Passenger Cars Safety Assessment on Interchange Ramps

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ABSTRACT
Despite the importance of interchanges in highway design, not much research has been conducted regarding vehicle safety on interchange ramps. The research aims to assess the safety margins for vehicles travelling on ramps with curved sections. Since the ramps of trumpet interchanges consist of various curvature rates, such an interchange configuration was selected, at the ramps of which instrumented field measurements were performed. More specifically, geometry, speed, friction and lateral acceleration data were collected along curved sections of the trumpet ramps. The 85th percentile speed of passenger cars (in free flow conditions), as well as the associated lateral acceleration measurements, for both wet and dry pavement conditions, were correlated against vehicle skidding from two separate approaches, namely; the point mass model and a vehicle dynamics model. The safety margins were assessed through steady state cornering conditions of the vehicle dynamics model, which was used as a quantification reference for both speed and lateral acceleration variations. The analysis revealed many interesting findings. In general, it was shown that vehicles maintain a sufficient safety margin in terms of traveling at impending skid conditions for both dry and wet pavement conditions, where a comparison between the relevant operational speed values revealed a reduction of approximately 9% in the latter case. Moreover, besides the fact that the point mass model underestimates lateral friction, it was found that the measured lateral acceleration values do not fall within the comfort limits as defined by the AASHTO guidelines.
Keywords: Interchanges, Safety, Lateral Acceleration, Operational Speed

INTRODUCTION AND PROBLEM STATEMENT

Interchanges are integral elements of motorways since they have a significant role in controlling entrance and exit traffic volumes. In particular, vehicles enter and exit interchanges at rather high speeds, where in certain interchange configurations vehicles are required to follow a sequence of sharp horizontal curves and/or steep gradients. Interchange ramps with high speeds combined with steep gradients and sharp turns, may result in vehicle skidding regarding passenger cars, especially under wet pavement conditions, and rollover of heavy vehicles (e.g. commercial trucks), on dry pavements.

Based on experience, drivers tend to increase or decrease their speeds during on-ramp entrance and exit maneuvers respectively. However, besides speed and curvature data, the assessment of additional parameters during ramp cornering such as accelerations – decelerations or the interaction between the pavement and vehicle tires in terms of friction, hasn't been thoroughly examined.

In addition many interchange ramps designed in the past (40 or more years ago), do not meet the requirements of more recent research, such as provision of decision sight distance or road perspective in 3D (e.g. 1,2). Such cases are common in Greece, where at that time there were no official design guidelines for interchanges and as a result, areas of potential safety violations may exist.

The present study aims to assess safety during vehicle motion on the ramps of such an interchange for which instrumented field measurements were performed and further analyzed.

METHODOLOGY

After selecting a study interchange, the safety assessment of vehicles travelling on interchange ramps was performed by measuring the running speeds of the vehicles and correlating the data against respective maximum constant speeds resulting from the vehicle's retention requirements during a curved path. More specifically, initially the required data were measured through appropriate equipment, where as a second stage the measured data were processed through specialized software.

In the following sub-sections each step of the data collection for this study is further analyzed.

Interchange Selection

The basis for selecting the study interchange configuration was to be heavily used by passenger vehicles and commercial trucks, and, at the same time, as unfavorably designed as possible. Following this concept, an existing trumpet interchange form was selected (Schistos interchange) at the area of Skaramagkas (towards Piraeus), located at the entrance area of Athens, as part of the Athens – Patras motorway.

The reason for selecting such an interchange configuration, is that the ramps of trumpet interchanges consist of various curvature rates, and therefore the potential risk is higher. Moreover, trumpet interchanges are among the most widespread forms of three legged interchanges in Greece.

The present interchange (Figure 1) is a reverse trumpet type interchange (type A) meaning that vehicles enter the motorway through the loop consisting of consecutive sharp curves.

Figure 1 Schistos Interchange

As already mentioned, there is a wide diversity of vehicles travelling on the Schistos interchange due to the fact that Skaramagkas is an industrial area and thus traffic consists of both passenger vehicles and commercial trucks rather equally distributed.

It is worth noting that at the selected interchange, there is traffic congestion almost at all times and especially during the busy hours. This is the reason a new interchange is planned to be designed able to improve the low operating level.

Interchange characteristics

The design characteristics of the study interchange were obtained through official drawings showing both its horizontal and vertical alignment. Furthermore, in total, 5 spots were selected in order to measure the vehicle speeds. The travel lane width of the ramps is 3.75m and the design characteristics of the interchange at the measurement spots are shown in Table 1.

TABLE 1 Geometrical Characteristics of the Study Interchange at Measurement Spots

Measurement spot	*Curve radius*	*Road gradient*	*Superelevation*
ATC-1	110 m	-1.57 %	2.00 %
ATC-2a	65 m	2.48 %	2.00 %
ATC-2b	30 m	-3.80 %	3.50 %
ATC-3(Pir)	220 m	-4.00 %	-2.00 %
ATC-3(Kor)	220 m	4.00 %	2.00 %

Speed and traffic data collection

Traffic as well as speed data of vehicles using the interchange for a period of three consecutive days were collected through automatic traffic counters (rubber tubes). The equipment used was the MetroCount MC5600 portable traffic classifier, using pneumatic tubes laid across the road. The basic work principle of this type of traffic counters is as follows: One set of at least two rubber tubes are placed across traffic lanes and when a set of wheels passes over the first tube, the air pressure changes and activates a recording device noting the time of the event. The moment the vehicle passes over the second tube, the device records the time of this event and with the distance between the two rubber tubes known, the supplied software easily calculates the speed of the vehicle. The software also categorizes the vehicle by comparing the length of the two axles (or more) of the vehicles passing over the pneumatic tubes with a standard vehicle classification system that relies on wheelbase length. The passenger cars are the only vehicle category that is examined in this paper.

This data collection was performed for 5 days, starting on the July 5, 2018 (12:00 local time) and ending on July 9, 2018 (9:00 local time). The first and the last day of the measurements were not taken into account since only part of the daily traffic was measured. Three consecutive days (July 6, July 7 and July 8) were studied around the clock, as 24 hours of traffic recordings were available, thus giving a more clear idea of the speed and traffic conditions occurring on the interchange.

Meteorological data

The speed of a vehicle is effected by weather conditions and especially by wet pavement conditions. In general, the weather was reported mild with the exception of Sunday July 8 where heavy rainfall was recorded in the afternoon. These data were collected in order to correlate them with speed and road geometry parameters of the ramp alignments in order to compare the results with relevant research.

Lateral Acceleration Measurements

For the maximum constant speed that a vehicle can reach during a curved path two main theoretical models were utilized; the point-mass model (1-3) and an existing vehicle dynamics model (4-6).

The point-mass model assumes the vehicle as a point on the surface, from where all the external forces interact. This model is very simple and allows for quick calculations with more or less satisfactory results regarding lateral forces acting on the vehicle. However, it does not take into account the road gradient and assumes that vehicles travel on a perfect circle path during their curved motion. This approach ignores many parameters, such as the actual forces acting on the vehicle's wheels, as well as the load transfer during cornering, driving configuration, etc.

In order to take into account the disregarded factors affecting a vehicle during a curved path, a more detailed model has been developed. This vehicle dynamics model analyzes all forces and moments acting on all four wheels of the vehicle, takes into account the gradient of the road, thus delivering the actual demanded values of both longitudinal and lateral friction factors and correlating them against the available peak friction of the roadway.

The calculations for this model are far more complicated; therefore, a specialized software has been developed in order to reach the necessary results with given vehicle data and road parameters. Given the fact that the examined ramps of the trumpet interchange are characterized by steep road grades, this analytical and more precise model was used for the calculation process of the demanded lateral acceleration values.

The validation of both theoretical models was drawn in terms of lateral acceleration outputs against the outputs of a test vehicle utilized at the study interchange. The test vehicle used was a Toyota Yaris (where HP supply was set to 100hp), the most widespread passenger car in Greece in recent years, supplied with a Garmin GPS receiver and a Vericom VC4000DAQ accelerometer mounted on the frontal windshield. In total, 10 test runs were performed on the study interchange, 5 runs on each direction at different speeds. The speed of the test runs was selected based on the speed data of the interchange that were measured from the automatic traffic counters.

The results revealed satisfactory results, which were rather expected based on previous research of the authors (4-6).

Accident data

In order to address more accurately the safety assessment of vehicles motion at the interchange, an effort was made to collect accident data as well. However, after contacting local police authorities as well as the association of insurance companies in Greece, no accident data were recorded at the study area of the interchange. However, minor accidents due to vehicle skidding were evident at the study area as concluded from the deformed barriers on the outer side of the horizontal curves.

ANALYSIS

The raw data collected from the automatic traffic counters were processed through a spreadsheet software in order to initially determine the traffic volume at the interchange ramps. From this task it was shown that the number of vehicles travelling with direction to Korinthos is higher compared to vehicles travelling to Piraeus. This finding further strengthens the assumption that this particular interchange is potentially dangerous as the higher volume traffic is occurring on the loop ramp of the interchange.

As stated before the paper aims to assess safety of passenger cars travelling at interchanges by examining their speed. The most basic speed utilized in road design is the "design speed" and it is the maximum permissible speed for all vehicles and depends on the road type. At the study interchange the "design speed" was found to be the same for all ramps at 50 km/h excluding the loop for which the design speed was set to 40 km/h.

The second very important speed characteristic is the 85th percentile speed. This value is defined as the speed that is not exceeded by 85% of all passenger car vehicles travelling in free-flow conditions in wet road surface. In general, road surface conditions do not greatly affect the 85th percentile speed of passenger cars, however, in the present paper the speed difference between dry versus wet surface was further examined. In order to calculate the V_{85} speed, the collected raw data were recorded, as far as between two successive vehicles there was at least 6 seconds time gap (headway), thus meaning that it travels in free-flow conditions.

The 85th percentile speed was calculated for the different radii values of the horizontal curves that measurements took place, for all the 3 days. The ATC-3 measuring spot was ignored during the analysis due to the fact that there are traffic lights less than 150m away meaning that the results are indirectly affected. For all the remaining measuring spots, the results are presented in Table 2.

TABLE 2 85th Percentile Speed Measured at the Study Interchange

	85th percentile speed (km/h)			
Measurement spot	***6/7/2018***	***7/7/2018***	***8/7/2018***	***Average***
ATC-1(R=110m)	64.4	68.8	65.9	66.4
ATC-2a(R=65m)	54.8	56.5	54.9	55.4
ATC-2b(R=30m)	37.2	38.5	38.0	37.9

Along with the 85th percentile speed, the average speed of free-flow travelling vehicles, the 15th percentile speed, the minimum and the maximum speed values were calculated and embedded into the graph, shown in Figure 2. A closer look at Figure 2 reveals the tendency of drivers to increase the vehicle's speed as the radius of the curve raises. Similar findings can be also found in a similar research (7).

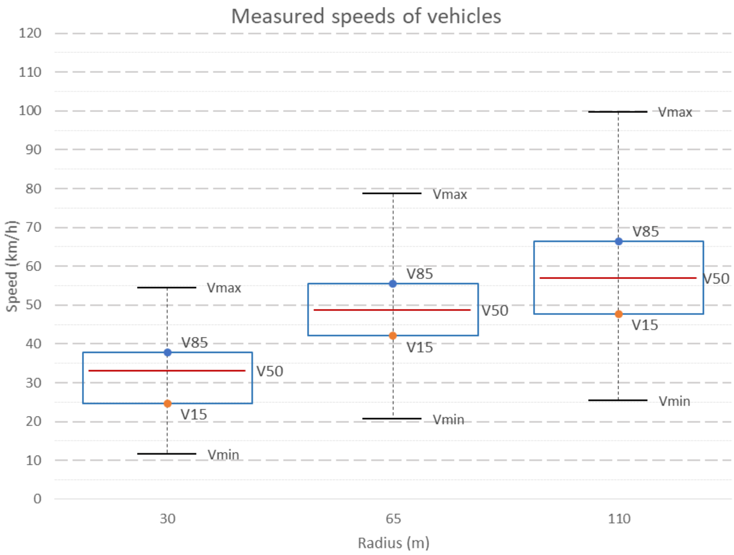

Figure 2 Measured Vehicle Speeds Travelling at the Study Interchange

During the measurements, heavy rainfall was observed on July 8, thus providing the opportunity to examine the 85th percentile speed in dry and wet conditions. By measuring the speeds observed an hour prior to the rain event, the $V_{85,dry}$ speed was determined for every curve. During the rainfall the $V_{85,rain}$ was determined and an hour after the rainfall had stopped the $V_{85,wet}$ was calculated as well. For all the examined conditions, the results are presented in Table 3, where besides observed speeds, their relative reduction in respect to dry conditions is also shown.

TABLE 3 85th Percentile Speed on Various Road Surface Conditions

Radius(m)	Speed dry (km/h)	Speed rain (km/h)	Speed wet (km/h)
110	64.6	42.6 (-34.1%)	58.9 (-8.7%)
65	54.2	42.8 (-21.1%)	48.8 (-10.3%)
30	38.9	30.7 (-21.1%)	35.4 (-9.2%)

After calculating the speeds of vehicles at the interchange ramps, the next step was to examine the lateral acceleration caused by these speeds. By driving the test vehicle mentioned in the previous section, at speeds approaching the observed speeds, the lateral acceleration was able to be calculated. It was found that the lateral acceleration felt by drivers at the interchange is beyond the comfort limit as defined by AASHTO (1) for all ramps of the interchange. More specifically on the curve with 30m radius, the comfort limit is 0.210g where from the test results the driver experiences lateral acceleration of 0.364g. The same is true for the curves with 65m and 110m radii where the limit is 0.150g but the driver experiences 0.386g and 0.320g respectively.

Due to the steep gradient of the interchange, the more analytical vehicle dynamics model was selected in order to assess the accuracy of the test results. Since the test vehicle is front wheel drive (FWD), the comparison of the lateral acceleration concerns the front axle. In order to apply the vehicle dynamics software it was crucial to know certain road characteristics. Most of these data were available except for the available friction factor of the road surface. This assessment was performed based on previous research (6), where, utilizing the accelometer, the available friction factor of the road surface was calculated f=0.88. The outputs of the model in terms of lateral acceleration results, as expected, revealed the performed field measurements.

The safety of a vehicle travelling at the interchange was assessed by comparing the measured speeds to the maximum constant speed calculated by vehicle's retention requirements during a curved path. Using the vehicle dynamics model, the maximum attainable constant speed at impending skid conditions was calculated for all the examined curves of the interchange. This calculation was performed for different friction factors, including the existing available friction as well as relevant friction factors referring to wet pavement surface. The maximum attainable constant speed of the vehicle as a function of the examined curved sights as well as the available friction values of the roadway is shown in Figure 3.

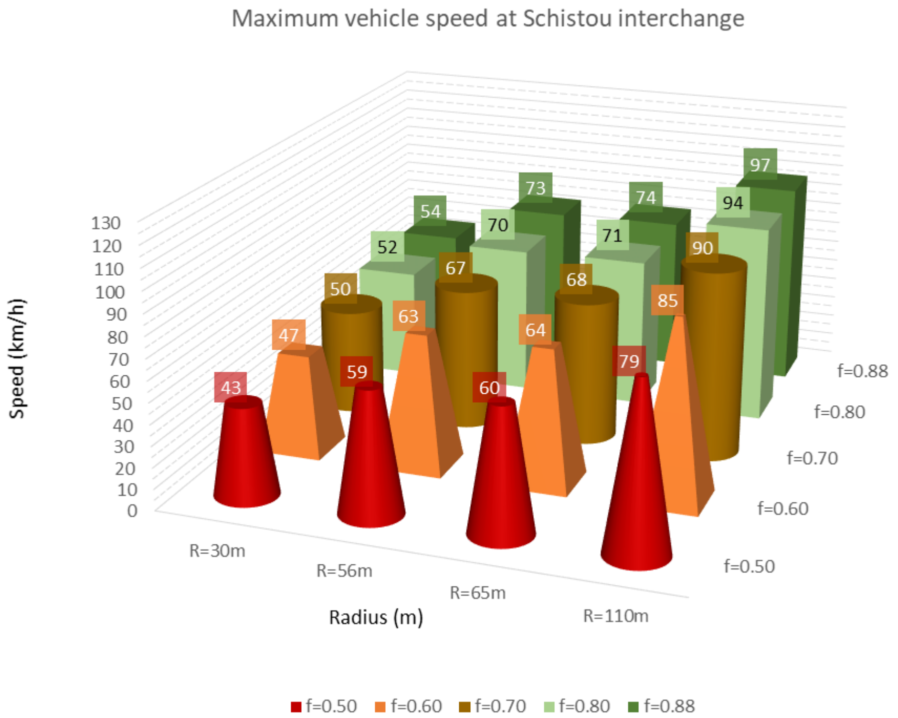

Figure 3 Maximum Constant Speed Calculated through the Vehicle Dynamics Model

Having already performed speed measurements of the vehicles, it was possible to compare them with the maximum obtainable constant speeds at the interchange and examine the differences between them. This was performed for two friction factors, one referring to the existing friction factor (f=0.88) and the other referring to wet road surface where f=0.50.

Through this approach, the measured 85th percentile speeds were subtracted from the maximum obtainable constant speed at each examined curve of the interchange for dry and wet surface conditions. The results shown in Table 4 represent the margin of the measured passenger cars' speed in each radius of the interchange.

TABLE 4 Comparison between Measured and Maximum Speed for Dry and Wet Road Surface

Speed difference (km/h) in **dry** surface	
Radius (m)	V_{85}-$V_{max,theory}$
30	-16.2
65	-18.3
110	-30.6

Speed difference (km/h) in **wet** surface	
Radius (m)	V_{85}-$V_{max,theory}$
30	-8.4
65	-10.2
110	-20.5

From the above Table 4, it can be seen that the vehicles maintain a sufficient margin from the impending skid speed on dry surface. However on wet pavement conditions, the speed margins drop and combined with the fact that wet surface increases the chance of vehicle skidding, the possibility of an accident occurring is greater. The observation that vehicles maintain a sufficient safety margin with respect to the maximum speed is confirmed by the lack of documented accidents on this particular interchange.

Since the paper examined only one interchange type, it is obvious that the present analysis needs to be performed on more interchange types. In order to assist future researchers with relevant tasks, and based on the specialized vehicle dynamics model software, two graphs were delivered that calculate the maximum attainable constant speed of passenger vehicles taking into consideration the available friction factor, grade as well as the superelevation of the road and the radius of the horizontal curve. These graphs are presented in Figure 4 and Figure 5, for a superelevation rate of 2.50% and 7.00% respectively.

By using these graphs a researcher can select the appropriate line that corresponds to the gradient and friction factor of the road and instantly calculate the maximum attainable constant speed for a given radius, and thus assess the safety margins with respect to the documented speeds at the study interchange.

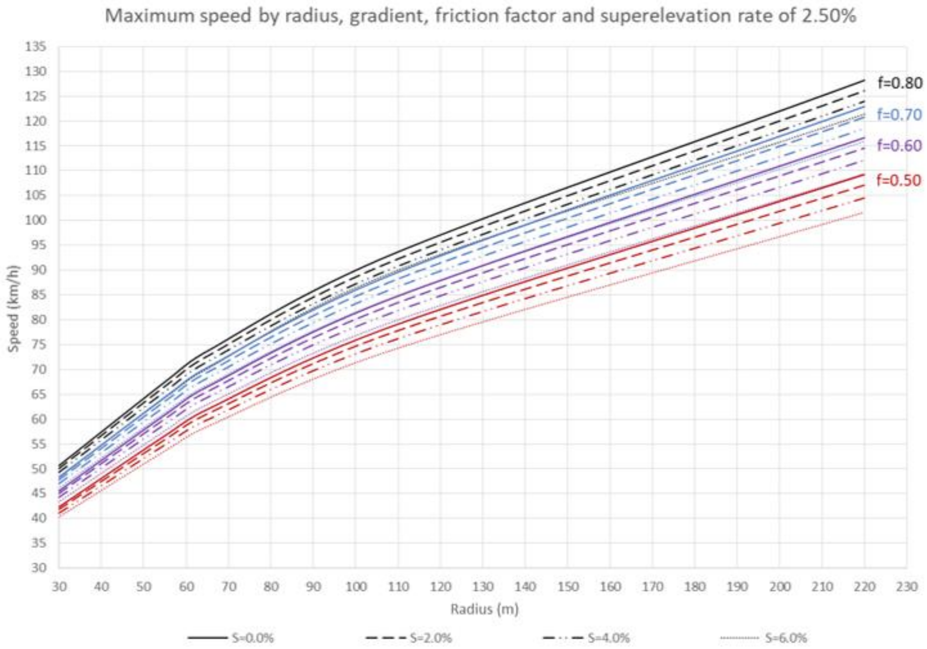

Figure 4 Maximum Speed Calculation for Superelevation Rate of 2.50%

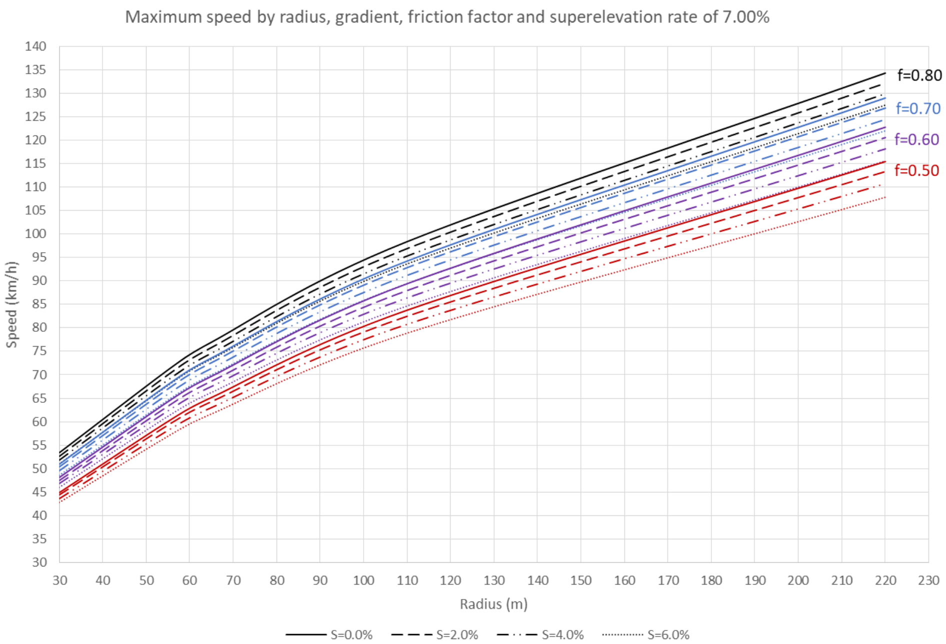

Figure 5 Maximum Speed Calculation for Superelevation Rate of 7.00%

DISCUSSION AND CONCLUSIONS

The present paper examined the safety of passenger cars travelling on a trumpet type interchange, namely the Schistos interchange in Greece.

More specifically, the investigation was carried out by comparing the speeds of vehicles travelling on the study interchange with the maximum speeds resulting from the vehicle's retention requirements during a curved path.

Traffic and speed data of vehicles using the interchange for a period of three consecutive days were collected through automatic traffic counters in the form of rubber tubes. By examining the motion of passenger cars under free flow conditions and respecting the 6 seconds headway, the 85^{th} percentile speed was determined.

The measurements were performed under dry road conditions, where also the impact of wet and heavy rainy pavement was also examined.

Using a typical passenger car, on site ramp cornering travels were performed at different speeds in order to correlate lateral acceleration and speed data of a typical vehicle and examine whether these results are in agreement with the theoretical approach of calculating lateral accelerations. An existing vehicle dynamics model was used for this analysis.

Based on the above analysis, the results of the recorded speeds, namely the 85^{th} percentile speed of passenger cars, were compared with the maximum attainable constant speed values that can be obtained according to the vehicle's retention requirements during a curved path.

Through the above analysis the following results were determined:

- The 85^{th} percentile speed is reduced by 9% on wet road surface compared to dry road surface.
- Speeds in all horizontal curves of the ramps of the interchange cause lateral accelerations outside the comfort limits as defined by the American AASHTO, 2018 design guidelines.
- Vehicles do not travel at impending skid conditions and maintain a sufficient safety margin with respect to the speed calculated from the lateral friction coefficient requirement.
- Vehicles maintain a significantly lower safety margin with respect to the speed calculated from the lateral friction requirement on wet road surface compared to dry road surface.

The present analysis needs to be extended further on more interchange types in order to solidify the findings of this paper. Figures 4 and 5 provide an easy way for quantifying the safety margin for standard superelevation rates and thus can provide future researchers with more input.

Furthermore, since only passenger cars were examined, it is suggested that further studies need to be conducted in order to incorporate the entire vehicle fleet (SUV's, sport cars, commercial trucks, etc.) from which a more clear view regarding safety can be reached.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: PP, KA, VM, FM, SM; literature collection: PP, KA, VM, FM, SM; review and synthesizing: PP, KA, VM, FM, SM; draft paper preparation: PP, SM. All authors reviewed the results and approved the final version of the manuscript.

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