety reasons, the passing distance should be as short as possible. On the other hand, it should be long enough for other drivers not to be surprised.

Figure 5, in which Vehicle A passes Vehicle B and the maneuver is over by the time Vehicle C comes from the opposite direction, can be used for an analysis of the process of passing.

The process of passing can be divided into five phases:

1. The driver of Vehicle A decides to pass Vehicle B. The driver turns the steering wheel but the vehicle continues its straight-line motion because of the flexibility of the steering system and the necessity to remove plays in the steering system. Vehicle A covers distance \( x_1 \) during time \( t_1 \).
2. Vehicle A begins to change lanes: The wheels are first turned left, then right, and finally back to the neutral position. The longitudinal component of the Vehicle A path equals \( x_2 \). Vehicle A moves during time \( t_2 \).
3. Vehicle A passes Vehicle B after covering straight-line distance \( x_3 \) during time \( t_3 \).
4. The driver of Vehicle A begins turning the steering wheel to the right but Vehicle A, because of elastic strains and plays in the steering system, continues along a straight line for a distance \( x_4 \) during time \( t_4 \) (cf. Phase 1).
5. Vehicle A begins to change lanes to return to the previous lane. The wheels are turned like in Phase 2 but with mirror reflection symmetry. The longitudinal component of the Vehicle A path equals \( x_5 \) and Vehicle A moves during time \( t_5 \).

The total distance covered by Vehicle A during the process of passing is:

\[
x_p = x_1 + x_2 + x_3 + x_4 + x_5
\]

and the total time of the process of passing is:

\[
t_p = t_1 + t_2 + t_3 + t_4 + t_5.
\]

Detailed considerations about calculating values \( x_i \) and \( t_i, i = 1 \ldots 5 \), for each phase are presented in Wicher (1993).

Some results of calculating the passing distance and the passing time are presented in Table 1. It has been assumed that Vehicle A (passing) is traveling with the maximum possible acceleration of the current speed and the velocities of Vehicle B (being passed) and Vehicle C
TABLE 1. Overtaking Distance and the Time Obtained During a Computer Simulation

<table>
<thead>
<tr>
<th>No. of Vehicle</th>
<th>Mass of Vehicle (kg)</th>
<th>Engine Power (kW)</th>
<th>Passing Distance (m)</th>
<th>Passing Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1150</td>
<td>55.2</td>
<td>270</td>
<td>11.7</td>
</tr>
<tr>
<td>2</td>
<td>1300</td>
<td>55.2</td>
<td>282</td>
<td>12.4</td>
</tr>
<tr>
<td>3</td>
<td>850</td>
<td>30</td>
<td>324</td>
<td>14.6</td>
</tr>
<tr>
<td>4</td>
<td>1300</td>
<td>48</td>
<td>354</td>
<td>16.2</td>
</tr>
<tr>
<td>5</td>
<td>750</td>
<td>17.7</td>
<td>376</td>
<td>17.3</td>
</tr>
<tr>
<td>6</td>
<td>850</td>
<td>23</td>
<td>413</td>
<td>19.2</td>
</tr>
</tbody>
</table>

(approaching from the opposite direction) are constant and equal to 70 km/h. The following conclusion about the safety of the process of passing can be formulated: If traffic is heavier than 150 to 160 vehicles per hour (in both directions), it constitutes a traffic stream. In that case, the passing time should be less than 20 s and the passing distance less than 390 m. The results in Table 1 show that the allowable passing time is greater than the estimated passing time for the vehicles considered; however, the passing time for Vehicle 6 is very close to that limit. Passing in the assumed conditions can be dangerous for Vehicles 4, 5, and 6.

7. CONCLUSIONS

Automotive safety depends on the dynamic characteristics of the state of the moving vehicle, the road environment, and the driving skills. Drivers often make mistakes. Therefore, the problem of driver modeling seems to be very important. According to some studies, the probability of a mistake reaches a critical state when the accident rate is 1 per 1,000 cases. Because it is difficult for the driver to eliminate accidents below a certain level, an analysis of important situations which can cause an accident should be made and structural improvements should be made in automotive construction. Computer simulation constitutes an important means to analyze the problem. However, adequate mathematical models are necessary.

REFERENCES


