Glaser, Sebastien and Rakotonirainy, Andry and Gruyer, Dominique and Nouveliere, Lydie (2007) An Integrated Driver-Vehicle-Environment (I-DVE) model to assess crash risks. In *Proceedings 2007 Australasian Road Safety Research, Policing and Education Conference*, Melbourne, Australia.

An Integrated Driver-Vehicle-Environment (I-DVE) model to assess crash risks

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Abstract. A wide range of driver and vehicle models have been proposed by traffic psychologists, engineers and traffic simulation researchers to assess crash risks. However, existing approaches are often confined within a single discipline and lack concepts that formally express the complexity of interactions between the driver, vehicle and environment as well as the broader scope and the interdisciplinary nature of the driving behaviour modeling. For example, traffic psychologists have defined a driver performance model as the driver's perceptual and motor skills (capabilities), or what the driver can do. In contrast, a driver behavior model refers to what the driver actually does do while driving (Evans, 1991). A driver behaviour model is determined by an infinite and complex number of factors related to the environment, driver and vehicle but is not explicitly modeled in Evans (1991). Existing driver models lack substantive concepts that express the interactions between the Driver, Vehicle and Environment (DVE). A new Integrated Driver-Vehicle-Environment (I-DVE) model is formally presented as a set of concepts and equations representing interactions between the driver, vehicle and environment with the view to assess crash risks. The I-DVE model features realistic and measurable attributes, which ultimately influence the driving performance and associated crash risks. I-DVE model is validated in a simulation. The simulation uses empirical data related to Time To Collision (TTC), Energy Equivalent Speed (EES), injury severity and driver profile to assess crash risks. This paper *(i)* reviews existing driver modeling approaches and highlights the need for an integrated approach, *(ii)* defines a novel model capable of expressing risks associated interaction between the driver, environment and vehicle and *(iii)* provides directions for further research in driver behaviour modeling.

I. Introduction

One of the main objective of ITS research is to model, develop and validate technology that increase road users' safety. To guarantee a reliable and accurate modelling, it is necessary to investigate the driving behaviour; capturing the interactions between the driver, vehicle and the environment.

A model of driving behavior is a mathematical construct used as a tool in the study of the driving system. A driving behaviour model facilitates the design and benefit analysis of road safety interventions. A model helps to elucidate the complex structure and behavior of driving, and moves us toward a deeper appreciation of the general nature of driving.

A realistic driving behaviour is determined by an infinite number of factors related to the environment, driver and vehicle The road crashes statistics show unambiguously that the likelihood for being involved in a crash depends on complex interactions between several factors related to the:

- driver such as age, gender, experience, fatigue, sensation seeking, wearing seatbelt;
- vehicle such as speed, type of vehicle (sport vehicles, SUV), equiped with ESP;
- environment such as geometry of the road (curves, intersections).

The complex interactions between the driver, environment and vehicle are arguably the main reason why it is difficult to classify a driving behaviour as normal or risky. Existing ITS-based road safety interventions to remediate road crashes have focused on individual contributing factors without considering the whole driving context. As far as we know, there is no comprehensive model of driving behaviour which comprehensively integrates factors related to the interactions between driver, vehicle and environment. This paper presents an integrated model I-DVE, capturing information related to the Driver, Vehicle and Environment.

II. Related work

Several cognitive models of driving behaviour has been defined in the road safety literature (Ranney,1994). However, these models remain subjective. As a consequence, it is neither theoretically nor practically clear how driving performance and behaviour could be accurately modelled and measured with existing models. A driving situation is too complex to be understood by direct inferences from subjective and observed data.

Models representing full car dynamics have been proposed. They often used for numerical simulation. The simplest model, the bicycle model, has formed the basis for many vehicle control studies (Peng and Tomizuka ,1990). The bicycle model has been shown to be a relatively accurate representation for the dynamics of a normal passenger vehicle

Models representing the driving environment have been thorougly addressed by traffic engineers. Environment models include road geometry, road marking, position and number of signs or traffic models expressing flow and capacity. Research into modeling how a driver control a vehicle as an optimal control problem was pioneered by Baron et al (1970)

Models integrating elements related to the driver, vehicle environment are still rare. Torsten and von Stryk (2005) defined a model which integrates vehicle and driver elements using optimal control theory. The vehicle model includes longitidunal and lateral steering movements and geometrical axel parameters. The driver optimizes path and speed trajectories and therefore directly influences the vehicle model. The model can express actions/scenarios for different drivers and vehicles but does not explicitly include driver's motivations or profiles.

Cheng and Fujioka (1998) presented a hierarchical model representing the decision-making process, dividing it into a set of task plannings, manoeuvres and actions. The task planning is modeled with Fuzzy logic. Drivers do not require precise, numerical information input, and yet they are capable of controlling a vehicle and avoid crashes. A computational model that accepts noise, and imprecise inputs, would be much more closer to human thinking. Fuzzy Logic is a method for sorting and handling data which have the above constraints. Fuzzy Logic has been proven to be an excellent choice for many control system applications since it mimics human control logic. The central concept consists of maintaining a safe distance D_s, defined as follows:

$$D_s = \frac{V_f^2}{2B_{\max}} + \tau.V_f + \delta$$ where

- V_f is the speed of the following vehicle
- $B_{\max}$ the maximum deceleration

- τ the delay time of the driver
- δ a safety margin . separation between two vehicles when they stop.

The driver will initiate a passing, decelerating or return manoeuvre based on the assessment of D_s . The model does not represent explicitly the notion of risk, which is central to human decision making.

Im E. et al (2000) presented a bicycle model which includes longitidunal, lateral and yawing motion. The driver model corresponds to a risk model relative to the physical position of other vehicles, right/left side edges of the road and road curvature. These risks are represented as exponential functions. For example the risk element of right side edge of road is represented as:

$R_r = A_r e^{-\frac{1}{L_r} y_r}$ where $A_r = f(v), L_r = f(v)$, v velocity

Pellechia et al (2005) modeled the tactical level of driving decision. The driver model is purely reactive to the risk value thresholds recorded in the immediate vicinity of the vehicle. The vicinity is divided into 6 cells where the risk function is:

$\rho_i = \omega_v.vel + \omega_{\Delta v}.\Delta vel_i + \frac{\omega_x}{dist_i}$ where vel is the velocity , Δvel relative velocity, $dist$ distance to

a car in the cell into a single scalar weighted with $\omega_v, \omega_x, \omega_{\Delta v}, \omega_{vel}$. The model does not express driver's motivation model.

III. Risks and hierarchical decision making

Driving is a complex task. The decision-making is the most important cognitive aspect of the driving task. The driver's decision making is conditioned by the driver's perception and understanding of information from the environment and the vehicle. The decision making process is not amenable to a mere set of computational constructs.

A pattern of behaviour can be divided into a discrete set of rules covering strategic and tactical level of decision making (Michon, 1985) . For instance, a strategic rule could be "respect right of the way" and a tactical could be "minimum headway distance". The driver abides by these rules in "normal" situations. A deliberate action to violate a rule increases the driver's subjective risks. For example, the driver intentionally takes risks by decreasing the headway distance under the minimum distance.

Michon (1985) has defined a model to express the cognitive process of driver decision-making. This model allows quantitative measurement, and covers some concepts covered in functional models. Each level of the model corresponds to a decision making level requiring a different type of information. The three levels are strategic, tactical and operational:

- The strategic level is the highest level where general goals such as route choice, navigation and timing are set. Driving plan are formed and modified, goals established, prioritized, re-prioritized and satisfied or forgotten in real time as the driving task goes by continually assess different factors from the environment, driving and vehicle. Expectancies and preferences are also part of this level.
- The tactical level involves decision making related to the management of current driving activity such as manoeuvring. Tactical actions follow a pattern specific to drivers and can be assimilated to a profile. For example the length of the headway is a gap that each driver keeps based on their profile (e.g. aggressivity).
- The operational level involves vehicle handling or executive actions which implement the manoeuvres decided at the tactical level. This level is performed almost without conscious thought. The result of such actions are directly measurable as vehicle dynamics.

Michon's model corresponds roughly to the information processing model defined by Rasmusen (1986), whose hierarchical model exploits three levels of information characterized by their degree of complexity, namely knowledge, and skill base.

Our I-DVE model is based on Michon's three levels. I-DVE matches Michon's highly subjective factors with measurable crash factors related to DVE. Such a matching between objective and subjective contributing factors strengthens our multidisciplinary modelling. It also allows us to model realistic driving behaviours. The parameters we are taking into account for each level are:

- Operational level: Parameters related to vehicle handling and specific manoeuvres are often studied in driving assistance research. We use longitudinal control, lane keeping and lane change manoeuvres which have been used separately as robust control processes to model this level.
- Tactical level: Measuring factors related to this level is the core contribution of this paper. The main objective at this level is to define which is the most suitable manoeuvre that the driver model must choose in order to reduce risk
- Strategic level: Has two objectives in our model. First one is to achieve general goals, such as routing. This topic is well studied by map and personal navigation devices providers and can integrate multiple goals, such as toll-less trip, local interest point or re-routing as a result of road work or traffic jams. The second objective of this level in I-DVE is to act as a risk-cost balance according to the driver profile. This will be described in the following section.

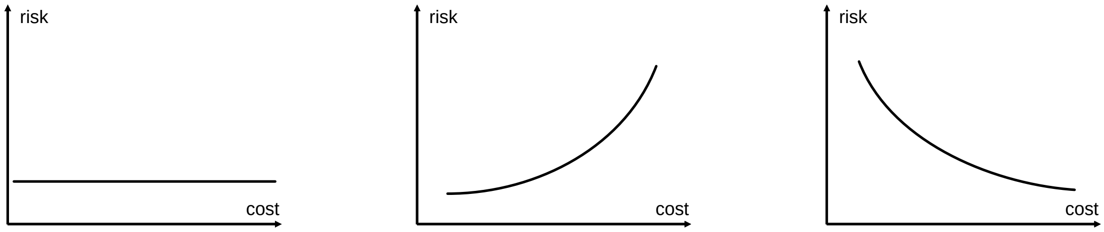
IV. Modelling Driver's profile as a risk-cost function

Drivers act in such a way as to maintain a certain level of risk (Wilde, 1982). A risk is often associated with a cost. For example driving fast is a highly risky behaviour that may lead to high cost. The cost is represented as the cost of hospitalization, property damage or fatalities. We model the driver's profiles as function of two variables:

- risk taking (, e.g, the average speed given the typology of road, the estimated duration of his trip…)
- cost, measurable consequence of a given behaviour (risk).

Concretely, this function defines the risk the driver is willing to take during the driving decision making. Each time the driver performs a task, a cost representing the consequence of the chosen behaviour is associated. This simple representation allows us to represent three generic driver profiles. These profiles were inspired by the social theory work by Abric (1984). Such a theory has been used in the French project, LAVIA on Intelligent Speed Adaptation (ISA), to study the "negative" and "positive" representation of speed among 394 participants. These generic profiles are:

- *Careful driver:* This profile is shown on figure 1(a). The driver maintains a constant level of risk regardless of the cost. For instance, on a highway, if his/her speed is constrained by another vehicle at a limit lower than his desired speed, the non contentment of this variable will not make him take hazardous decision, even with an increase in time and associated the cost.
- *Disregarding driver:* This driver, with the risk cost function 1(b), accepts an increased risk as the cost increases. As a result, using the previously described situation, the driver will react with a rapid lane change manoeuvre, which may be risky, in order to achieve a higher speed.
- *Hedonistic driver* is described in figure 1(c), and could be defined as the opposite of the disregarding driver profile. When the cost is low, the driver accepts risky situation, but, the driver becomes careful as the cost increases. For instance, on a highway the driver could drive at high speed in normal situation. However, when approaching a speed radar, he decreases his speed to reach legal limit.



(a) Careful driver (b) Disregarding driver (c) Hedonistic driver

Figure 1 : Risk function associated to driver profile

We acknowledge that drivers cannot have explicit or precise information that would enable them to accurately assess the riskiness of their behaviours. Driver's error can be the result of bad risk estimation.

Our approach consists of relating risk to the cost of choosing a particular action (consequence of a behaviour). Cost can be measured in different ways. For example drivers are more likely to experience serious injury if they do not wear seatbelt, driving whilst fatigue or speed over the limit. In this example cost is represented as severity of a crash, which in turn can be represented as the cost of hospitalization, insurance claim or social cost of fatality. Other types of costs have been widely discussed in the literature, such as the cost of waiting behind a slow moving vehicle.

The I-DVE model uses the cost-risk function, described in Figure 1 to determine the driver's behaviour in a vehicle following situation. For instance, let's assume that a driver A with a "Disregarding" profile is following another vehicle B. The speed of vehicle A is lower than its target speed. A cost will be associated with this such a low speed. If the risk associated with potential crashes against vehicle coming from the other lane is lower than the addition of risk in the current lane and the risk related to driver A's profile, then the model will imply the driver A will change lanes. It will stay on the same lane otherwise.

Our cost is based on the severity of a crash which is likely to occur if a particular action is performed. The cost related to the current and previous situation enable the modelling of a given amount of risk. Risk evaluation will be discussed in the next section.

V. Estimating risk

The risk, related to a manoeuvre, is modelled with two criteria:

- The probability that a crash (collision) will occur;
- Crash severity associated with the event which has occurred.

The type of crash we are considering in this paper are rear-end collisions between two vehicles. Therefore, the type of manoeuvre we are modelling are avoidance actions prior rear-end collisions. We only consider the first collision (impact) and not the other crashes caused by the initial impact.

VI.3. Crash severity

We focus on rear-end or frontal collisions. Such a focus simplifies the model. The driver could perform two types of manoeuvres prior the collisions. He/she could:

- Stay in the same lane in which the other vehicle is located. The driver has the potential to collide the following or previous vehicle.
- Change lanes, where the driver could potentially collide with vehicles in the other lane.

Equivalent Energetic Speed (EES) has been widely used to model the severity of crashes related to vehicle speed before and after the vehicle collision. EES corresponds to the deformation energy of a damaged vehicle during a collision given their respective speed and mass. The speed can be computed using the following equations:

$$\begin{cases} MV + M_iV_i = M\hat{V} + M_i\hat{V}_i \\ \frac{1}{2}MV^2 + \frac{1}{2}M_iV_i^2 = \frac{1}{2}M\hat{V}^2 + \frac{1}{2}M_i\hat{V}_i^2 \end{cases} \quad (1)$$

M and V are, respectively the mass and speed of the considered vehicle, variables with an indices i are related to the vehicle I and hat(?) variables are after collision. Thus, one can deduce the EES for the considered vehicle:

$$EES = \frac{2M_i}{M + M_i}(V_i - V) \quad (2)$$

Using data on EES and probability of injuries, we can define a scale of severity relative to the probability of light injury, heavy injury or fatality. Figure 2 represents the likelihood of a minor injury (MIAS >1, Maximum Abbreviated Injury Scale), a moderate injury (MIAS>2) and a severe injury (MIAS>3) based on Hobbs and Mills (1984).

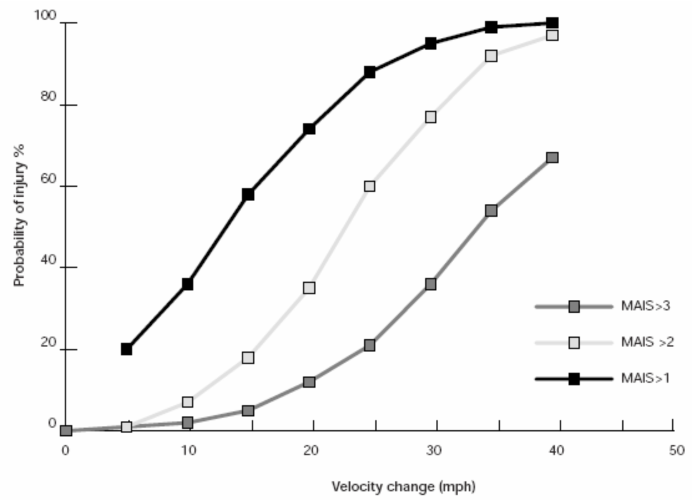


Figure 2 : Probability of injuries for a given EES

VI.4. Probability of collision

The probability of collision is the second aspect of the risk component. A collision occurs if the distance between two vehicles is zero. In such a case the crash probability is equal to one. From the opposite perspective, if the distance between the two vehicles is greater than the stopping distance, then probability of collision is equal to zero. The main problem is to define a function between these two extremes. In order to define the probability of collision, we summarize the variables describing the longitudinal behavior of the driver. For each of the criteria, their boundaries and advantages and disadvantages will be analyzed. The basic scenario is for a lead vehicle, namely vehicle i, and the considered vehicle behind.

Interdistance

The interdistance is the first level of description of longitudinal risk between vehicles. When the distance between vehicles is high, the risk is low and when the distance is low, the risk is high. This variable does not clearly describe the risk between vehicles, but gives a few indications. Some values are especially meaningful. First one is the distance of reaction, the distance the vehicle advances before driver reacts:

$$D_r = T_rV \quad (3)$$

Where T_r is the reaction time. Another remarkable distance is the stopping distance; it is given for a defined deceleration, gamma (taken positive):

$$D_s = T_r V + \frac{1}{2}\frac{V^2}{\gamma} \quad (4)$$

Beyond this distance, we could say that a vehicle is not exposed to a large risk.
We can propose a first definition of the probability of collision using this criterion which is shown on figure (3).

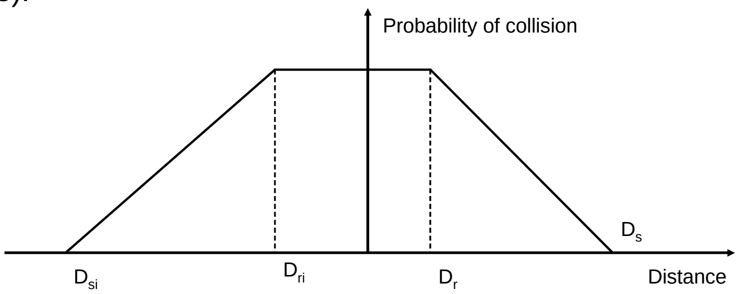


Figure 3 : Probability of collision based on a distance definition

When the vehicle *i* is behind, the considered parameters in the formulae are those of the vehicle *i*, so the probabilities are symmetric.

The main problem with this indicator is that it does not take into account the relative speed of vehicles, thus, the probability of collision is the same if the vehicles are approaching or moving away. A solution shall be to use the time to collision.

Time to Collision (namely TTC)

Hayward (1972) defined TTC as: "The time required for two vehicles to collide if they continue at their present speed and on the same path". The TTC formula is:

$$TTC = \frac{D}{V - V_i} \quad (5)$$

When the relative speed is null, the TTC is infinite, but this does not take into account the relative distance, which could be small. If the TTC is negative, the probability of collision is low, as the vehicles are moving away from each other. TTC low positive values represents a high probability of collision as the vehicles are either near or (and) quickly approaching. The problem is to define TTC boundaries. First one will be a TTC limiting the probability of one and second one from which, the probability of collision is considered as null.

The ARCOS project defined the TTC boundaries, giving a scale of action to drivers. At a TTC of 1.5s, the system emits a first level of warning. This warning is strengthen if TTC drops below 1.3s and finally, under 1s, an automatic system is switch on. On the other hand, the Prevent project proposes to follow a potential risky vehicle as soon as their TTC drops below 10s. We chose these boundaries to define our probabilities, according to the figure (4).

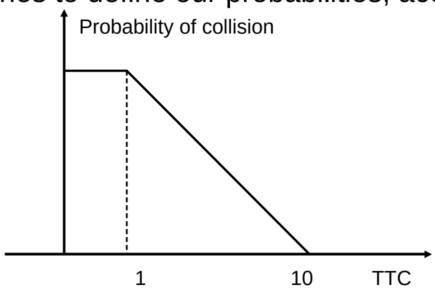


Figure 4 : Probability of collision based on a TTC definition

VI. Case study, evaluation of risk

Given the previous definition of the severity and probability of collision, we have to assess risk in various situations. These situations could be risky or non-risky, and we will see how the two attributes interact. For the sake of simplicity, our scenarios consist of car following wth two straight lanes on a highway. We only considered a leading vehicle with a given speed V_i at a distance D_i. The vehicle i mass is M_i. All simulations are running with the MatLab environment. Risk is computed as the product of probability and gravity.

VI.1. Scenario 1

The vehicle i is in front of the considered vehicle, at a distance D_i of 20 meters, its speed is 30m/s, all reactions times are set to 1s and the deceleration is 4m/s².

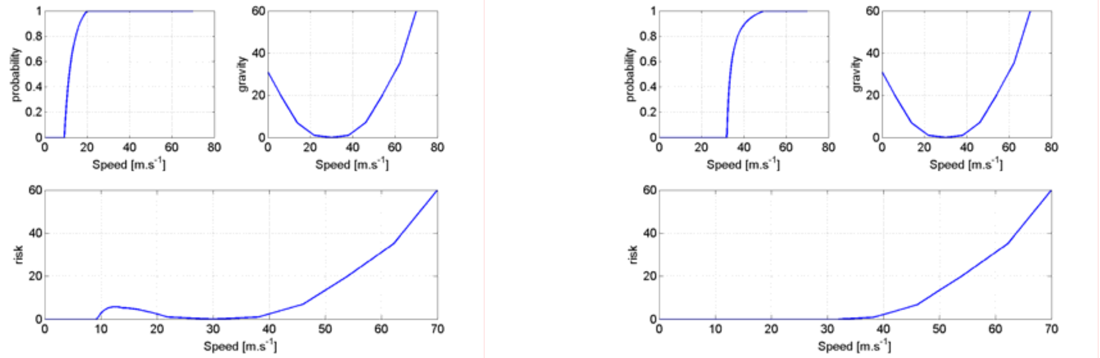


Figure 5 : Evaluation of risk using distance (left) and TTC (right) criteria

For each computation of risk, presented on figure 5, the speed of 30m/s is a good trade-off for achieving high speed with low risk.

However, at such a speed, the inter-vehicular distance is below the distance of reaction which may represent a risky situation if the driver of vehicle i was to make an emergency brake. The evaluation using distance presents an artefact of our model: in reality, the situation is less risky at 15m/s than 30m/s but the final risk is higher.

VI.2. Scenario 2

The other vehicle is now behind the studied vehicle, at a distance D_i of -30m and its speed is 20m/s. All others parameters remain unchanged.

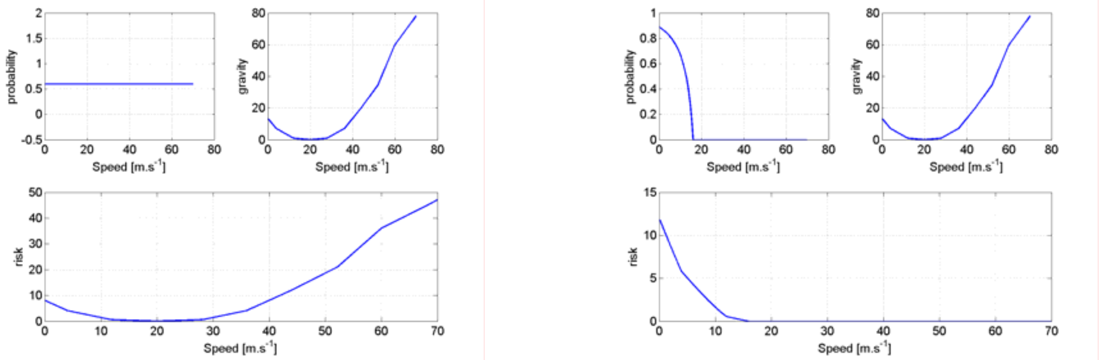


Figure 6 : Evaluation of risk using distance (left) and TTC (right) criteria

The evaluation of risk using distance, shown in figure 6, is meaningless: the situation is not risky, as the distance is higher than the distance of reaction time of the i vehicle but the evaluation shows the opposite. On the other side, the evaluation using TTC has good behavior, but the risk at speed close to 20m/s does not integrate the situation of an emergency brake, as previously.

As a partial conclusion, the risk evaluation using TTC has a good behavior, but not to the risk related to an emergency braking, so the relation of a low inter-vehicular distance must be taken into account.

Evaluation of inter vehicular distance related risk

The leading vehicle, *i*, is supposed to do an emergency braking procedure, with a given deceleration, after a reaction time T_r, the following vehicle decelerates with its maximal deceleration. Three cases may occur:

- The following vehicle collides with lead vehicle within the given reaction time
- The following vehicle collides with the lead vehicle after reaction time concludes
- Both vehicles stop without collision

The first case may happen if speed of the vehicle *i* is high enough and the inter-vehicular distance is below a first limit, D_{nr}:

$$D_{nr} = (V - V_i)\,T_r + \frac{\gamma_i}{2} T_r^2 \quad (6)$$

The difference of speed is, at the time of the collision:

$$\Delta V = V - V_i + \gamma_i T \quad (7)$$

In the second case, the speed of the vehicles can be given using the following equation:

$$\begin{cases} X_i = Di + V_i T - \frac{\gamma_i}{2} T^2 \\ X = VT - \frac{\gamma}{2}(T - T_r)^2 \end{cases} \quad (8)$$

A collision occurs if Xi = X and if this collision occurs, the difference of speed will be:

$$\Delta V = V - V_i + (\gamma_i - \gamma)\,T + \gamma T_r \quad (9)$$

Under the assumption that both vehicles brake with the same deceleration, the maximal inter-vehicular distance in this case is Dr, described previously. Moreover, using equation (9), a small inter-vehicular distance could be assimilated to an additional risk as an increase of the EES of γTr. This correction on the EES is applied accordingly to the distance, as shown on figure 7.

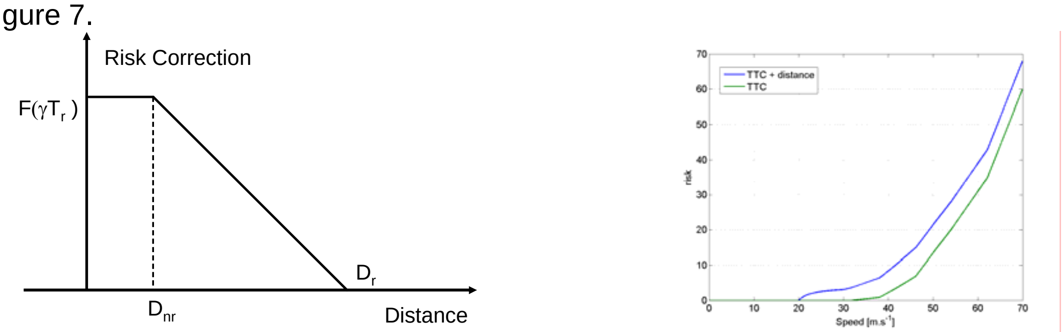


Figure 7 : EES correction and impact on scenario 1

According to scenario 1, the new maximal speed for minimal risk is now 20m/s. This speed achieves the regular inter-vehicular distance, which enables sufficient time for driver reaction in an emergency braking situation.

VI.3. I-DVE Model and driving decision

On a simple lane or a multi lane road, the main problem that we simulate with our driver model is to choose which manoeuvre is the most suitable (e.g pass or keep following). One example has already be given in section 4, now we will explain in-depth the algorithm that our model follows.

According to previous simulation, the risk criteria can now be computed for each vehicle in the direct vicinity of the considered vehicle. Two possibilities arise:

1. On a one lane, summing the contribution of risk for front and rear vehicles directly leads to a risk definition of a given speed, looking for a minimum risk value gives a speed to follow by our model in the considered lane.

2. On a multi-lane road, the sum is now calculated for each lane. Minimum values of risk on each lane give the best suitable speed for each lane.

On a multi-lane road, the driver can choose to change lanes instead of staying in the same lane, behind the front vehicle. The choice between this two manoeuvres is determined by risk minimization. The level of risk doesn't change when the driver choose so stay on the same lane. A driver will undertake a changing lane manoeuvre if the new risk is below the previous one. The new risk would be calculated from the crash/severity relative to the driver's profile. Driver's profile is related to the driver's strategic decision level (Michon, 85) Therefore our model explicitly combine risks related to vehicle dynamics and risk related to psychological profile of the driver to model driver behaviour

VII. Conclusion

We have presented in this paper an integrated Driver Vehicle Environment model which takes into account a three-layer representation of driver behaviour. We focus our development on the strategic layer, where risk cost function is defined and balanced, and on the tactical layer, where risk is evaluated and the manoeuvre assessed.

Using this model, we could be sure that at any time step, the vehicle is in a less risky situation. Moreover, a risk-cost balance at a strategic level enables the driver model(led) to accept more risky situations in order to achieve his goals.
The model has been validated on the simple case of an obstacle or a slow moving vehicle. Further improvement of this model will need the knowledge of real situation and naturalistic studies of the driver.

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