Identification of Safety Indicators for Road Traffic Management in Tunnels Using Microsimulation Techniques

Prof. Lorenzo Domenichini
Department of Civil Engineering – University of Florence

Eng. Andrea Giaccherini
PhD Student – Department of Civil Engineering – University of Florence

Eng. Neri Di Volo
Department of Civil Engineering – University of Florence

SYNOPSIS

Microscopic traffic simulators are tools that realistically emulate the flow of individual vehicles inside a generic network: this is achieved by employing car-following and lane changing models that take into account both global and local phenomena that can influence each vehicle's behavior.

Today, microsimulation techniques are becoming a very powerful tool for safety analysis: the main problem to keep into account is that a microscopic traffic simulation is an ideal world where no crash occurs, which is due to the basic hypothesis in car-following model where each vehicle keeps a "safety braking distance". The paper refers about the studies performed to identify traffic parameters allowing to predict the occurrence of critical conditions inside tunnels.
The relation between the main flow parameters, such as traffic composition, speed, density, time/space headway between vehicles and longitudinal accelerations have been analyzed in order to quantify the degree of vehicle interactions occurring in the different possible road service conditions: the probability of accident should increase when the vehicle interactions become more frequent.

Taking into account a typical user behavior, traffic demand and geometric characteristics, these concepts have been developed and the results compared with the new European standards for road tunnels safety which considers the time headway as the safety control parameter.

The study performed could provide interesting information to define which management strategies and ITS devices can be used to monitor and manage the motorway traffic conditions inside tunnels, with the target of improving both the quality and safety of circulation.

Identification of Safety Indicators for Road Traffic Management in Tunnels Using Microsimulation Techniques

INTRODUCTION TO ROAD SAFETY IN TUNNELS

The fires in the Mont Blanc and Tauern tunnels in 1999 and in the Gotthard tunnel in 2001 have raised concerns for safety in road tunnels.

The number of accidents in tunnels is relatively limited as tunnels are not exposed to adverse weather conditions such as snow, ice, wind and rain, and this is especially true for long tunnels. However, the effects of any accident occurring in tunnels are potentially greater, because of the confined environment. Consequently road traffic risk is likely higher in tunnels than in road sections at open air and this calls for the provision of special engineering measures both at the tunnel planning and design stages and during the tunnel service life. The most recent international recommendations and standards reflect these needs and underline the urgency of adopting higher safety standards in road tunnels.

Traffic volume and composition are two of the parameters usually considered in the evaluation of the tunnel risk class because they do not only increase the risk exposition but they also affect the accident probability. Traffic management measures considered by current standards require to control actuated speeds and vehicle interdistances to increase safety conditions inside tunnels. Safety values for these quantities should be suggested to drivers according to the traffic situations and enforcement measures should be introduced if necessary. For instance, a time interdistance of 2 seconds is suggested between light vehicles under normal traffic conditions, to be increased to 4 seconds for heavy goods vehicles.

The meaning of the latter recommendation is clear when the vehicles entrance in the tunnel is controlled and actuated, such as in the Mont Blanc tunnel, but it becomes less evident for all the tunnels in which the traffic flows freely, as it occurs in most of the tunnels present along the road network. In these cases, vehicles headways can not be easily evaluated, controlled and enforced, especially in monodirectional carriageways with two or more lanes and mixed traffic, unless providing each tunnel entrance with special engineering solutions such as traffic buffer areas and gate systems that limit accesses. It is reasonable to consider such traffic control solutions only if and when necessary, according to actual traffic conditions, thus introducing concepts of preventive safety in the traffic management procedures.

The aim of the present paper is to investigate if it is possible to identify traffic conditions potentially contributing to higher levels of risk, so as to confine to these situations the introduction of special safety control measures, leaving the traffic to flow freely inside the tunnel in all the other situations, which should be defined as “normal”.

PREVENTIVE SAFETY ANALYSIS IN TUNNELS USING MICRO-SIMULATION TECHNIQUES

Micro simulation techniques can provide a valuable analysis tool to understand the dynamic relationships existing between traffic and safety conditions. They allow to identify the traffic conditions that can potentially bring to unsafe situations, in order to determine the relevant factors in this process and to evaluate their importance in order to plan and adopt specific traffic management strategies that can reduce the risk potentials.

Good examples of preventive safety measures and of micro-simulation to assist in their design and evaluation are the advanced traffic management systems proposed for heavy goods vehicles in the tunnels of Saint Gothard in the Swiss Alps (M. Rapp and C. Albrecht, 2003) and Vielha in the Spanish Pyrenees (J. Barceló, J. Casas, J. Ferrer and J. Perarnau, 2003).

To implement a preventive safety analysis it is necessary to identify safety indicators apt to describe unsafe traffic conditions and to define trigger or alarm values for them, based on statistical safety analysis. In the present paper different traffic descriptors have been considered and analyzed: spatial and time vehicle headway, speeds and accelerations and their time or spatial variations.

The spatial vehicle headway has been considered at first by the European safety standards for tunnels. A minimum distance of 50 meters for passenger cars and 100 meters between heavy vehicles have been suggested and the safety meaning of such parameters has been considered in a previous paper (L. Domenichini, N. di Volo, A. Giaccherini, J. Barcelo, J.L. Ferrer, 2004).

The new European Directive for the “minimum safety standards in the transeuropean road network” (European Commission, 2004) refers to vehicles time headway. This parameter represents the distance, in seconds, between two consecutive vehicles. Its value depends on the relative speed and on the type (light or heavy vehicles) of the consecutive users, on the traffic amount and composition and on the physical road characteristics (longitudinal grade and cross section composition). In a certain moment, the time headway inside the tunnel will be different from point to point. The average time headway represents a statistical representation of the traffic condition inside the tunnel, related to the value of the average vehicle density. It is a measure of the degree of actual vehicles interaction. When this time value decreases, the risk conditions inside the tunnel are expected to increase because of the reduced safety distances and increased interactions between vehicles. As mentioned above, according to the European Directives the time between consecutive vehicles has to be greater than 2 seconds if there are only passenger cars or greater than 4 seconds between two consecutive heavy vehicles.

The vehicle interaction can also be described by means of the speed profile of each vehicle running inside the tunnel. In free flow conditions the vehicle speed is relatively high and rather constant, because each vehicle runs according to its desired speed. When vehicle density increases, interactions become likely higher and the vehicle speed profile should be characterized by reduced average speed values and increased speed variations. This introduces accelerations and decelerations, whose average absolute value and time variation can thus be assumed to represent traffic conditions characterized by lower or higher risk: the higher the variation the higher the potential risk, and viceversa. It is assumed that the vehicle densities, which characterise different values of the level of service (LOS) for the traffic flow, can be related to the risk level inherent to each specific traffic flow condition. If this is true, the control of the safety conditions inside the tunnel should be implemented by monitoring the traffic speed and flow, and special control measures should be applied when these values reach alarm thresholds.
According to these concepts, microsimulation can permit a preventive analysis of all these values simulating the potential traffic conditions in different situations, such as roads characteristics and/or typology and the performances of the traffic management system.
The application of this kind of analysis to a hypothetic road section with standard characteristics is described in the following paragraphs.

IMPLEMENTED SIMULATION MODEL

The relationships existing between vehicle interdistances, densities, speed and acceleration profiles have been studied considering a generic 500 m long road segment loaded with variable traffic flows. The achieved results have general validity and can be considered applicable also to tunnels, should the driver behaviour inside tunnel be considered similar to the one characterising a normal (open air) driving condition. It is believed that the latter hypothesis is not true but studies to differentiate the driver behaviour inside and outside tunnels and to characterize it according to the needs of the microsimulation could not be found in the literature. Specific deepening of this subject are therefore envisageable to increase the reliability of the preventive traffic management procedures in tunnels.

The simulation experiments have been performed using the AIMSUN package (TSS, 2002).

The geometric characteristics of the considered road segment are:

- carriageway: two lanes plus emergency
- lane width: 3.75 m
- legal speed limit: 130 km/h
- longitudinal slope percentage: 0%
- alignment: straight section

The window control section provided by the software used is visible in Figure 1.

With respect to the traffic demand, the simulations performed have considered different flow conditions ranging from zero to capacity, according to Highway Capacity Manual (Transportation Research Board, 2000). Two specific percentages of heavy vehicles have been considered, 0% and 50%.

The parameters related to the users behaviour have been defined with reference to the vehicle type (car and truck) and referred to mean values for the attributes of each vehicle type, their deviations and minimum and maximum values. The particular characteristics for each vehicle inside the traffic flow have been sampled from a truncated normal distribution. The attributes that characterise each vehicle are reported in Table 1, with the following meaning:

- Length: this parameter is used both for graphical and modelling purposes. It has influence on traffic modelling, as vehicle length is taken into account in all the vehicles behaviour models
- Width: it is only used for graphical purposes and does not have a direct influence on the traffic modelling;
- Maximum desired speed: this is the maximum speed, in km/h, that each vehicle type can travel at any point in the network;
- Maximum acceleration: this is the maximum acceleration, in m/s^2, that the vehicle can achieve under any circumstances;
- Normal deceleration: deceleration that the vehicle can use under normal traffic conditions. This value is used in the Gipps car-following model implemented in AIMSUN;
- Maximum deceleration: this refers the most severe braking that a vehicle can apply under special circumstances, such as emergency braking;
- Speed acceptance: this parameter can be interpreted as the ‘level of goodness’ of the drivers or the degree of acceptance of speed limits. A value ≥ 1 means that the vehicle will take as maximum speed for a section a value greater than the speed limit, while a value ≤ 1 means that the vehicle will use a lower speed limit. In the model, the speed acceptance has been assumed equal to 1, then the user will drive according to the imposed speed limit
- Minimum distance between vehicles: this is the distance that a vehicle keeps between itself and the preceding vehicle when queuing.

During the simulation experiments, data concerning the considered vehicle location and speed have been gathered at every simulation step (equal to 0.75 sec.): for each specific traffic flow value, the time headway, speed and acceleration profiles have been constructed for a sample of about 180 vehicles. The speed and acceleration variation of each single vehicle has been recorded going through the 500 m long road section considered. Each profile then has been characterized by means of the average value and standard deviation values of the occurred speeds and accelerations.

To obtain all these information from the model in AIMSUN, and in particular the speed variation, each vehicle has been tracked during its trip in the model: to achieve this purpose a specific Getram Extension (specific routines that work as a plug-in of the main program) has been built, using C++ language. The technique used is called “vehicle tracking”: every simulation step or reaction time (in AIMSUN this is the time it takes to a driver to react to speed changes of the preceding vehicle; it is used in the car following model and for implementation reasons it is also taken as the Simulation Time Step or cycle) speed, time, lane and distance travelled by each vehicles have been recorded.

		Mean	Deviation	Min	Max
Car	Length (m)	3.55	0.54	2.5	4.99
	Width (m)	2	0	2	2
	Max desired speed (km/h)	120	20	70	200
	Max acceleration (m/s^2)	2.8	0	2.8	2.8
	Normal deceleration (m/s^2)	4	0	4	4
	Max deceleration (m/s^2)	8	0	8	8
	Speed acceptance	1	0	1	1
	Min distance vehicles (m)	1	0	1	1
Heavy vehicle	Length (m)	11.08	4.17	5.00	18.75
	Width (m)	2.30	0	2.30	2.30
	Max desired speed (km/h)	90	15	50	150
	Max acceleration (m/s^2)	1	0	1	0
	Normal deceleration (m/s^2)	3.5	0	3.5	3.5
	Max deceleration (m/s^2)	7.0	0	7.0	7.0
	Speed acceptance	1	0	1	1
	Min distance vehicles (m)	1	0	1	1

Table 1: Average vehicle type characteristics

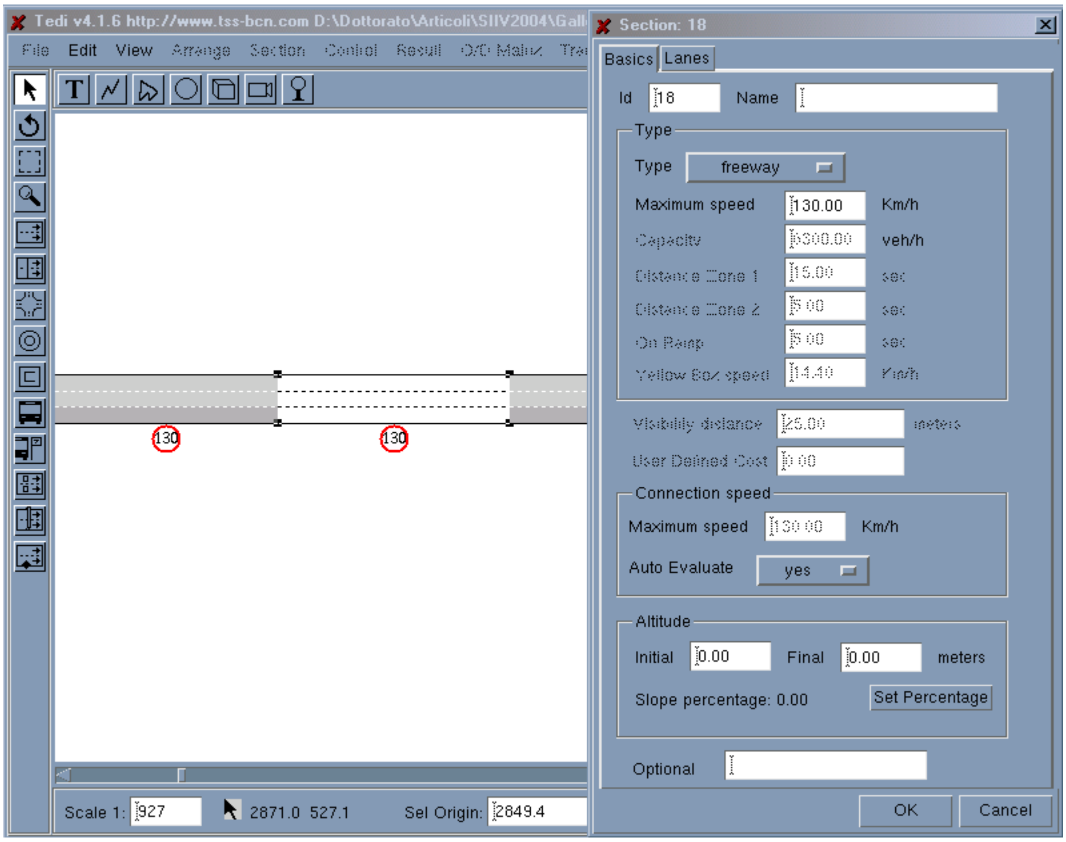

Figure 1 : Implemented Section model

SIMULATION RESULTS

The results are shown in the diagrams of Figure 2, Figure 3, Figure 6 referred to the average time headway, the average speed and to the standard deviation of the vehicle acceleration values. Each diagram shows the relationship between the considered variable and the traffic flow for the two traffic compositions analyzed. They also report the vehicular densities related to each traffic condition in order to allow to show the value of the level of service (LOS), according to the Highway Capacity Manual (Transportation Research Board, 2000), characterizing each traffic conditions considered. The latter information is shown by drawing on the plot horizontal lines representing the conventional density limits of each LOS situation (from LOS A to LOS F). The density values are expressed in terms of ”passenger cars/km/lane”, and derived by the following relation:

$$D = \frac{V_p}{S}$$

where V_p is the hourly flow rate (pc/h/ln) and S is the passenger-car speed. The hourly flow rate reflects the influence of heavy vehicles, the time variation of traffic flow (with PHF), and the characteristics of drivers population. These effects are reflected by adjusting hourly volumes (reported in veh/h and derived from the simulation model) using the heavy-vehicle and peak-hour factors.

Figure 2 shows the relation between the flow rate V_p, the average time headway and the density when the percentage of heavy vehicles is 0% or 50%. For instance, for a V_p of 500 pc/h/ln which corresponds to a density of 5 pc/h/ln and to a LOS value equal to LOS A, the average time headway assumes a value of about 3.8 seconds if the percentage of heavy vehicles is 0% and 3.4 seconds with a 50% of commercial vehicles in the traffic flow.

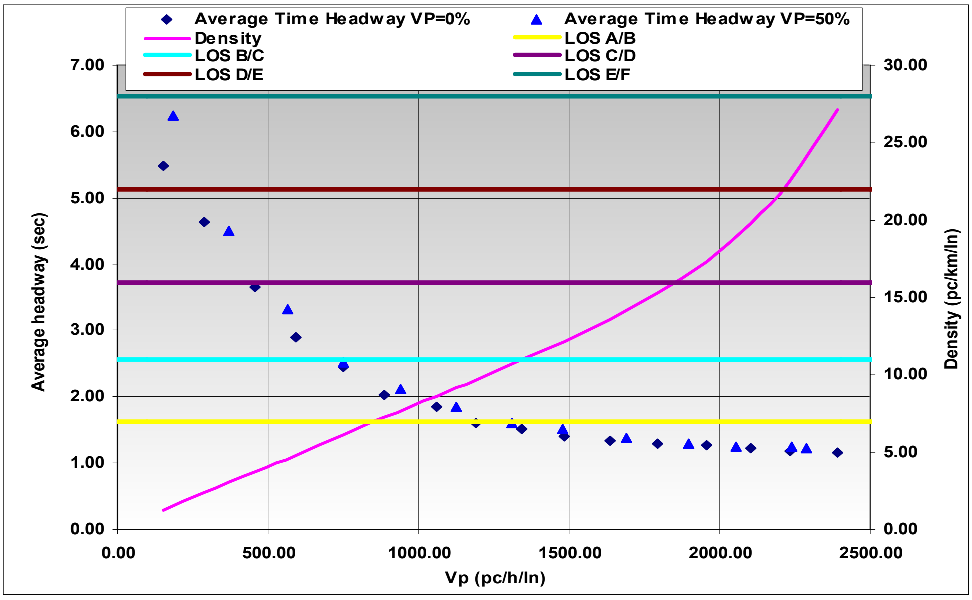

Figure 2: Time headway – Flow relation

Considering a time headway of 2 seconds to identify safe traffic conditions as suggested by the European Directive, in the specific situation considered, means to refer to a traffic condition characterized by a density of about 900 pc/h/ln, corresponding to the transition between LOS A and LOS B conditions. From this traffic condition, up to the capacity, the spatial time headway between vehicles seems to be independent from the percentage of heavy vehicles, approaching to an asymptotic value of about 1 sec.

Figure 3 shows the relation between speed and density under different flow conditions and for the two considered percentages of heavy goods vehicles.
For 0% of HV, when Vp ranges between 0 and 950 pc/h/ln, the density changes from 0 to 7 pc/km/ln (LOS A) and the average speed assumes values ranging between 115 km/h and 105 km/h about; if the percentage of HV is equal to 50%, for the same level of service (in terms of Vp and density) the average speed decreases, assuming values ranging between 100 km/h and 85 km/h.

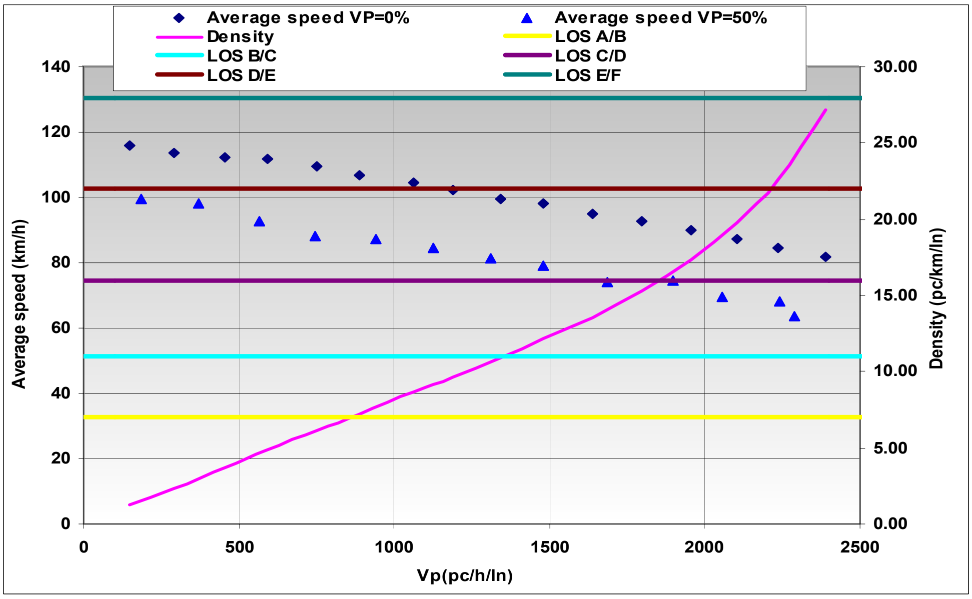

Figure 3: Speed-Flow relation

As it is logical to expect, when the density increases the speed decreases. The presence of commercial vehicles reduces the average speed value, but the decreasing trend remains the same.
For each level of service it has also been possible to define a speed distribution representing the variability of the average speed of the vehicles belonging to the traffic flow of the given entity. Assuming a normal distribution, Figure 4 e Figure 5 show the obtained density functions, according the relation:

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

with μ and σ equal to the mean and standard deviation of the vehicles' speed.

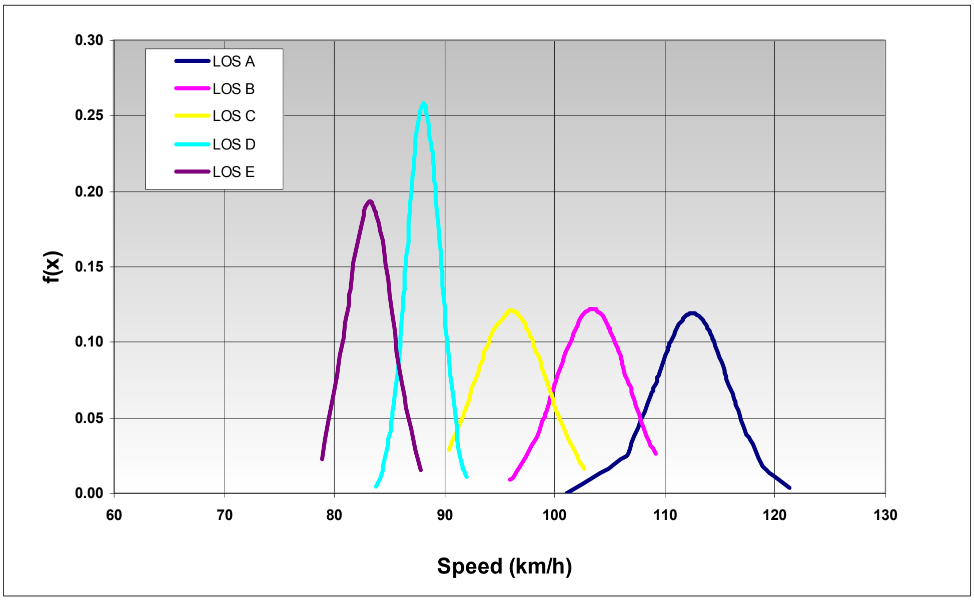

Figure 4: Speed distribution (%HV=0)

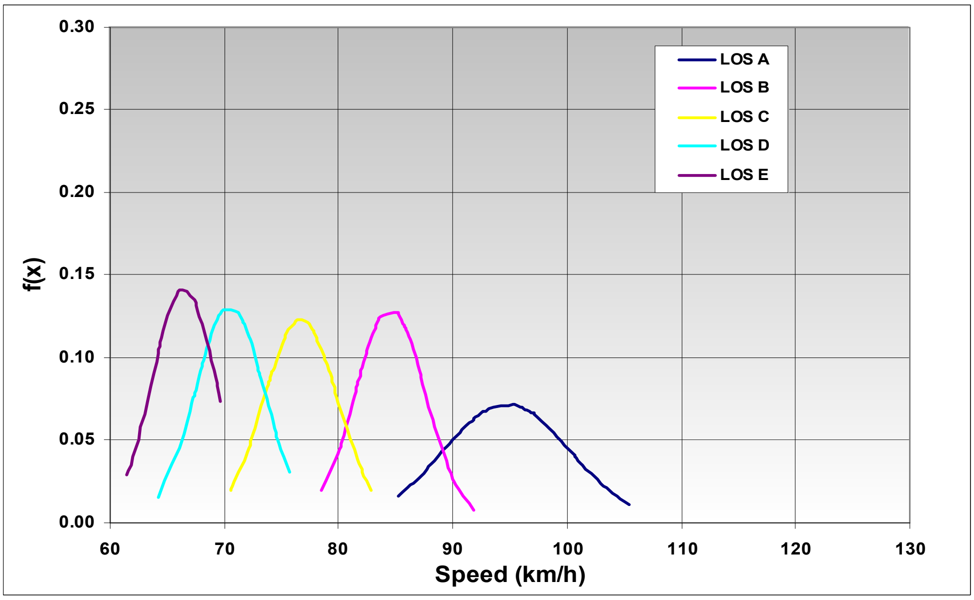

Figure 5: Speed distribution (%HV=50)

The variability of the average speed operated by the vehicles within each considered traffic conditions reduces when traffic conditions go from LOS A to LOS E. This result was also expected since a reduction in the LOS means an increase of the vehicles interactions and a consequent reduction of freedom in the choice of the operative speed. As it can be observed, they both tend to decrease with the increase in traffic volumes, that could be considered as a factor of increased safety. Thus, the average speed and the speed variability actually do not seem to be good safety indicators. In fact they represent the result of the interactions occurred between the vehicles belonging to the same traffic flow: if the speed value is low (which again could be a good result itself), the desired speed remains the same and the user, obliged to a reduced speed, will try, as soon as the traffic conditions allow it, to accelerate to reach his desired speed, being obliged, later on, to rapidly decelerate when the interaction with the next vehicle occurs. This fact is emphasized if commercial vehicles are present in the traffic mix as it can be deduced comparing Figure 5 with Figure 4. The speed variability in the vehicular flow is lightly higher if the commercial vehicles are present (HV=50%) and this can result in reduced safety conditions.

On the other hand, the actual level of interactions among vehicles can be derived from the observation of acceleration/deceleration of each vehicle, since these parameters indicate the continuous speed and position adjustment that each user has to perform under high density traffic conditions: when the interaction between vehicles increases, accelerations and decelerations become more frequent. This likely requires a higher driving attention and a higher risk of improper manoeuvres. As mentioned in the previous sections, microsimulation is an ideal world where no real crash can occur, since users mistakes can not be represented, but the more frequent are the corrections requested to drivers (acceleration/deceleration), the higher is the risk of a potential error in reality.
The different behaviour of the vehicles in the traffic flow can be therefore represented by the average value of the acceleration/deceleration characterizing their path, where a bigger variability of these values can represent an increase of the interaction degree between the vehicles.
According to the above considerations, the variation of the accelerations/decelerations could be therefore considered to be a proper safety indicator.

In Figure 6 the average standard deviation of acceleration/decelerations of the vehicles, under different flow conditions, has been plotted: the black line represents the interpolation curve for a percentage of heavy vehicles equal to 0; the red line the interpolation curve with a 50% of HV.
For HV=0%, while the flow increases the variation of the accelerations increases up to a maximum value, which is reached when the road segment attains the capacity (in the considered case 2400 pc/h/ln, which corresponds a LOS E); the same relationship has been derived for HV=50%, but the maximum value occurs for a reduced flow rate (1700 pc/h/ln) corresponding to density values between LOS C and LOS D conditions.

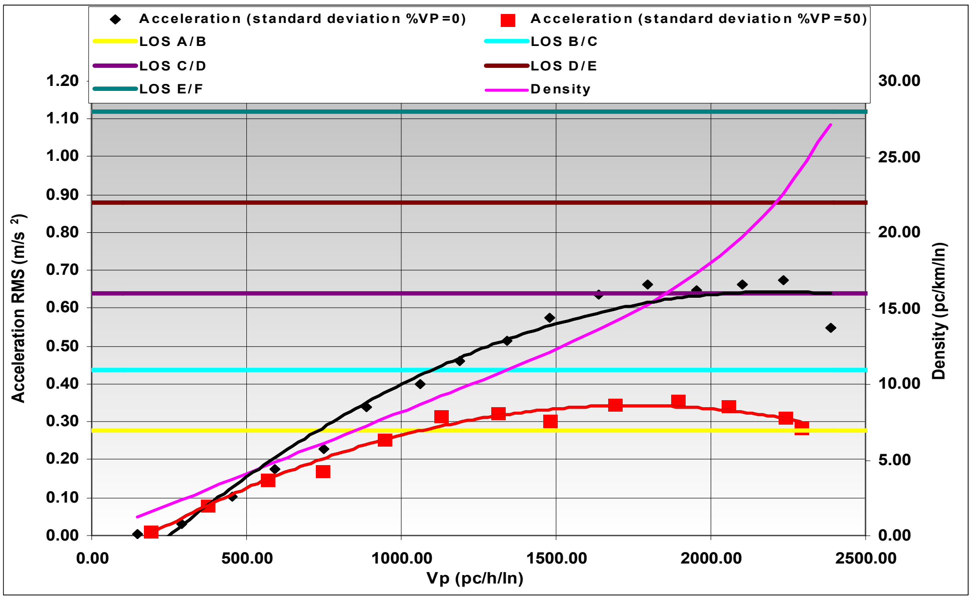

Figure 6: Average standard deviation of acceleration

The traffic conditions characterized by the higher values of the accelerations/decelerations variability can be considered to be the most unsafe conditions, that for this reason should be avoided inside tunnels. By means of Figure 6 it is possible to define the related critical traffic values (flow rate) and, by considering an adequate safety margin, the related alarm thresholds, above which special traffic control measures should be introduced. These values depend on the traffic mix compositions as suggested by the new EU safety standards for tunnels.

The results obtained allow to understand the safety margins adopted by the EU standards, as shown in Figure 7. From Figure 2, the flow values corresponding to the time headways of 2 and 4 seconds have been defined as 900 and 400 pc/h/ln respectively for light and heavy vehicles, Both represent LOS A traffic conditions and are really far from the critical situations identified from Figure 6. When dealing with tunnels freely opened to traffic, operating in normal traffic conditions, restricting traffic when LOS≤A seems very critical.
Therefore a reduction of the safety margins adopted by the EU standards, when dealing with this type of tunnels, seems envisageable as outlined in Figure 7. For a traffic mix composition with HV=0% the threshold

flow value could be identified in 1250 pc/h/ln corresponding to the transition between LOS B and LOS C conditions and to a time headway of 1.8 sec. (see Figure 2). For HV=50%, the threshold value reduces to 900 pc/h/ln, corresponding to the time headway of 2 sec.

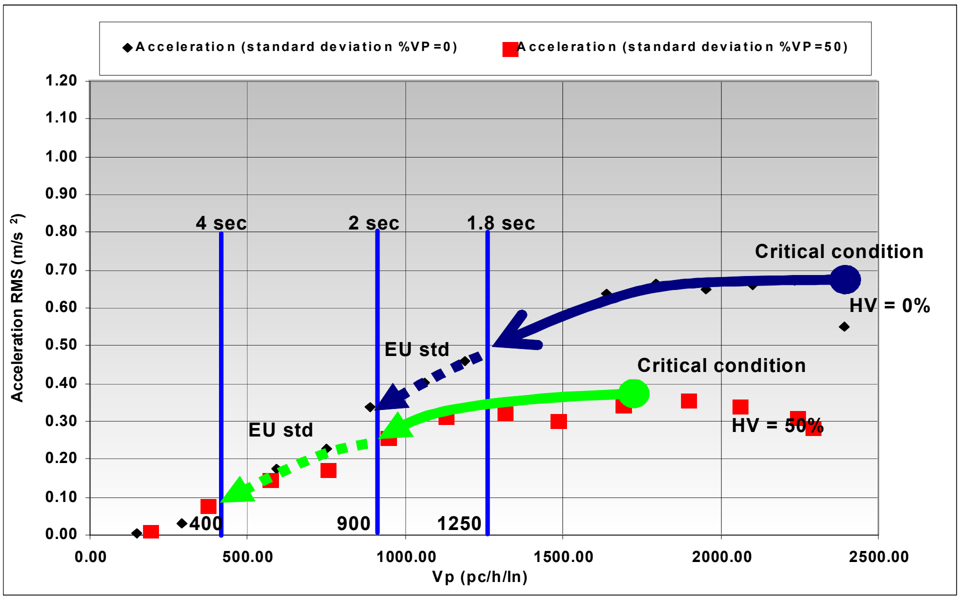

Figure 7: Safety thresholds for traffic flows inside tunnels

CONCLUSIONS

From the evaluation of the relationships existing between flow, density, speed, time headway and acceleration, threshold values for traffic flow or speed (easy to register) on a section could be established, according to the principle of ensuring average headways higher than the chosen reference minimum value. This approach can be of a very practical usage in designing traffic management schemes targeted to improve safety.

The proposed threshold flow values have been defined considering, as safety indicator, the variability of the accelerations/decelerations of the vehicles included in the traffic stream. The higher is this variability, the higher the interaction between the vehicles. The threshold values depend on the traffic mix composition and could be defined in a value of 1250 pc/h/ln, in case of light vehicles traffic, and of 900 pc/h/ln in case of a percentage of 50% of heavy vehicles present in the traffic mix. These values correspond to vehicle time headway respectively of 1.8 sec. and 2 sec. and are characteristic of traffic conditions characterized by LOS=B.

With respect to tunnels, these values have been compared with those that can be derived from the standards fixed by the European commission to ensure safety in tunnels. These are expressed in terms of vehicle time headway and are 2 or 4 seconds, depending on the traffic mix. These time intervals, according to the evaluation performed, correspond to flow values respectively equal to 900 and 400 pc/h/ln, corresponding to the traffic conditions characterized by LOS A. The EU standard values are therefore more conservative than the proposed ones but seem less realistic than them.

The proposed approach, based on microsimulation and on the indicators derived from it, works at two levels:

- it permits a preventive identification of potential risk situations, when the time headway and the interaction level between vehicles becomes critical for the safety conditions inside the tunnel;
- it represents a tool to plan and design traffic management strategies, capable to control traffic conditions within predefined safety ranges, i.e. to maintain the safety distance below the allowable selected value. With reference to the analyzed case, this can be obtained, for instance, by equipping the infrastructure with a specific ramp metering system partially preventing the traffic to enter the tunnel, when necessary, therefore using the traffic flow as a derived reference parameter for safety. With the automatic detection of traffic flow (or speed) at the entrance of the tunnel tubes, once the recorded values are reaching the predefined safety threshold values, the ramp metering system could intervene diverting traffic to a specifically designed traffic storage area, constructed next to the tunnel entrance, and allowing the entrance of the vehicle in the tunnel with a predefined cadence, thus increasing the distance between two consecutive vehicles up to safe values and re-establishing safe traffic conditions.

REFERENCES

Rapp M. and Albrecht C. (2003), *Capacity and Slot Management for Heavy Goods Vehicle Traffic Across the Swiss Alps*, *Paper* #2336, Proceedings of the 10th Worls Conference on ITS, Madrid.

Barceló J., Casas J., Ferrer J. and Perarnau J.,(2003), *A Simulation Study to Evaluate the Performance of Adaptive Control Strategies for Traffic Safety Conditions in the Vielha Tunnel*, *Paper* #3759, 82nd TRB Meeting, Washington.

Domenichini L., di Volo N., Giaccherini A., Barcelo J., Ferrer J.L. (2004), *Microsimulation Techniques for the Analysis of Safety Management in Tunnels*, ITS Safety and Security Conference, Miami, USA , FL.

Commission of the European Comunities (2004), *Directive of the European Parlament and of the council on minimum safety requirements for tunnels in Trans-European Road Network*, Brussel.

Domenichini L., di Volo N., Serventi R. (2003), *Microsimulation Model for the New Italian Motorway System A1 – A1bis from Bologna to Firenze*", ASECAP Portoroz International Workshop.

Commission of the European Comunities (2002), *Directive of the European Parlament and of the council on minimum safety requirements for tunnels in Trans-European Road Network*, Brussel.

Transportation Research Board (2000), *Highway Capacity Manual*, National Research Council, Washington, D.C.

TSS Transport Simulation Systems (2002), *Getram Extensions user's manual.*