A Microsimulation Traffic Model to Estimate Accidents due to Reduced Sight Distance

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Synopsis

The sight distance available on existing roads is very often lower than the stopping sight distance needed to avoid the collision with standing obstacles in the travelled way. When this occurs many rear-end crashes can happen because each follower could not see his/her leader. The investments needed to increase the sight distance to the value arising from the actual speed of the vehicles are usually very high. Due to budget constraints road agencies have to select the road segments to improve by estimating their safety performance. This activity is not an easy task. The most useful approach to address this type of problem is to use a microsimulation traffic model, which has to consider roadway configuration, sight distance, roadway surface condition, braking lights, human behaviour, etc. With this type of tool it would be possible to define the number of collisions or loosing control vehicles, their corresponding speed, the number of vehicle at collision “risk” in the queue, etc.

In this paper the structure of a microsimulation model tacking into account most of the influencing factors is presented. It has been conceived with the aim to reproduce what happens in situations where the sight distance is reduced.

The first part of the paper concerns the description of the modules in which the model is organized. The second part presents an application to a road segment where a standing obstacle exists in a curve and the sight distance is limited by a retaining wall. This situation has been compared with a similar road segment where the sight distance complies with the Italian Standard.

The results obtained show the higher is the flow rate the lower are the rear-end crashes and loosing control vehicles. This is due to the fact that for high flow rate the vehicles are slower and a very high interaction exists among them, so that the braking lights of the leaders suggest to the followers to adopt a prudential behaviour.

A Microsimulation Traffic Model to Estimate Accidents due to Reduced Sight Distance

The sight distance, available on existing roads, is very often lower than the stopping sight distance needed to avoid the collision with standing obstacles in the travelled way. When this occurs many rear-end crashes can happen because each follower vehicle could not see its leader. The investments needed to increase the sight distance to the value arising from the actual speed of the vehicles are usually very high. Due to budget constraints road agencies need to select the road segments to improve by estimating their safety performance. This activity is not an easy task. The most common approaches comprise: averages from historical accident data, predictions from statistical models based on regression analysis, results of before and after studies and judgments made by experienced engineers. The Federal Highway Administration has developed for the IHSDM an accident prediction algorithm that combines the previous approaches.
The methods above cited, however, could be considered of intermediate level and are the result of experiences gathered on different sites. As a matter of fact, they are not able to estimate the number of collisions due to sight obstructions or local decreases/increases of tire-pavement friction. The most useful approach to address this type of problem is to use a microscopic traffic simulation model, which has to consider roadway configuration, sight distance, roadway surface conditions, brake lamps, “realistic” human behavior, etc. With this type of tool it would be possible to define, for every specific situation, the number of collisions or loosing control vehicles, their corresponding speed, the number of vehicles in the queue at collision “risk”, etc. A general and complete microsimulation model taking into account all the influencing factors has not been developed yet. An overview of the models available and their validity is presented in the paper of Brackstone and McDonald (1).
In this paper the structure of a new microsimulation model is presented. It has been conceived with the aim to reproduce what happens for a not visible standing obstacle on the carriageway. The first part of the paper concerns the modules and the corresponding tasks in which the model is organized. The second part presents the application of the model to a road segment where an obstacle exists in a curve and the sight distance is limited by a retaining wall. This situation has been compared with a similar road segment where the sight distance complies with the Italian Standard. This application has to be considered only as an example. In the future, after a tuning task carried out by a driving simulator and an instrumented vehicle, the model will be used in a large research activity aimed at estimating the safety performances of situations not complying with design standard. The model will be also improved taking into account external signals which show the presence of not visible standing obstacles.

MODEL DESCRIPTION

The aim of the micro-simulation model proposed is to estimate the number of rear-end crashes and the loosing control vehicles that may occur as a consequence of a standing obstacle on the carriageway. Examples are: stopped vehicles because of a motoring breakdown, objects fallen down from a truck, motorcycles lying on the road, vehicles crossing a median barrier etc. Through this model we are able to define, as a function of time, the position, the speed and the acceleration of each vehicle on the road taking into account roadway configuration, sight distance, roadway surface conditions, brake lamps, “realistic” human behaviour and vehicle interactions.
It is a stochastic model where almost all the variables are defined by probability functions. Its application allows to define the probability function of accident number, given the presence of the obstacle, the speed at which accident occur, the accident process time, etc.
The model doesn’t consider the lane changing of the vehicles. In this conditions a vehicle cannot overtake a slower one, but is constrained to reduce its speed in order to follow it. For this reason the results of the model are restricted to the conditions where the lane changing is forbidden (segments of two lane roads where overtaking is prohibited) or not possible (lanes next to the median on divided highways).
The model includes different modules having specific tasks:

- the generation module;
- the perception module;
- the tactical module, defining the driving pattern;
- the control module, defining the user behaviour for each driving pattern;
- the operative module, defining the acceleration or the deceleration values the vehicle really adopts;
- the collision module.

In the following sections, the mentioned modules are described in detail. The basic assumption in these modules will be checked by several experiments carried out with a dynamic driving simulator and an instrumented vehicle able to gather most of the parameters used to characterize driver behavior. These advanced instruments will be available at the “Centro di Competenza Trasporti” of the Campania Region in Italy.

Generation Module

- *Road generation*

The procedure defines a road segment by four parameters as a functions of the progressive distance, *s*: the curvature radius, *r(s);* the grade; the distance, *DTLC(s)*, to the external lane edge used for Time to Lane Crossing calculation (2); the sight distance, *D(s)*, allowed by the road and a tire-pavement friction correction factor, *FFAD1(s)*.
The sigth distance takes into account the position of obstacles on the roadside(safety barriers, retaining walls, trees etc) and in general is defined with reference to the axis of the travelled lane. The last condition however is almost correct if the leader vehicle is running or has stopped without colliding with the vehicle in front of it (figure 1). If the leader vehicle, instead, has a high speed rear–end crash with the vehicle in front of it and stops after a high rotation around its yaw axis the sight distance for the follower may be greater (compare figure 1 with figure 2). The procedure considers this difference in the sight distance.
The pavement friction correction factor is used to take into account of local roadway surface conditions eventually existing. The model also takes into account two other correction factors: *FFAD2* and *FFADabs*; which are related to vehicles and they will be discussed in the following section. The final tire-pavement friction is therefore obtained by the following expression:

$$AD(s, veic, v) = FFAD1(s) \cdot FFAD2(veic) \cdot FFADabs(veic) \cdot FAD(v) \quad (1)$$

being:

- *AD(s, veic,v)* : final pavement friction coefficient;
- *FFAD1(s)* : correction factor related to local roadway surface conditions;
- *FFAD2(veic)* : correction factor related to the vehicle;
- *FFAabs(veic)* : correction factor due to ABS;
- *FAD(v) :* pavement friction coefficient related to the speed of the vehicle.

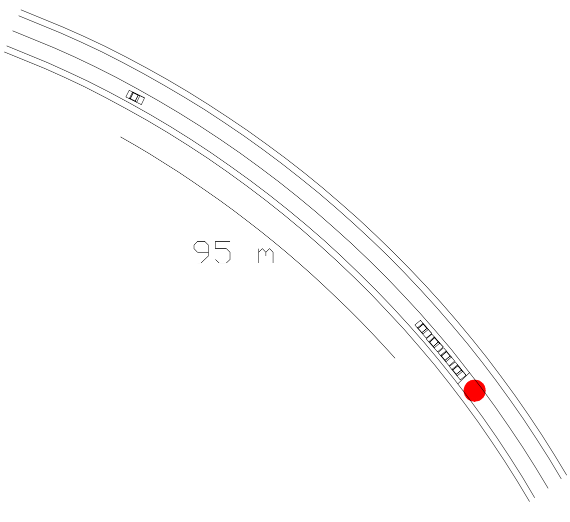

Figure 1 – Sight distance when the leader vehicle stops without colliding with the vehicle in front of it

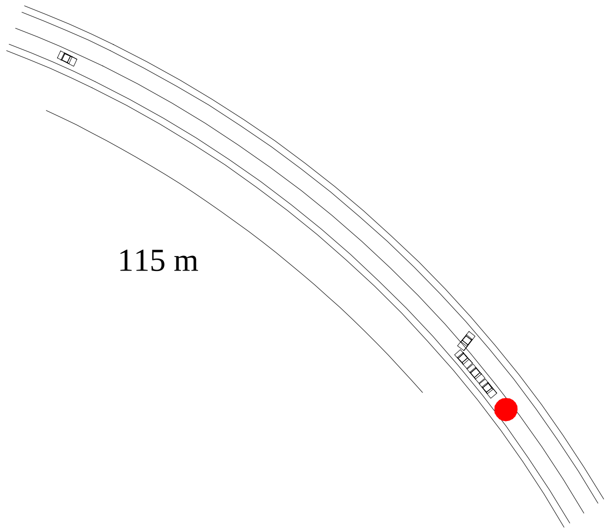

Figure 2 – Sight distance when the leader vehicle stops after a high rotation around its yaw axis

➢ *Obstacle generation*

The obstacle is characterized by its position and appearance time

➢ *Vehicle-user generation*

Each vehicle-user is characterized by means of the departure time (*tstart*), the speed he/she wishes to reach on tangents (*Vdes_tan*), the speed he/she wishes to reach in curve (*Vdes_cur*), the perception and reaction time for unexpected obstacles (*Prt_ob1*), the perception and reaction time for alerted users (*Prt_att*), the presence of ABS device, the friction correction factor related to tire conditions (*FFAD2*), the mean Time gap (*Tg_mean*), the critical Time gap (*Tg_crit*), the mean Time to Collision (*TTC_mean*). All these factors are generated for each vehicle by means of their probability functions.
The numerical values below reported (mean and standard deviation for the factors considered) have to be intended as an example and they can be changed for specific situations.

Departure time (*tstart*) : it is generated according to the probability function of temporal distance , that it is assumed to be a Gamma type one:

$$f(\tau) = \frac{\lambda}{\Gamma(k)}(\lambda\tau)^{k-1}e^{-\lambda\tau} \qquad (2)$$

where Γ(k) is the Gamma function:

$$\Gamma(k) = \int_0^{\infty} y^{k-1}e^{-y}dy \qquad (3)$$

the parameter k is obtained by the expression (4) as function of the flow rate on the lane Q (veh/h/lane):

$$k = 10^{-0,051+0.00044*Q} \qquad (4)$$

the parameter λ is obtained by the parameter k and flow rate Q:

$$\lambda = k \frac{Q}{3600} \qquad (5)$$

The departure time of a generic vehicle *i* is obtained therefore by the expression:

$$t_i = \sum_{j=1}^{i} \tau_j$$

Desired speed on tangent (*Vdes_tan*) : the desired speed on tangent is considered as a stochastic variable whose probability law is a Gaussian type:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \qquad (6)$$

being:

- μ is the mean speed in free flow conditions;
- σ is the speed standard deviation.

A suggestion for the mean and standard deviation of the speed can be drawn from the studies of Grossi and others (3). These researches, carried out about some two lane roads and divided highways, have shown that the mean and standard deviation can be obtained by the following expressions:

- $\mu = 137.25 - 0.0028 \cdot Qc$ [km/h] for divided highways; (7a)
- $\mu = 100.89 - 0.008 \cdot Qc$ [km/h] for rural two lane roads; (7b)
- σ = 15-20 km/h.

where Qc is the traffic flow on the carriageway expressed in vehicles per hour
Many studies, among which the Kyte's ones (4), show that, in conditions of wet road, there is a reduction of the flow speed from 10 to 20 km/h.

Desired speed in curve (*Vdes_cur*) : in order to evaluate this speed Grossi (3) suggests:

$$V85_{curve} - V85_{tagent} = -\frac{3512}{R} \qquad (8a)$$

being:

- V85 is the 85th percentile of the speed [km/h];
- R is the curve radius [m].

Assuming that the speed can be represented through a Gaussian probability law, the 85th percentile of the speed can be obtained by the expression:

$$V85 = \mu + 1.04 \cdot \sigma \qquad (8b)$$

and considering the same standard deviation, the link between mean speed values on tangent and curves become:

$$\mu_{curve} - \mu_{tagent} = -\frac{3512}{R} \qquad (9)$$

Perception and reaction time for unexpected obstacles (*Prt_ob1*) : this parameter has been also characterized by means of a Gaussian probability law. The values of mean and standard deviation could be defined by Lerner studies (5), where they are 1.5 and 0.4 seconds respectively.

Perception and reaction time for alerted obstacle (*Prt_att*) : also in this case it is used a Gaussian probability law. The values of mean and standard deviation could be obtained by Olson and Sivak studies (6), where they are 0.72 and 0.10 seconds respectively.

Presence of the ABS device on board (*ABS*) : the presence of this device is established by assigning its percentage of diffusion. Its effect can be modelled as an amplification factor for the tire-pavement friction. It could be assumed equal to 1.25.

Friction correction factor related to the vehicle (*FFAD2*) : this factor has been considered in order to take into account the different conditions of the tires among the vehicles. Currently, it has been considered equal to 1. Researches have already been planned to define a specific probability law.

Mean Time gap (*Tg_mean*) : this parameter, together with others, allows to define the limit beyond which the follower perceives the leader in car following condition. The choice of such value could be done referring to the set of 117 users included in the report of Delorme and Song (7) and assuming it as representative of road users. The *Tg_mean* is also used in order to define the "equilibrium" distance between leader and follower after the car following process is completed (see figure 6).

Critical Time gap (*Tg_crit*) and mean Time To Collision (*TTC_mean*) : these two parameters, together with *PRT_ob1* allow to define the limit beyond which the user decelerates taking his foot out the accelerator pedal or he start to press the brake pedal. Both parameters could be generated using the set of users included in (7).

As evidenced by Brackstone and McDonald (8), a common assumption about car-following is that each driver maintains a constant time gap, which is all time “safe”. A peculiarity of this model consists in using two different values of time gap and not ensuring drivers to be “safe”.

Perception Module

- *Geometry Perception*

The user road perception is carried out by estimating the Time to Line Crossing (*TLC*) in every position given by the expression:

$$TLC(s) = \frac{DTLC(s)}{v(s)} \qquad (10)$$

- *Leader visibility*

The leader vehicle becomes visible if the difference between its progressive distance and the follower one is smaller than the sight distance calculated in the follower vehicle position:

$$s_l - s_f < D(s_f) \qquad (11)$$

- *Leader perception*

The leader perception relates on six entities: the relative distance between the rear part of the leader vehicle and the front bumper of the follower vehicle (the range *R*), the relative speed of the leader respect to the follower (the range rate $\dot{R}$), the speed of the follower (v_f), the turned on brake lamps of the leader, the speed of the leader vehicle (v_l) and its acceleration (a_l).
Some of such entities are arranged in order to obtain other entities that are used to define if the leader vehicle is perceived or not. The relative distance and the follower speed allow to define the current Time gap, *Tg*:

$$Tg = \frac{R}{vf} \qquad (12)$$

R and $\dot{R}$ are used in order to obtain the angular velocity ($\dot{\theta}$) and the Time to Collision (*TTC*) by means of the following expressions:

$$\dot{\theta} = -\frac{d \times \dot{R}}{R^2} \qquad (13)$$

$$TTC = -\frac{R}{\dot{R}} \quad (14)$$

where *d* it is the vehicle leader width.

The leader could be considered completely "absent" for the follower if *Tg* is greater than 5 seconds. In such condition the speed of the follower is constrained only by the alignment of the road. If *Tg* is smaller than 5 seconds and no one of the following conditions is satisfied, the leader vehicle is present but the follower does not perceive any speed difference:

$$Tg \le Tg\_mean \quad (15)$$

$$\dot{\theta} \ge 0.003 \text{ [rad/sec]} \quad (16)$$

Some researches, carried out by Hoffmann and Mortimer (9), indicate the driver perceives the relative speed when the angular velocity is above a threshold value of about 0.003 rad/s. So, if at least one of the conditions (15) and (16) is satisfied the follower perceives the speed difference and therefore, after a time interval (in the following paragraph defined), he/she will perform at first a deceleration manoeuvre and then a weak acceleration in order to reach the leader speed with a time gap equal to *Tg_mean*. When this last condition occurs, the follower is considered "joined" to the leader. In figure 3 it is reported the region of the space ($\dot{R}$, R) where the speed difference is perceived. The perception curve is obtained from the following two equations:

$$\dot{\theta} = 0.003 \text{ [rad/sec]} \quad \text{valid for} \quad |\dot{R}| > |\dot{R}_{Tg\_mean}| \quad (17)$$

$$Tg = Tg\_mean \quad \text{valid for} \quad |\dot{R}| \le |\dot{R}_{Tg\_mean}| \quad (18)$$

being:

$$|\dot{R}_{Tg\_mean}| = \frac{(Tg\_mean \times v_f)^2 \times 0.003}{d}$$

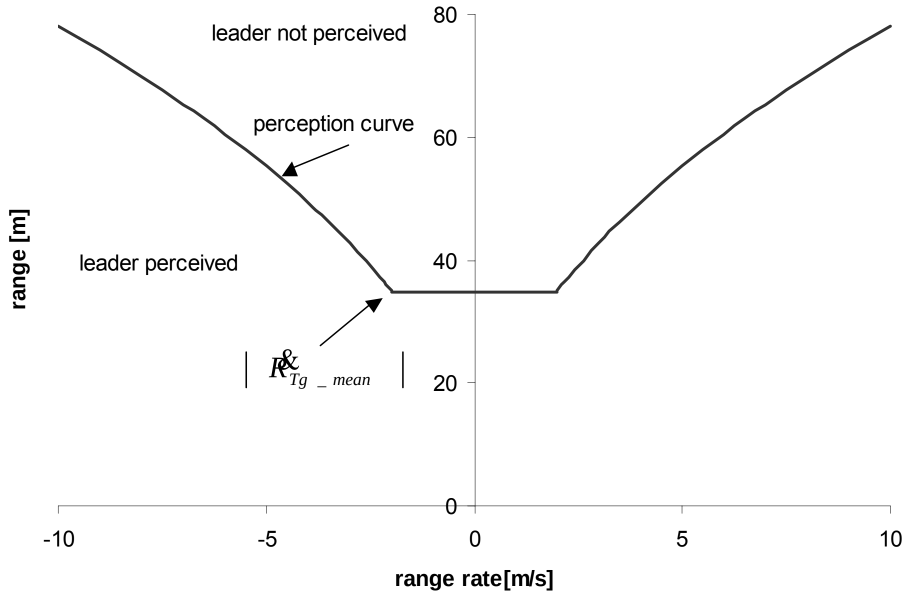

Figure 3 – Range rate-range domain with perception curve

If the leader vehicle is visible, its brake lamps are turned on but it results absent (*Tg* > 5 sec) .It is not taken into account by the follower. If the leader is visible and *Tg* < 5 sec then the turned on brake lamps affect the follower behaviour.
The perception conditions are summarized by means of three variables: *percep*, *join* and *st_on*. The first variable, *percep*, assumes value 0 if the leader is not visible or "absent" or not perceived; it assumes instead value 1 if the leader is visible and, at the same time, the follower perceives the speed difference. The second variable, *join*, assumes value 0 until the follower has not reached the rear part of the leader vehicle with a *Tg* equal to *Tg_mean*; it assumes instead value 1 if the follower is joined to the leader. The third variable, *st_on*, assumes value 0 if the leader is not visible or if the *Tg* is greater than 5 seconds or if the leader brake lamps are off; it assumes instead value 1 if at the same time the leader is visible, the *Tg* is smaller than 5 seconds and the brake lamps are on or the leader vehicle has stopped its run. When the value of each variable changes from 0 to 1 the time of this variation is defined. In this way three others variables are obtained: *Tpercep*, *Tjoin* and *Tst_on*.

Tactical module

By the variables *percep*, *join* and *st_on* defined previously, this module characterizes in a dynamic way the driving pattern performed by the user. The possible driving patterns are:

1. free vehicle;
2. vehicle in car following with leader having braking lamps off;
3. vehicle in car following with leader having braking lamps turned on;
4. vehicle influenced by the leader with braking lamps turned on but not being in car following;
5. vehicle joined to the leader at the same speed;
6. vehicle joined to the leader which decelerates or turns on his/her braking lamps.

When driving, each user adopts one of the previous patterns accordingly to the situation he/she is experiencing.

- The driving pattern 1 *(free vehicle)* occurs when *st_on = 0, percep = 0* and *join = 0* at the same time. In such condition the vehicle speed is constrained only by the road alignment.

- The driving pattern 2 *(vehicle in car following with leader having braking lamps off)* occurs when: *percep = 1, join = 0, st_on = 0*. The time variables result in this case: *Tpercep = Tp*, *Tjoin = 0*, *Tst_on = 0*, where *Tp* refers to the instant in which the variable *percep* is changed from 0 to 1. In such situation, the driving behavior of the follower is influenced by the road alignment and by the leader behavior. The response to the motion of the leader starts after a time interval defined in the control module.

- The driving pattern 3 *(vehicle in car following with leader having braking lamps turned on)* occurs when *percep = 1, join = 0, st_on = 1*. In this case the time variables result: *Tpercep = Tp, Tjoin = 0, Tst_on = Ton*, where *Tp* and *Ton* correspond to the instants in which the variable *percep* and *st_on* change from 0 to 1. In such situation the driving behavior of the follower is conditioned by the road alignment and by the leader behavior. The response to the motion of the leader starts after a time interval defined in the control module.

- The driving pattern 4 *(vehicle influenced by the leader with braking lamps turned on but not being in car following)* occurs when: *percep = 0, join = 0, st_on = 1*. In this case the time variables result: *Tpercep = 0, Tjoin = 0, Tst_on = Ta,* where *Ta* refers to the instant in which the variable st_on changes its value from 0 to 1. In such situation the driving behavior of the follower vehicle is conditioned by the road alignment and by the leader behavior. The response to the motion of the leader starts after a time interval defined in the control module and equal to *Prt_ob1*.

- The driving pattern 5 *(vehicle joined to the leader at the same speed)*occurs when: *percep = 0, join = 1, st_on = 0*. In this case the time variables result: *Tpercep = 0, Tjoin = Tjoi, Tst_on = 0,* where *Tjoi* refers to the instant in which the variable *join* changes from 0 to 1. In such situation the follower is very attentive to the leader driving behaviour and his/her motion is conditioned by the road alignment only.

- The driving pattern 6 *(vehicle joined to the leader which decelerates or turns on his/her braking lamps)* occurs when: *join = 1* and at least one of the two variables *percep* and *st_on* is equal to 1. In such situation the driving behaviour of the follower is conditioned by the road alignment and by the leader behaviour. The response to the motion of the leader starts after a time interval defined in the control module and equal to *Prt_att*.

Control Module

For each driving pattern a control is defined in this module; in particular, the instant when the follower reacts to the leader and the deceleration that he/she would like to perform are determined.

- *Control for the driving pattern 1*

In this driving pattern the user maintains his/her speed until *TLC* is greater than 2 seconds. When the *TLC* becomes smaller than 2 seconds the user tends to decelerate linearly with the progressive distance until the desired speed in the curve is reached. The expression used is:

$$v(s) = v_{TLC=2} + \frac{v_{des\_cur} - v_{TLC=2}}{s_{cur} - s_{TLC=2}} \cdot (s - s_{TLC=2}) \qquad (19)$$

where:

- $v_{TLC=2}$ is the speed where TLC = 2 seconds;
- $s_{TLC=2}$ is the progressive distance where TLC = 2 seconds;
- v_{des_cur} is the desired speed in curve;
- s_{cur} is the progressive distance at the beginning of the curve.

Figure 4 shows the speed profile performed during the transition from the tangent to the curve in the hypothesis that on the tangent the speed is equal to the desired speed.

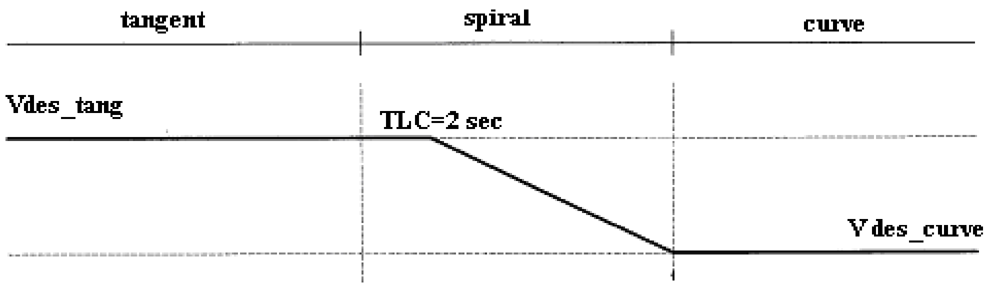

Figure 4 – Speed reduction schema from tangent to curve

- *Control for the driving pattern 2*

In this driving pattern it is firstly performed the control due to the road alignment and then the control due to the perception of the leader. The first control is similar to the one of the pattern 1 and the corresponding deceleration, if necessary, is evaluated. The second control evaluates at first the instant when the follower begins to decelerate and then the deceleration that he/she would like to perform.
The instant in which the vehicle begins to decelerate (*Tperc_react*) is obtained taking into account the perception and reaction time for unexpected obstacle (*Prt_ob1*) and evaluating the time *Treaz** when at least one of the two following conditions is satisfied:

$$TTC \leq TTC\_mean \qquad (20)$$

$$R \leq Tg\_crit \times v_f \qquad (21)$$

If the following condition is verified:

$$Treaz^* \geq Tpercep + Prt\_ob1 \qquad (22)$$

then:

*Tperc_react = Treaz** (23)

Instead, if the following condition is verified

Treaz < Tpercep+ Prt_ob1* (24)

then:

Tperc_react = Tpercep + Prt_ob1 (25)

If this control was not carried out it could happen that the user reacts, during the simulation, to the perception of speed difference before than he/she would react to a leader braking with brake lamps turned on.

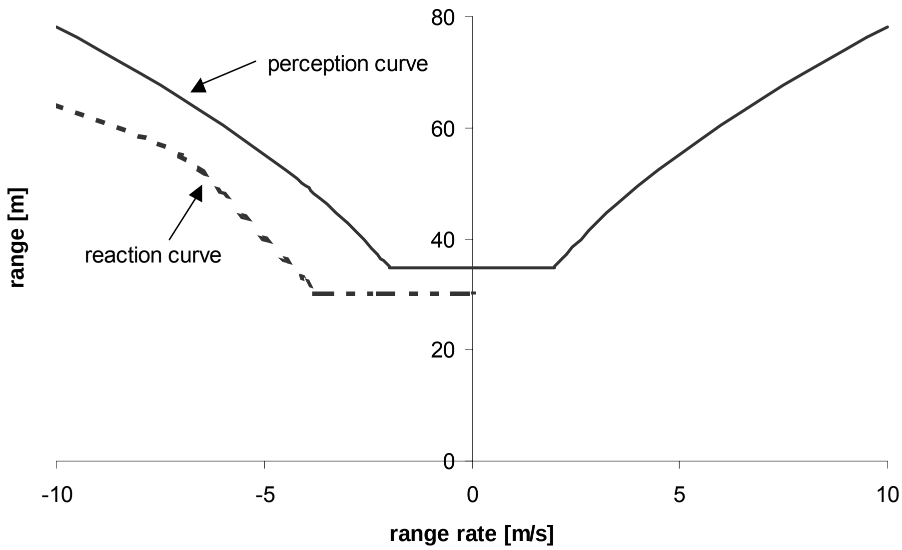

Figure 5 – Range rate-range domain with perception and reaction curve

In figure 5, in the space ($\dot{R}$, *R*), the curves representing perception and reaction for a follower running at 26 m/s and for a leader running at 23 m/s, are reported. The last mentioned curve takes also into account the verification on the *Prt_ob1*.

If the leader speed is constant, the joining process of the follower is performed in two phases. The first phase consists in a deceleration and leads the follower to a speed lower than the one of the leader, the second phase is instead a weak acceleration (0.3 m/sec^2) and leads to a speed equal to the speed of the leader and to a *Tg* equal to *Tg_mean*.

Figure 6 show how the entire perception-joining process has been structured. Until the point A the speed difference is not perceived. In the B point the reaction begins and the deceleration that leads to the point C is reached. The deceleration continues until the point D, then an acceleration of 0.3 m/sec^2 leads to the point E. In this point we have $v_f = v_l$ and *Tg = Tg_mean* (and obviously *R = Tg_mean x* v_l). In the entire joining process the follower reaches the leader speed two times: in C (where *R = Tg_crit x* v_l) and in E. The acceleration used in the deceleration phase (t > *Tperc_react)* can be calculated by imposing the "passage" through the C point:

$$a_f = -\frac{(v_f - v_l)^2}{2 \cdot [R - (v_l \times Tg\_crit)]} \quad (26)$$

If the leader is instead in deceleration, the joining process is performed by defining for each time step the acceleration that allows the follower to reach the leader speed when *R = Tg_crit x* v_l:

$$a_f(t) = a_l(t) - \frac{\left(v_f(t) - v_l(t)\right)^2}{2 \cdot \left[R(t) - (v_l(t) \times Tg\_crit)\right]} \quad (27)$$

After the instant where $R = Tg\_crit \times v_l$, the follower acceleration is assumed to be equal to the leader one. At the end of the control procedure the deceleration the user would like to perform is the bigger one between the deceleration due to road alignment adaptation and the deceleration needed to join the leader.

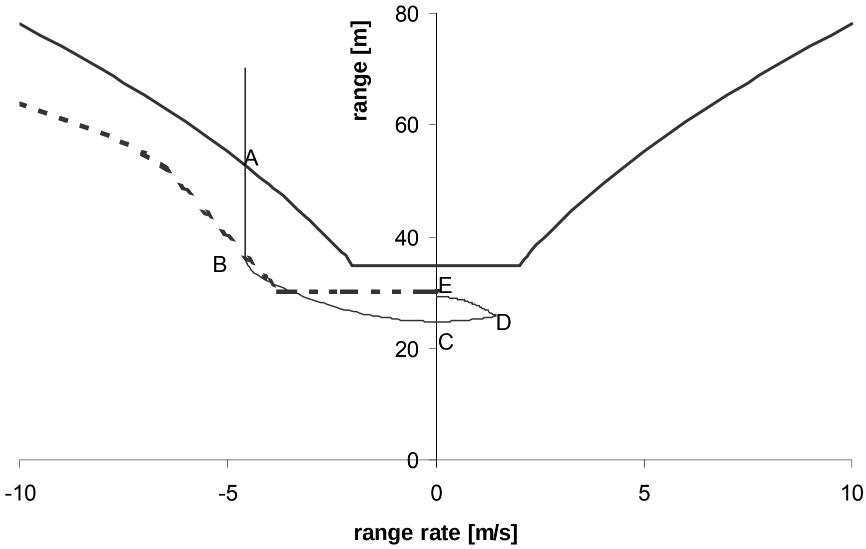

Figure 6 – Car following process in the range rate-range domain

➢ *Control for driving pattern 3*

In this driving pattern, as in the previous one, at first it is performed the control imposed by road alignment and then the one due to the leader perception.
The first control is performed in the same way of the pattern 1; it is calculated, if necessary, the deceleration the user intends to perform in order to make his/her current speed equal to the one he/she wishes to perform in curve.
The second control evaluates at first the instant in which the follower begins to decelerate and then the deceleration that he/she would like to perform.
With reference to the moment in which the follower begins to react, the speed difference and the leader brake lamps turned on represent two stimuli for the follower. It has been considered that the first received stimulus induces the follower to act as alerted, for this reason his/her reaction to the second stimulus, if not excessively delayed, occurs after a time equal to *Prt_att*.
For this driving pattern the time T*react_cfst* in which the follower begins to decelerate is defined by two groups of cases. The first one is characterized by *Tst_on* ≥ *Tpercep* and the second one by *Tst_on* < *Tpercep*.

1. *Tst_on* ≥ *Tpercep* (speed perception before braking lamps are turned on)

   - First case:
     T*perc_react* < (T*st_on* + *Prt_att*) ⇒ T*react_cfst* = T*perc_react*

   - Second case:

Tperc_react $\geq$ *(Tst_on + Prt_att)* $\Rightarrow$ *Treact_cfst = Tst_on + Prt_att*

Being *Tperc_react* evaluated by the equations (23) or (25).

2. *Tst_on* < *Tpercep* (speed perception after braking lamps are turned on)

   - First case:
     (Tpercep + Prt_att) < (Tst_on + Prt_ob1) $\Rightarrow$ *Treact_cfst = Tpercep + Prt_att*

   - Second case:
     (Tpercep + Prt_att) $\geq$ *(Tst_on + Prt_ob1)* $\Rightarrow$ *Treact_cfst = Tst_on + Prt_ob1*

The deceleration needed to join the leader, that exists for t > *Treaz_cfst*, is evaluated by defining step by step, the acceleration that the follower requires to reach the leader speed when *R = D(t)*:

$$a_f(t) = a_l(t) - \frac{\left(v_f(t) - v_l(t)\right)^2}{2 \cdot \left[R(t) - D(t)\right]} \qquad (28)$$

where:
- *D(t) = Tg_crit x* $v_l(t)$ if $v_l > 5.44$ *m/s;*
- *D(t) = 5 m* if 2 *m/s* $< v_l \leq 5.44$ *m/s;*
- *D(t) = 1 m* if $v_l \leq 2$ *m/s.*

After the instant in which *R = D(t)*, the acceleration of the follower is assumed to be the same of the leader one.
At the end of the control procedure, the deceleration the user would like to perform is the bigger one between the deceleration due to road alignment adaptation and the deceleration needed to join the leader. The deceleration performed by the user is defined within the operative module.

- *Control for the driving pattern 4*

In this driving pattern, as in the previous ones, it is firstly performed the control imposed by the road and then the one due to the perception of leader braking lamps turned on.
The first control is performed in the same way of the pattern 1; it is calculated, if necessary, the deceleration the user intends to perform in order to make his/her current speed equal to the one he/she wishes to have in curve.
The second control allows to evaluate at first the instant in which the follower begins to decelerate and then the deceleration that he/she would like to perform. The follower deceleration starts when *t = Tst_on + Prt_ob1* and it is evaluated by an expression similar to the (28).

- *Control for the driving pattern 5*

In this driving pattern the user is influenced only by road alignment and therefore the procedure is the same of the one related to the control for driving pattern 1.

- *Control for the driving pattern 6*

In this driving pattern it is firstly performed the control due to the road alignment and then the control due to the perception of the leader vehicle or to its braking lamps turned on.
The first control is performed in the same way of the pattern 1; it is calculated, if necessary, the deceleration the user would to perform in order to make his/her current speed equal to the one he/she wishes to have in curve. The second control evaluates at first the instant in which the follower begins to decelerate and then the deceleration he/she would like to perform.
The deceleration of the follower starts when at least one of the two following conditions is satisfied:

t = (Tst_on + Prt_att) (29)
t = (Tpercep + Prt_att) (30)

The deceleration is evaluated by an equation similar to (28).

Operative module

Within this module the deceleration actually performed by each user and his/her braking lamps condition are defined.
The deceleration performed by the user is equal to the one he/she would like to perform taking into account the limitations due to the available tire-pavement friction defined with the expression (1) and the friction used by the vehicle in transversal direction because of the road curvature.
The brake lamps of the vehicle are turned on if the deceleration the user would like to perform is greater than the one due to the motion resistances and engine brake.

Collision Module

This module evaluates if a rear-end crash occurs and the corresponding speed. A collision is assumed to happen if two conditions are satisfied: 1) the space headway R between follower and leader is lower than 0 (the front bumper of the follower is forward the rear bumper of the leader) and 2) the relative speed is greater than 8 km/h.
The module evaluates also the number of vehicles not equipped with the ABS and completely using the tire-pavement friction available. These vehicles are at impending skid and therefore the driver could loose the control. The result could be an accident different from a rear–end crash.

APPLICATION

The microsimulation traffic model has been applied to an old two lane road segment including a tangent 885 m long, a spiral 240 m long and a curve with a radius of 250 m and 300 m long. The superelevation rate is equal to 7%. A standing obstacle object is placed on the travelled way 280 m after the beginning of the curve. The roadway is 10.5 m wide and includes two shoulders 1.5 m wide. The sight distance inside the spiral and the curve is obstructed by a retaining wall. The minimum sight distance for objects in the same lane is about 94 m and begins inside the spiral about 50 m before the curve (see Figure 7). This distance however increase to 115 m if the leader vehicles stops with a high rotation around its yaw axis (see figure 2). This condition has been assumed if a leader vehicle collides with a speed greater than 40 km/h with the vehicle in front of it. The Italian Standard (10) requires for this curve around 110 m as minimum sight distance on the same lane. At the end a comparison with a situation complying with the Standard will be also provided.

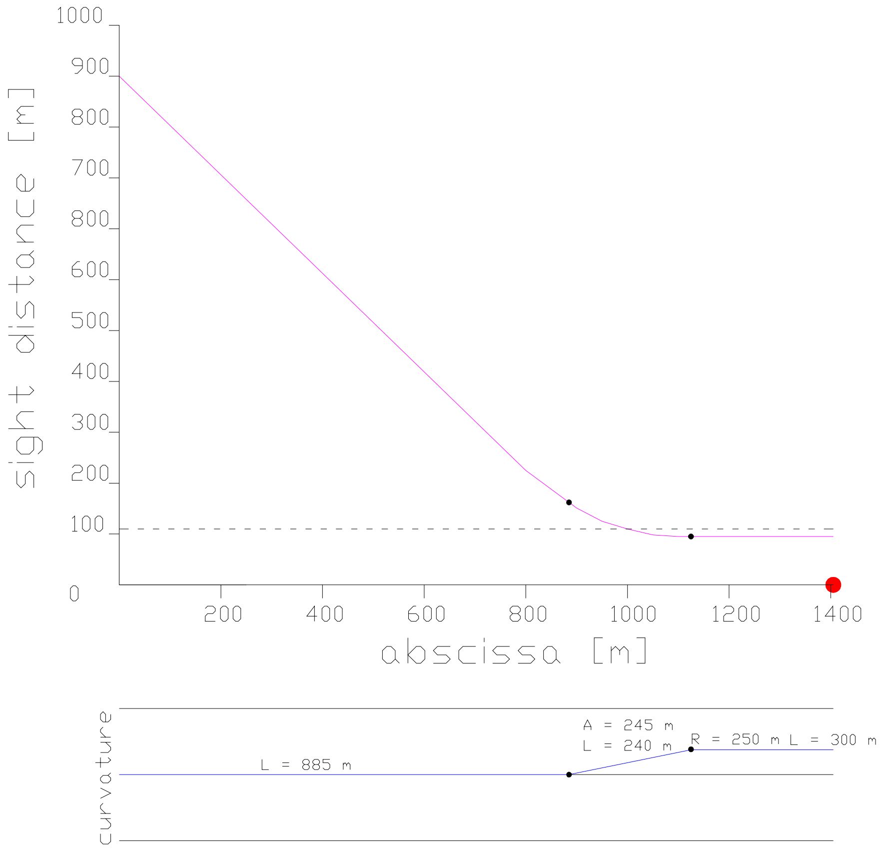

Figure 7 – Sight distance in the same lane

Four values for the flow rate in each lane have been considered: 300, 400, 600 and 800 (v/h/l). A wet condition has been assumed and the skid value of the tire-pavement friction has been obtained from the following expression:

$$FAD(V) = 0.000015 \times V^2 - 0.005 \times V + 0.604 \qquad \text{(V in km/h)}$$

The presence of vehicles equipped with ABS has been considered equal to 20%. The values for the other factors included in the model accord with the values suggested in the previous sections. In particular as far as the speed is concerned the following assumptions have been done: expression 7a for the mean value, standard deviation equal to 15 km/h, reduction of 10 km/h for the rain. With these values the mean and the 85^{th} percentile of the speed in the circular curve (R=250m) for a very reduced traffic flow are 77 km/h and 92 km/h respectively. 50 simulations have been carried out for each value of flow rate and in each of them the variables included in the model have been defined according to their probabilistic law. The number of vehicles considered in each simulation has been enough to lead the queue inside the tangent section.
The results obtained are the average number of rear-end crashes, the maximum and minimum number of rear-end crashes, the average impact speed, the number of crashes with initial speed greater than 56 Km/h, the average distance among the first and the last crash, the number of vehicles at impending skid.
The number of crashes with initial speed greater than 56 km/h has been considered because this value corresponds to the initial speed adopted in the crash tests aimed at assessing the behaviour of the vehicles during frontal impacts. The evaluation of the results arising from many crash tests leads to the conclusion, in particular for vehicles equipped with the current passive safety devices, that the outcomes in terms of passenger injuries are not very severe if the initial speed is lower than 56 km/h. In general, it is not possible to draw the same conclusion for higher speed because in this case the behaviour of the vehicles is unknown.
The average distance between the first and the last rear-end crash defines the length of the segment where the vehicles are at collision "risk" (however inside not all the followers collide with their leaders). Outside, all vehicles stop without rear-end crashes and the tire-pavement friction needed doesn't attain the skid value.
The outcomes of the simulations performed are included in table 1 and in figures 8,9,10. In these figures the limits for the Level of Service in terms of flow rate are also indicated for a level terrain condition. It is important to be aware that the flow rate refers to each lane and not to the road. The results show that the number of rear-end crashes and the corresponding speed reduce with the flow rate. The same happens for the number of vehicles inside the segment at collision "risk". This happens because the greater is the flow rate the lower are the speed and the space headway between vehicles. The first effect reduces the braking distance needed and the second allows, through the braking lamps, a sort of "communication" of the presence of the obstacle to vehicles that are far from it (the warning signal of the braking lamps turned on of the first vehicle quickly move backwards suggesting followers to adopt a prudential behaviour). To explain why this happens it's useful to compare figure 11 with figure 12, which concern a low and a high flow rate respectively. In the first figure, due to the high space headway, the follower cannot see the leader braking (the vehicle 2 is not allowed to see the braking lamps turned on of the vehicle 1): each driver acts as he/she was alone on the road. Probably all of the vehicles 1,2 and 3 would be involved in the collision. In figure 12, on the contrary, each follower is able to see the braking lamps turned on of the leader vehicle and therefore begins to brake very far from the obstacle: probably only the vehicle 1 will collide with the obstacle.

Table 1- Results of the simulations

	Flow rate			
	300 v/h/l	400 v/h/l	600 v/h/l	800 v/h/l
Average number of impacts	16	15	4	1
Maximum number of impacts	20	19	9	4
Minimum number of impacts	13	5	1	0
Average impact speed	38	38	26	21
Average number of impact at speed > 56 km/h	2	1	0.5	0
Average distance of the last impacting vehicle from the obstacle	330	300	220	120
Average number of vehicles at impending skid	18	14	7	4

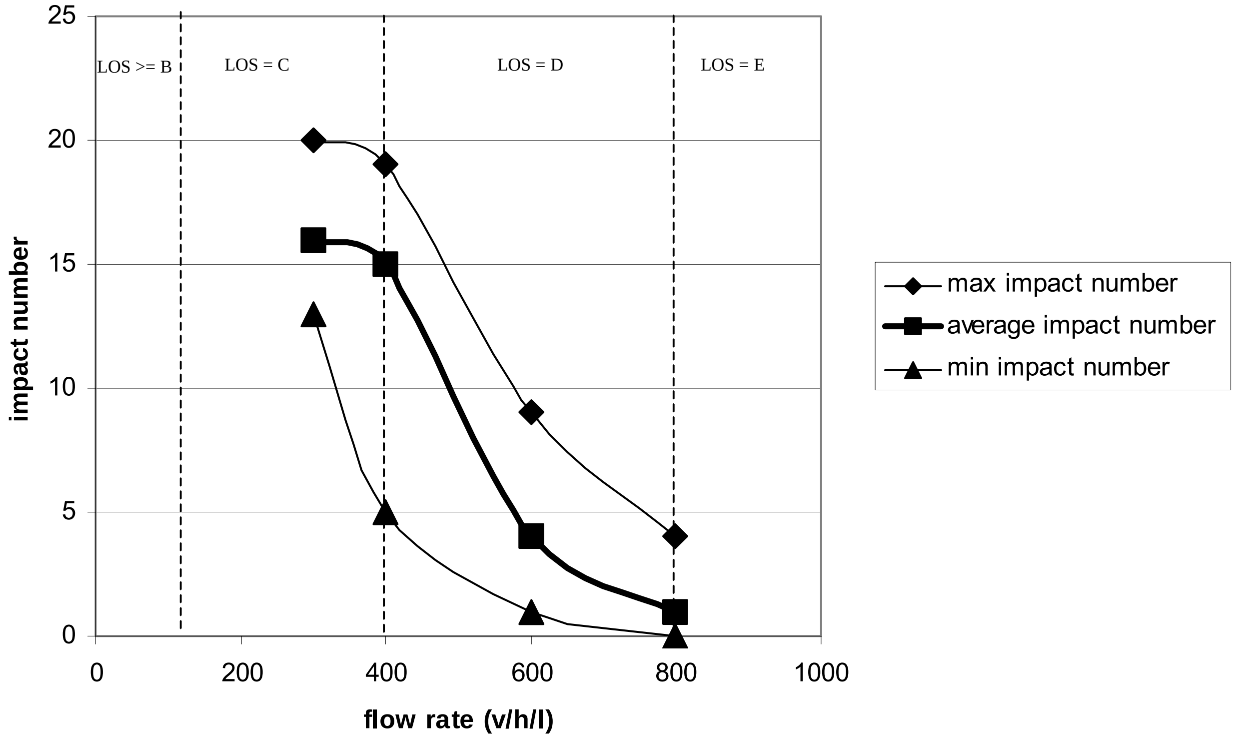

Figure 8 – Maximum , average and minimum number of rear-end collisions versus flow rate

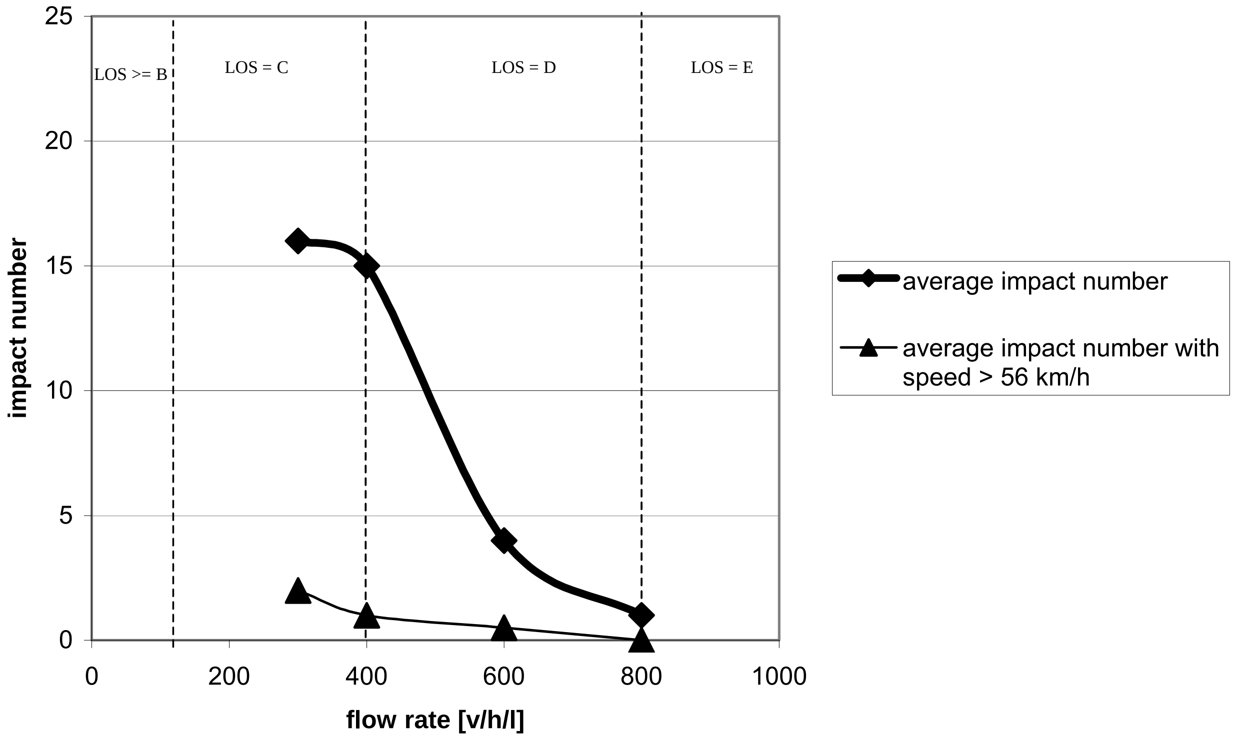

Figure 9 – Average number of rear-end collisions with speed > 56 km/h versus flow rate

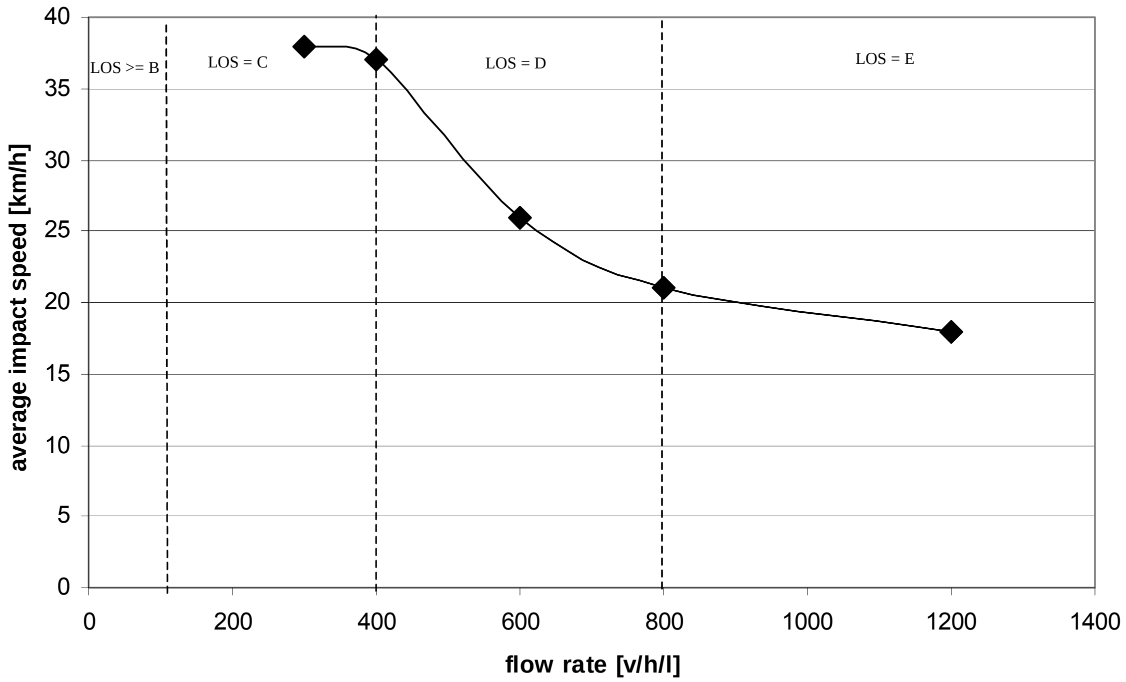

Figure 10 – Average rear-end collisions speed versus flow rate

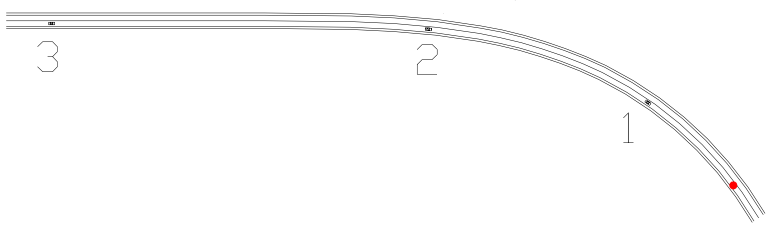

Figure 11 – Example of space headway for a low flow rate

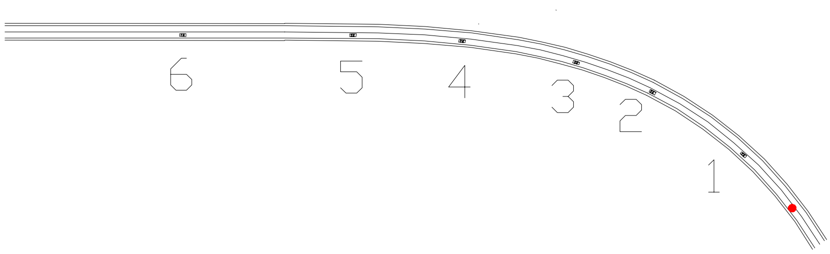

Figure 12 – Example of space headway for a high flow rate

These behaviours are also depicted in figures 13 and 14, where two sets of 9 vehicles trajectories are included, for a flow rate of 300 and 800 v/h/l respectively (the trajectory of the 1st vehicle is on the left side and the others follows in sequence on the right). The abrupt change in the slope at the end of a trajectory means that the corresponding vehicle is impacting the object or the previous vehicle. On the contrary a smooth decrease in the slope means no-impact. Figure 13 shows that almost all vehicles collide, instead figure 14 shows that no one vehicle impacts and that the braking lamps signal of user 4 affects the behaviour up to user 9.

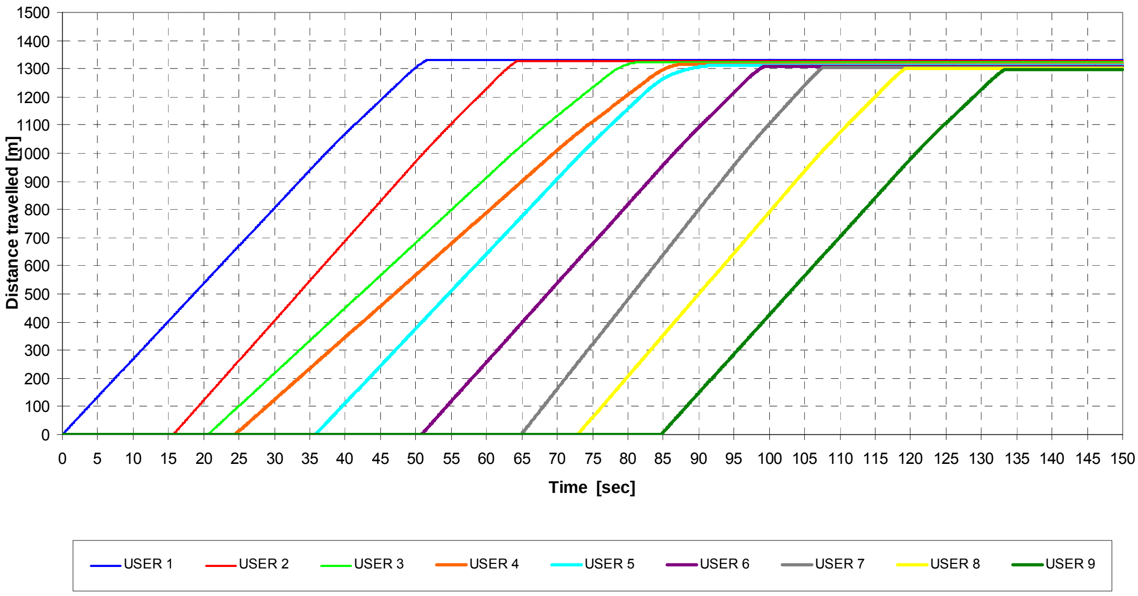

Figure 13 – Trajectories of the vehicles for a flow rate of 300 veh/h/lane

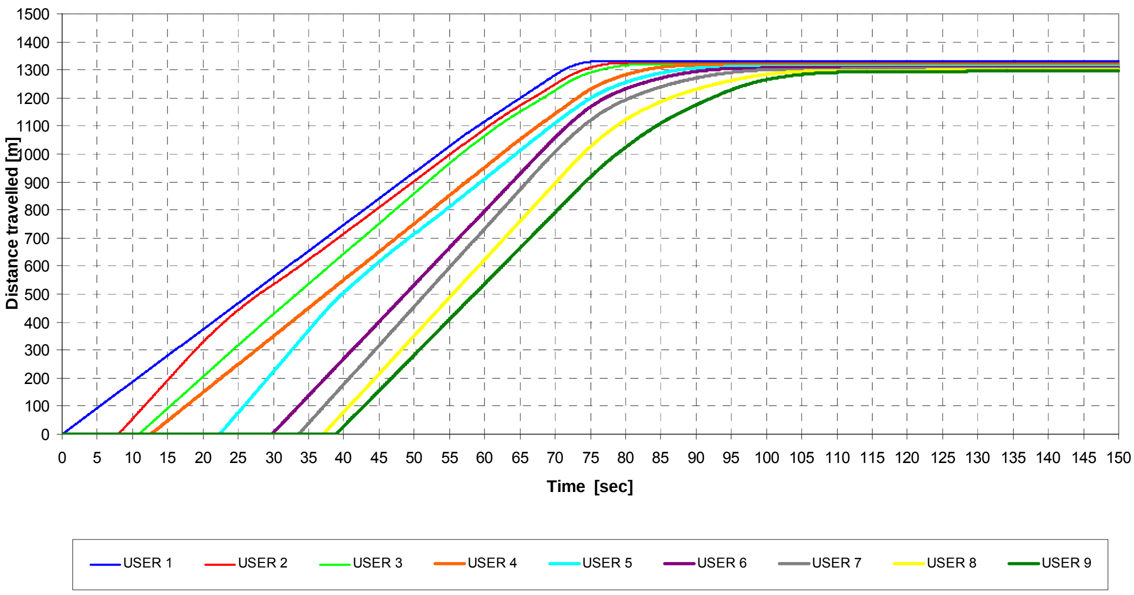

Figure 14 – Trajectories of the vehicles for a flow rate of 800 veh/h/lane

In order to assess the influence of the speed in comparison to the space headway a set of simulations concerning an imaginary traffic flow has been carried out. It concerns a flow rate equal to 400 v/h/l with a reduced speed: the speed distribution has been assumed equal to the one of a flow rate on the carriageway equal to 1600 v/h (800 v/h/l). The results obtained are included in table 2 along with the outcomes achieved for the normal traffic flows of 400 and 800 v/h/l. They show that the number of rear-end collisions and impact speed are more similar to the ones obtained for the flow rate of 400 v/h/l. The reduction in the speed, therefore, induces a moderate decrease in the number of collisions, the greater reduction pertains to the lower space headway.

Table 2- Comparison of the results obtained for an imaginary traffic flow where the space headway relates to a flow rate of 400 v/h/l, but the speed distribution relates to a flow rate of 800 v/h/l

	Flow rate		
	400 v/h/l	**imaginary traffic flow**	800 v/h/l
Average number of impacts	15	**10**	1
Maximum number of impacts	19	**14**	4
Minimum number of impacts	5	**3**	0
Average impact speed	38	**30**	21
Average number of impact at speed > 56 km/h	1	**0.5**	0
Average distance of the last impacting vehicle from the obstacle	300	**320**	120
Average number of vehicles at impending skid	14	**11**	4

Table 3- Comparison of the results obtained for a flow rate of 300 v/h/l when the minimum sight distance complies with the Italian Standard and when it doesn't complies

	Flow rate 300 v/h/l		Flow rate 400 v/h/l	Flow rate 600 v/h/l	Flow rate 800 v/h/l
	Sight distance complying	Sight distance not complying	Sight distance not complying	Sight distance not complying	Sight distance not complying
Average number of impacts	**10**	16	15	4	1
Maximum number of impacts	**12**	20	19	9	4
Minimum number of impacts	**5**	13	5	1	0
Average impact speed	**34**	38	38	26	21
Average number of impact at speed > 56 km/h	**0**	2	1	0.5	0
Average distance of the last impacting vehicle from the obstacle	**320**	330	300	220	120
Average number of vehicles at impending skid	**12**	18	14	7	4

The results in table 1 show that the sight distance available in the road segment could be considered sufficient to avoid severe rear-end collisions if the traffic flow is greater than 600 v/h/l. This result put in evidence that the road is safe, with reference to this type of road accident, only if the operating conditions correspond to a Level of Service D or lower; in free/stable flow condition many rear-end crashes, someone also severe, could happen as a consequence of a standing obstacle on the travelled way. The values in table 1 concerning the average and maximum number of collisions are very similar when the flow rate is lower than 400 v/h/l. This occurs because the space headway becomes very large in comparison with the sight distance available and therefore each vehicle acts as it was alone.

In order to know what will happen if the standard is respected and to do a comparison with the previous results a set of simulations has been performed considering that the retaining wall has been moved to have a sight distance (on the same lane) equal to the minimum value the Italian Standard requires (110 m). This distance has been increased to 130 m if a leader vehicle stops after a high rotation around its yaw axis (read road generation in the section “Generation module”). The flow rate has been assumed equal to 300 v/h/l, this because for lower values the average and the maximum number of collisions are the same.

The results obtained are included in table 3. They show that the respect of the standard is not able to eliminates all the rear-end crashes. This happens because the speed the standard considers for the circular curve (80 km/h) becomes equal to the 85th percentile of the speed distribution assumed in the curve only for a flow rate equal to 1100 v/h (550 v/h/l). The 85th percentile in free flow condition however is about 90 km/h and so it is not very far from the speed assumed in the standard.

The comparison between the two situations (table 3) gives the idea that the traffic flow needed to have the same safety performance that the standard allows in this specific road segment is about 600 v/h/l. This result is very important for an engineer who wants to know how far the situation with the reduced sight distance is from the standard in terms of safety, and would like to assess the benefits due to the increase of the sight distance at the minimum established by the standard.

CONCLUSIONS

In this paper the structure of a microsimulation model tacking into account most of the influencing factors is presented. It has been conceived with the aim to reproduce what happens for a partially visible standing obstacle. The first part of the paper concerns the description of the modules and corresponding tasks in which the model is organized: an input module, a perception module, a tactical module, a control module, an operative module and a collision module.

The second part presents, as an example, the application of the model to a situation where an obstacle is placed in a curve having the sight distance limited by a retaining wall. The results obtained show that the higher is the flow rate the lower is the number of the rear-end crashes and of the vehicle that loose the control. This is due to the fact that for a high flow rate the vehicles are slower and a very high interaction is present among them, so that the warning signal of braking lamps turned on of a vehicle quickly move backwards suggesting followers to adopt a prudential behaviour.

The application of the model also to a situation where the minimum sight distance complies with the Italian Standard shows that the rear-end crashes are reduced but not eliminated.

The application has to be considered only as an example. In future, after a tuning task carried out by a driving simulator and an instrumented vehicle, the model will be used in a large research activity aimed at assessing the safety performance of many road design standard. The model will be also improved to take into account external signals communicating to road users the presence of not visible standing obstacles.

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