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Simulation based safety margin assessment on speed variation between tangent to curved road alignment

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Abstract

This paper investigates the safety margins of drivers along tangent to curved road sections. A vehicle dynamics model is presented, allowing to assess the vehicle speed variation at impending skid conditions from tangent to curve on the basis of several parameters. This model returns the theoretical curve corresponding to the driver's maximum efficiency, i.e. the maximum safe speed and acceleration along the tangent to curve section when utilizing the outmost of the available vehicle horse power. On the basis of actual vehicle speed profiles, the model also returns the respective curve for the actual efficiency i.e. the utilized share of vehicle horse power, which reflects the driver's safety margin. Data from a driving simulator experiment are used to test the proposed methodology and identify the parameters affecting drivers' efficiency / safety margins. The results suggest that drivers' safety margins towards the examined curve are considerable, with the majority of the drivers using less than 55% of the available vehicle horse power. Higher initial speed was positively correlated with driving efficiency i.e. lower safety margins. On the contrary, a higher safety margin was associated with earlier deceleration before the curve. Driver characteristics were not found to significantly affect the safety margins, except from age <35 years old who were associated with higher share of vehicle motion used. The proposed method has advantages over existing methods; it allows for a better understanding of driver speeding behaviour and a more objective and insightful calculation of the safety margin through the vehicle dynamics, along the entire road section from tangent to curve, which may assist in improving design and interventions at curves.

Keywords – speed variation, safety margin, horizontal curve, driving simulator

1. Introduction and problem statement

The design consistency of a road project is directly associated to safety [1]. Many researches [e.g. 2-7] have pointed out that if design consistency is present, the successive elements of a highway system act in a coordinated way and therefore road safety may be improved significantly. In general, consistency on the alignment is achieved by avoiding abrupt changes of critical alignment elements.

The most common means utilized to assess the design consistency of a road is the operational speed [8-9], which consists a crucial parameter in road geometric design since it is quantifiable (it can be measured). Substantial differences between operational speeds or between design and operational speeds in successive design elements, especially between approaching tangents to horizontal curves [10], may increase erratic manoeuvres and crashes [8, 11]. In a relevant research where the speed differential between approach tangent and curve was examined [12], a direct correlation between safety and variability in speed was reported.

However, in terms of the safety margins utilized, solely the examination of the vehicles' speed variations to assess the drivers' behaviour between the curve and the preceding tangent seem inadequate. The reason is that for most models, through field measurements, spot speed values are collected at specific and/or random points during the vehicle motion on the approach tangent to the curve. Therefore, the accuracy of these models may be biased since vehicles' acceleration – deceleration is extracted assuming either a linear relationship between the measured spot speed data or a linear regression analysis based on the curvature [e.g. 10, 14]. However, the acceleration/deceleration process mainly depends on tangent length, but also on curve features. In addition, the phenomenon cannot be studied from an only tangent-to-curve transition, as the curve conditions significantly influence the deceleration process.

Moreover, in a given alignment, all drivers tend to have a different "breakpoint", i.e. the distance from the curve entrance along the approach tangent where the vehicle speed is beginning to decrease. This "breakpoint", besides the physical and/or psychological condition of the driver depends on the vehicle's speed as well, as vehicles traveling at higher speeds will generally begin the deceleration process earlier than vehicles traveling at lower speeds. However, this assumption is not generic and significant variation is involved in the way different drivers will behave, also depending on the type of vehicle used.

The present paper aims to examine the speed variation of a tangent to curved road design by assessing the influence of several parameters and their potential correlation to the actual safety margin during the vehicle motion on the approach tangent. This safety margin is assessed on the basis of the driver's efficiency, which is defined here as a percentage of the maximum available horse-power (hp) utilization at impending skid conditions, and is further explained in the following paragraphs. Driver characteristics examined include the initial speed on the tangent section, the breakpoint on which the driver begins to decelerate, as well as individual driver characteristics i.e. gender and age. A driving simulator experiment was carried out in order to test the proposed methodology and linear models were developed to test the statistical associations between the examined variables.

2. Proposed methodology

A novel and promising metric to assess the margin of safety experienced by a driver during the vehicle's cornering process, in accelerated or decelerated motion, is the drivers' "efficiency", defined as the drivers' ability to utilize the available horse power, i.e. the percentage of the maximum horse power safely attainable at impending skid conditions. In this sense, the safety margin can be expressed as the difference between the actual vehicle horse power used and the maximum attainable horse power during vehicle's performance at impending skid conditions. This metric is advantageous for two reasons: first, it estimates the safety margin on the basis of an objective reference point (the maximum attainable horse power at impending skid conditions), compared to i.e. the operational speed, and second, it allows for a continuous and non-linear representation of the speed profile along the examined alignment.

In general during vehicle motion on tangents, especially long ones, the drivers do not maintain a constant speed; they usually tend to accelerate their vehicles [8, 11]. However, at some point before entering a curve, the drivers adjust (decrease) their speed accordingly. In the present analysis, the safety margin was assessed during the acceleration process, just before vehicle deceleration for entering the curve. More specifically, a driving simulator experiment was carried out, under free flow conditions, on a 2km., 2-lane rural road alignment of 3.50m/lane without shoulders. In all curves passing was prohibited during curve negotiation (double continuous line marking on the centreline) and no signage was present. The vehicle entrance on a single curve was examined for a number of drivers where in terms of road geometry, the vertical alignment was assumed flat, consisting of a tangent approximately 100m long, followed by a circular curve of R=133m with no entrance spiral and cross slope values. Moreover, the selected alignment was visible throughout the driving process without any sight restrictions (see Fig. 1).

The speed data collected from the simulator experiment were used to calculate the proposed metrics on the basis of the vehicle dynamics model, and use them to assess driver speeding behaviour and the related safety margins.

The objective of the experiment was twofold: (i) to define the parameters associated to drivers' efficiency i.e. ability to utilize the available horse power rates as a percentage of the maximum attainable (at impending skid conditions), through the vehicle's speed – distance profile, and (ii) to investigate at which distance (breakpoint) from the curve the vehicle speed decreases, for different drivers and initial speed values

For each run, the collected speed – distance data during the acceleration process at the examined curved area were correlated against an existing vehicle dynamics model where two different speed – distance outputs were extracted; the vehicle's performance at impending skid conditions and the best fitting curve to the collected speed – distance data quantifying in terms of percentage of the maximum attainable (driver efficiency).

As a result the safety margins during the above tangent to curve design were addressed as a percentage of the vehicle motion at impending skid conditions, and correlated to parameters such as the initial speed at the beginning of the alignment, the approach distance to the curve where the drivers reduce speed, as well as individual characteristics of the participants such as their gender and age. It is noted that this analysis focuses on safety margin variations from the driver's viewpoint. Efficiency and the related safety margins naturally depend on numerous parameters e.g. vehicle parameters (speed, weight distribution, centre of gravity), road design values (road functional class, curve radius, tangent length prior to curve, sight distance etc.) and driver characteristics (experience, aggressiveness and risk taking, etc.). Most roadway studies are based on drivers' perception of alignment or signage based on questionnaires, as collecting objective performance data for all the potential determinants is difficult. This paper uses the controlled environment of a driving simulator in order to focus on human factors (directly observable or indirectly measured) associated with safety margins at curves. For that purpose, a single curve is examined and the same (simulator) vehicle is used by all drivers, eliminating thus non driver-related confounding factors. This approach has some limitations (see section 5 for a detailed discussion), but allows for an exploratory analysis of driver-related aspects of safety margins on the approach from tangent to curve.

2.1. Vehicle dynamics model

A previous vehicle dynamics model developed by the authors [15-17] was utilized according to which the motion of any vehicle can be analysed in three linear movements: longitudinal, lateral, and vertical, as well as three rotational movements: yaw, roll, and pitch.

The basic assumption of the present study is that vehicle motion is considered on a road surface, following the curve centreline, in which all three geometric parameters remain constant; namely, grade s, cross slope e, and horizontal radius R. All forces and moments applied to the vehicle are analysed into a moving three dimensional coordinate system, coinciding at the vehicle gravity centre and formed by the vehicle's longitudinal (X), lateral (Y) and vertical (Z) axis respectively. Through these axes, the influence of certain vehicle technical characteristics, road geometry and tire friction were expressed, such as vehicle speed/ wheel drive/ sprung and unsprung mass and it's position of gravity centre/ aerodynamic drag/ vertical lift/ track width/ wheel-base/ roll centre/ suspension roll stiffness/ cornering stiffness/ grade/ superelevation rate/ rolling resistance tire-road adhesion values and horse-power supply. Thus with respect to the laws of mechanics, and after slight simplifications the following formulas express the equilibrium around each axis accordingly:

$$\sum X = 0$$

$$m\frac{dv}{dt} = \sum U_i - \sum S_i\vartheta_i + \frac{mv^2}{R}\beta - mgs - A_d \tag{1}$$

$$\sum Y = 0$$

$$m\frac{dv}{dt}\beta = \sum U_i\vartheta_i + \sum S_i + \frac{mv^2}{R}\beta - mge \tag{2}$$

$$\sum Z = 0$$

$$\sum P_i = mg + \frac{mv^2}{R}e - A_n \tag{3}$$

where (*f*=front, *r*=rear):

dv/dt: vehicle's acceleration rate (positive value) (m/sec^2)
U_f, U_r : driving forces acting to front and rear axle respectively (N_t)
S_f, S_r : lateral forces acting to front and rear axle respectively (N_t)
P_f, P_r : vertical forces acting to front and rear axle respectively (N_t)
m : vehicle mass (kgr)
v : speed (m/sec)
A_n, A_d : air resistance forces acting vertically and on the frontal vehicle area respectively (N_t)
s : grade (%/100)
e : superelevation rate (%/100)
R: curve radius (m)
β : sideslip angle (rad)
θ : steer angle (rad)

The variables for the sideslip angle and the steer angle were taken from the literature [18]. Furthermore the model takes into account the actual wheel load due to the lateral load transfer and the corresponding alteration of the lateral force on each wheel thus creating a four-wheel vehicle dynamics modelling [18-20].

The available tractive effort of the vehicle (driving force minus rolling resistance) acting on the front or rear axle (depending on the driving configuration) should be associated to the vehicle's speed as well the net power available at the driving wheels. Since a vehicle cannot always be driven at 100% of its available horse-power rate, the horse-power utilization factor (n), was utilized through Eq. (4) as follows:

$$F_x = 745.6\frac{P}{V}n \tag{4}$$

where F_x is the tractive force (N_t); P is the net engine horse-power available at the driven axle (hp); v is vehicle speed (m/sec) and n is the horse-power utilization factor (%/100)

In the current vehicle dynamics model the vehicle's longitudinal acceleration or deceleration of Eq. (1) is expressed as a function of vehicle, road, and tire friction parameters creating a four degree polynomial equation [11-13]. At the same time, by applying laws of mechanics, the vehicle's instant acceleration or deceleration can be expressed as a function of vehicle's instant speed as well as driven distance, thus forming the following differential equation. which is resolved by applying numerical Runge-Kutta method [21].

$$a(v) = \frac{dv}{dd} v \tag{5}$$

where $a(v)$ is the acceleration-deceleration (m/sec^2) and d is the distance (m)

The solution of Eq. (5) delivers the vehicle speed variation as a function of the required distance in order to eliminate the vehicle's acceleration – deceleration [$a(v)$=0]. This procedure takes place at impending skid conditions utilizing the Krempel equation [22] both in longitudinal and lateral direction of travel by adapting each time the horse-power utilization factor 'n' from Eq. (4). In other words since the vehicle's speed variation is performed at impending skid conditions, the model delivers for every integration the vehicle's "best" possible performance.

However, it must be stressed that under the term "impeding skid conditions", the model delivers data for the critical wheel. This means that not necessarily vehicle skidding will occur; instead a transition to an unsTab. vehicle motion is evidenced, which is in every case undesirable. The accuracy of the suggested procedure is subject to the selected integration step (distance step), which in the present analysis was set equal to 0.10 m. The resulting vehicle speed is a function of the driven distance at any predefined alignment. The model's outputs were correlated against the known data derived by two other distinct cases: the final climbing speed of a truck travelling on a grade [23] and the output data from the well-known CARSIM Simulation Software [16]. Both cases revealed a satisfying match.

The parameters inserted to the vehicles dynamics model refer to a Front Wheel Drive (FWD) C-class passenger car, were borrowed from the literature [15] and are shown in Table 1.

Tab. 1 - Vehicle parameters inserted to the model

L (m)	2.650	Wheelbase
t_f (m)	1.538	Front track width
t_r (m)	1.536	Rear track width
m (kgr)	1300	Vehicle mass
l_f (m)	1,161	Position of GC from front axle
h (m)	0,620	Position of GC from surface
$K_{\varphi f}$	27502	Suspension roll stiffness (front)
$K_{\varphi r}$	14324	Suspension roll stiffness (rear)
C_{af}	2295.7	Cornering coef. (front)
C_{ar}	2120.7	Cornering coef. (rear)
m_{uf} (kgr)	92	Unsprung mass (front)
m_{ur}	120	Unsprung mass (rear)
h_{Rf} (m)	0,020	Roll centre height (front)
h_{Rr} (m)	0,410	Roll centre height (rear)
r_{dyn} (m)	0,290	Dynamic radius
A_f (m$_2$)	1,850	Frontal area
c_N	0,280	Lift drag
c_d	0,360	Aerodynamic drag
P (hp)	100	Horse power

2.2. Friction data

The actual friction in every direction of travel and for every wheel were addressed by the model. However, the peak friction coefficients, assumed equal for the longitudinal and lateral direction of travel (friction circle), were extracted from Eq. (6), widely applied in current practice [24-27].

$$SSD = v \times t + \frac{v^2}{2g(\frac{a}{g}+s)} \tag{6}$$

where :

SSD (m) : stopping sight distance
t (sec) : driver's perception – reaction time [2.5 sec]
g (m/sec^2) : gravitational constant
a (m/sec^2) : vehicle deceleration rate [3.4m/sec^2, AASHTO (20)]
s (%/100) : road grade [(+) upgrades, (-) downgrades]

3. Driving simulator experiment

3.1. Experiment design

In order to test the proposed methodology for the assessment of driver's safety margin, a driving simulator experiment was implemented at the driving simulator of the Department of Transportation Planning and Engineering of NTUA. The NTUA driving simulator is a motion base quarter-cab manufactured by the FOERST Company. The simulator consists of 3 LCD wide screens 40'' (full HD: 1920x1080pixels), driving position and support motion base. The dimensions at a full development are 230x180cm, while the base width is 78cm and the total field of view is 170 degrees. The simulator is validated against a real world environment, with satisfactory relative validity as regards gender, age groups and area type i.e. urban or rural - the rural route included both tangents and mild curves [28].

The experiment started with a practice drive for familiarization with the simulator without any time restriction; it took place on a similar road environment as the one of the main experiment, i.e. a rural road with mild horizontal curves, its duration was typically between 10-15 minutes, and the evaluation criteria included handling the simulator (starting, gears, wheel handling etc.), keeping the lateral position of the vehicle, keeping constant speed and appropriate for the road environment, braking and immobilization of the vehicle. The simulated driving task consisted of driving a rural route of 2 km length, single carriageway, lane width 3m, zero gradient, mild horizontal curves, speed limit equal to 70 km/h and low traffic (see Fig. 1). More specifically, ambient vehicles arrivals were drawn from a Gamma distribution with mean m=12sec, and variance σ2=6 sec, corresponding to an average traffic volume Q=300 vehicles/hour on both traffic streams. This resulted in moderate oncoming traffic on the opposite traffic stream and a lead vehicle at long headway ahead the simulator vehicle, aiming to enhance the fidelity of the virtual road environment with respect to actual conditions, but without affecting the driving behaviour of participants.

Participants were recruited among subjects of a large driving simulator study implemented at the same time at NTUA with more than 300 subjects in total, aiming to assess driving performance of all age groups with focus on elderly. Forty-three participants aged from 22 to 87 years of age carried out the simulated drive of the present research. The participants had no known health or vision problems, held a valid driving license and were frequent drivers (i.e. reported driving more than 3 times per week and more than 5,000 annual kilometres travelled). Twenty-two of the participant were males and 21 females, and their age distribution was as follows: 18 participants were less than 35 years old, 16 participant were between 35 and 55 years old, and 9 participants were older than 55 years (out of which 4 were older than 65 years). No specific instructions were given to participants as per the purposes of the specific drive; they were asked to drive at their preferred speed as they would normally do and observe the road signs and markings as usual.

For the analysis purposes, a specific road section of the examined route was selected (see Figure 1); this section was selected as being a typical mild curve after a tangent with no traffic signs, roadside obstacles or other features that might affect speeding behaviour. The examined section starts on the entrance from a 100m approximately tangent (at the beginning of which the curve became visible) to a circular arc of R=133m. The distance of 100m before the curve was selected on the basis of exploratory analysis of speed profiles, which indicated that all drivers began decelerating after that point (it is noted that this distance is case specific and in different settings the deceleration process may start earlier e.g. 12, 29-31). The examined alignment was visible throughout the driving process and there were no sight restrictions. There was quite some variation on the initial speed values at the entrance of the examined section. When approaching the curve, all drivers decelerated in tractive mode, by releasing the pressure on the accelerator and without using the vehicle's brakes.

3.2. Data and analysis methods

From the driving simulator metrics, point speed data were extracted for each participant. The speed – distance data during the utilization of the maximum attainable vehicle's horse power rates were also calculated for all drivers, allowing to identify the efficiency curve which best fits each driver's relevant data extracted for the same initial speed - an illustration is presented in the Results section below. The following parameters are examined in the present analysis:

- Drivers' efficiency (Eff): percentage of vehicles' maximum attainable horse power range during vehicle's performance at impending skid conditions
- Initial speed (V_o): the point speed at the entrance of the examined section e.g. 100 meters before the start of the curve
- Breakpoint (xbreak): the distance from the beginning of the curve at which the driver first starts to decelerate
- Driver gender
- Driver age group: <35 years, 35-55 years, >55 years

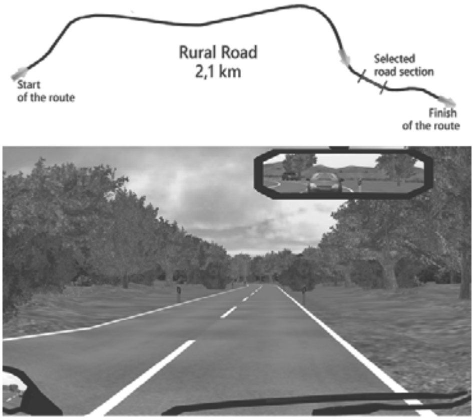


Fig. 1 - Plan view of the selected road section (top panel)
and simulated driving environment - tangent to curve (bottom panel)

4. Results

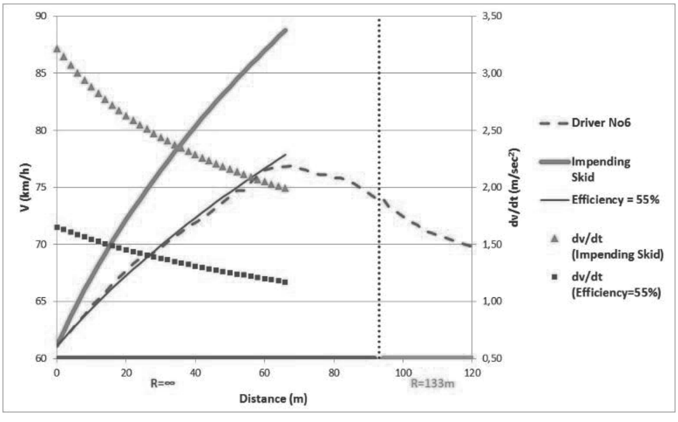
4.1. Estimation of driver safety margin

Figure 2 illustrates through the dashed line the actual speed – distance on the selected alignment, indicatively for driver #6. In the same Figure two additional speed – distance curves were extracted from the dynamic model, up to the "breakpoint" where the driver reduces speed. The bold continuous line represents the vehicle motion at impending skid conditions given by the vehicle dynamics model, and as expected the relevant vehicle speed values are as expected greater than the actual speed values. The non-bold continuous line shows the "best fit" of the actual speed data (in dashed line) to the vehicle dynamics model, and was calculated after various tests by setting each time the available horse power rate to a certain percentage of the horse power at impending skid conditions. Therefore, it can be seen that for the specific example, the vehicle, is driven with efficiency equal to 55% compared to impending skid conditions, and therefore a safety margin of 45% is involved on the specific approach from tangent to curve.

In the secondary axis, the relevant acceleration rates for both the runs performed by the dynamic model (maximum attainable horse power at impending skid conditions, and the percentage of this actually used) are shown. When the vehicle is driven at impending skid, the acceleration is far more increased (triangle line) compared to the case where the vehicle is driven with a 55% efficiency (square line).

4.2. Statistical analysis of parameters affecting the safety margin

In this sample drivers' efficiency calculated ranged from 8% to 55%, with a mean of 27.4 and a standard deviation of 13.4 (i.e. safety margins ranged from 45% to 92%, with a mean of 72.6), suggesting that drivers use a minor share of the available horse power on the examined curve. This may be due to the rural two-way road environment and the presence of oncoming traffic leading drivers to a more conservative driving behaviour. It is also noted that not all drivers exhibited a 'striking' peak in their speed profiles; especially in drivers of relatively low speed and efficiency, a 'plateau' shaped speed profile was observed, in which the desired speed was attained earlier and maintained up to the curve entrance. In this case, the "breakpoint" was defined on the basis of the distance at which the desired speed was first attained.



Note: The continuous lines at the bottom refer to the length of the utilized horizontal geometry

Fig. 2 - Example of speed-distance data run vs dynamic model's outputs

Driver efficiency estimates were found to best fit to a log-normal distribution i.e. the natural logarithm of efficiency was found to conform to a normal distribution. Table 2 presents the descriptive statistics and one-way ANOVA tests of the examined variables with respect to driver efficiency. It is noted that initial speeds at the entrance of the examined road section ranged from 38 to 94 km/h, i.e. in several cases well above the displayed speed limit, and this could have resulted in more efficiency / lower safety margins (e.g. more use of the vehicle horse power) when approaching the curve, but drivers approached the curve in a more conservative way by using higher safety margins. It is also noted that the breakpoints were situated along the entire tangent section, from 2 to 94 meters before the curve, revealing large variations in the way drivers negotiated the curve, from very early deceleration to very close to the curve. Safety margin appears to significantly vary with initial speed and with the breakpoint distance, but less so with driver gender and age group. This was further investigated as follows: it was tested whether initial speed and breakpoint distance are correlated with age and gender, but no strong correlation was found. Next, the safety margins of different age groups were investigated, and it was found that drivers <35 years old differ significantly in terms of efficiency from drivers >35 years old, but no further significant distinction between the second and third age group (i.e. 35-55 and >55) was observed.

It is possible that other (than initial speed and distance of the breakpoint), unobservable driver factors might better differentiate the safety margins between different drivers, e.g. aggressiveness, risk proneness etc. Although driver age and gender may be proxies of these factors (e.g. young males are known to drive more aggressively), they are not perfect correlates. The assumption here was that initial speed and distance of breakpoint are closer correlated of such unobserved driver human factors than age and gender.

A log-normal linear model was developed on the data, associating driver efficiency with the statistically significant parameters. Results in terms of parameter estimates and model fit are presented in Table 3. An R-squared equal to 0.47 was estimated, suggesting that the model explains only about half of the variation in the observed efficiency / safety margins on the basis of the available parameters. On the other hand, most of the variables tested were statistically significant.

More specifically, initial speed is positively associated with driver efficiency, suggesting that those entering the examined tangent at higher speed also tend to have a lower safety margin curve throughout the examined section, i.e. they are more efficient in utilizing greater percentages of maximum attainable horse power rates. Moreover, the breakpoint distance is negatively associated with efficiency, i.e. drivers who decelerate earlier before the curve have lower efficiency and thus higher safety margin, which is intuitive.

As regards the effects of driver characteristics, the safety margin does not appear to be affected by gender, but it appears to be affected by age group (the effect is significant at 93% confidence level). In particular, drivers aged less than 35% have higher efficiency curves, indicating that they use more of the available vehicle horse power when approaching the curve, which is consistent with the commonly known more ‘aggressive’ driving of younger age groups.

Tab. 2 - Descriptive statistics of explanatory variables and ANOVA results (F-tests) on safety margin

Variable	**Mean**	**Std.Dev**	**Min**	**Max**	**F**	**p-value**
Vo	58.481	12.148	38.650	86	14.573	.000
Xbreak	60.884	22.277	2.000	94	3.931	.055
Gender*	0.512	0.506	0	1	2.154	.151
AgeGroup**	1.791	0.773	1	3	2.149	.131

* mean represents the share of males and females in the sample i.e. 0 (males): 22 (51.2%), 1 (females):21

** mean represents the share of age groups in the sample i.e. 1 (<35 years): 18, 2 (35-55 years):16, 3 (>55 years):9

Tab. 3 - Parameter estimates of the log-normal model of driver efficiency

Parameter	**B**	**Std. Error**	**T-test**	**p-value**
Intercept	1.759	.578	2.999	.005*
Vo	.027	.007	3.718	.001*
Xbreak	-.007	.003	-2.026	.050*
[Gender=male]	.225	.160	1.409	.167
[Gender=female]	.000	-		
[AgeGroup <35 years]	.272	.146	1.865	.070**
[AgeGroup >35 years]	.000	-		

* significant at 95%, ** significant at 90%

5. Conclusions

The present paper investigated the speed variation and related efficiency / safety margins of drivers on a road section from tangent to curve. A vehicle dynamics model is proposed for the estimation of the safety margin, defined as the difference between the share of vehicle motion used by the driver (efficiency), compared to the maximum available horse power utilization to the impeding skid conditions. This approach is advantageous in two ways: first, it allows for a more objective calculation of the safety margin through the vehicle dynamics, compared to other commonly used criteria such as design speed, speed limit etc.; and second, the safety margin is explicitly considered as a profile varying along the entire road section from tangent to curve, taking into account the common acceleration / deceleration speed profile when approaching the curve, allowing for more complete insight on the actual speeding variations. This approach allows for a better understanding and a more detailed and accurate representation of speeding behaviour from tangent to curve road alignments, which may be useful in improving design but also in implementing appropriate interventions (signage, road markings etc.) to assist drivers in negotiating curves.

In order to test the proposed methodology, data from a driving simulator task were used on the basis of a sample of 43 drivers of both genders and all age groups. The data showed large variations in the speed along the examined section and consequently on the calculated safety margins. On average, a low share of vehicle motion was used by most drivers, less than 55%, revealing a conservative speeding behaviour (i.e. minimum safety margin was 45%). It is possible that drivers are reluctant in using the available horse power due to their perception of the rural road environment as a demanding one, their intentions to comply with the speed limit etc. Higher efficiency was associated with younger drivers, who also had higher initial speed at the entrance of the section and decelerated at a smaller distance from the curve. Moreover, the observed speed profiles had different shapes, with others showing a clear acceleration / deceleration peak, and others being rather ‘plateau-shaped’. It appears that there are numerous unobserved human factors that affect the examined speeding behaviour, even for a single given curve and a given type of vehicle, and thus it is not possible to generalise these findings.

The present research has some other limitations as well. Due to the relatively small sample and the known lower fidelity of a simulated environment compared to actual roads and the vehicle used by the participants in actual driving, the present results should be considered as exploratory. Moreover, only a single curve was examined, as a first step for understanding the various factors that affect drivers’ safety margin, with focus on driver characteristics (observed or unobserved i.e. random variation). Further analysis is needed to determine the impact of more parameters such as curves with various radii values, left and right curves (as it is known that drivers may behave differently), alignments with grades, but also their combined effect. Finally, data enriched by the actual curve path as well as alignments with different peak friction coefficients seem to be prerequisites before more definite conclusions can be reached.

Finally, it should not be ignored the fact that the human factor, in addition to perception – reaction procedure, might impose additional restrictions and consequently influence the braking process to some extent. The results of the statistical analysis suggest that a large part of speed variations remains unexplained by the variables considered, indicating that other and possibly unobserved factors may influence the speeding behaviour of drivers.

References

1. Polus, A. and D. Dagan. Models for Evaluating the Consistency of Highway Alignment (1987) Transportation Research Record, No.1122.
2. Gibreel, G.M., Easa, S., Hassan, Y., El-Dimeery, A. (1999) State of the Art of Highway Geometric Design Consistency. Journal of Transportation Engineering, Vol. 125, pp. 305–313.
3. Cafiso, S., G. La Cava and A. Montella (2007) Safety Index for Evaluation of Two-Lane Rural Highways. Transportation Research Record, No. 2019, pp. 136-145.
4. Lamm, R., B. Psarianos, T. Mailaender, E.M. Choueiri, R. Heger, and R. Steyer (1999). Highway Design and Traffic Safety Engineering Handbook. McGraw-Hill, New York, USA.
5. Montella, A., L. Colantuoni, and R. Lamberti (2008) Crash Prediction Models for Rural Motorways. Transportation Research Record, No. 2083, pp. 180-189.
6. Montella A., Imbriani L.L. (2015). Safety performance functions incorporating design consistency variables. Accident Analysis and Prevention, n. 74, pp. 133-144
7. Awatta M., Hassan Y., Sayed T. (2006). Quantitative evaluation of highway safety performance based on design consistency. Advances in Transportation Studies: An International Journal, n. 9, pp. 29–44.
8. Sánchez, J. (2012) Metodología para la Evaluación de Consistencia Del Trazado De Carreteras Interurbanas de dos Carriles. Ph.D. Madrid: Universidad Politécnica de Madrid, Spain.
9. Camacho-Torregrosa F.J., Pérez-Zuriaga A.M., Campoy-Ungría J.M., García A. (2013). New geometric design consistency model based on operating speed profiles for road safety evaluation. Accident Analysis and Prevention, n. 61, pp. 33–42.
10. Montella A., Galante F., Imbriani L.L., Mauriello F., Pernetti M. (2014). Simulator evaluation of drivers' behaviour on horizontal curves of two-lane rural highways. Advances in Transportation Studies: An International Journal, n. 34, pp. 91-104.
11. Park, P., L. Moreno-Miranda, and F. Saccomanno (2010) Speed-Profile Model for a Design-Consistency Evaluation Procedure in the United States. Canadian Journal of Civil Engineering, Canada.
12. McFadden, J. and L. Eleftheriadou (2000) Evaluating Horizontal Alignment Design Consistency of Two-Lane Rural Highways - Development of new procedure. Transportation Research Record 1737.
13. Fitzpatrick, K., P. J. Carlson, M. D. Wooldridge, and M. A. Brewer (2000). Design Factors that Affect Driver Speed on Suburban Arterials. FHA, TX-00/1769-3, Texas Transportation Institute.
14. Mavromatis S., B. Psarianos and C. Spentzas (1999). Influence of the Vehicle Acceleration on the Road Minimum Horizontal Curve Radius. Paper presented and published on the 32nd International Symposium on Automotive Technology and Automation (ISATA), pp.93-101.
15. Mavromatis S, B.Psarianos, M., D'Apuzzo and V. Nicolosi (2000). Design Speed Ranges to Accommodate a Safe Highway Geometric Design for Heavy Vehicles. Transportation Research Board. 2nd International Symposium on Highway Geometric Design, pp.339-351.
16. Mavromatis S., B. Psarianos and E. Kasapi, (2005) Computational Determination of Passenger Cars' Braking Distances Equipped with Anti-Block Brake Systems. Transportation Research Board. 3rd International Symposium on Highway Geometric Design, Chicago USA.
17. Gillespie T.D. Fundamentals of Vehicle Dynamics (1992) Society of Mining Metallurgy and Exploration Inc.

18. Dixon J.C., Tires, (1996) Suspension and Handling. Second Edition. Society of Autimotive Engineers, Inc Warrendale, Pa., UK.
19. Heisler H. (1993) Advanced Vehicle Technology. Edward Arnold. A Division of Hobber & Stoughton.
20. Edwards, C. H. Jr & Penney, D. E. (1996) Differential Eq.s and Boundary Value Problems: Computing and Modeling, Prentice-Hall, New Jersey.
21. Krempel G. (1965) Experimenteller Beitrag zu Untersuchungen an Kraftfahrzeugreifen. PhD diss.
22. Mavromatis, S., and Psarianos, B. Analytical Model to Determine the Influence of Horizontal Alignment of Two-Axle Heavy Vehicles on Upgrades. J. of Transportation Engineering, 129(6), 2003, pp. 583-589.
23. American Association of State Highway and Transportation Officials (AASHTO). A Policy on Geometric Design of Highways and Streets, Fifth Edition. Washington, DC., 2011
24. Ed.German Road and Transportation Research Association, Committee, Geometric Design Standards. Guidelines for the Design of Freeways, (RAA), Germany, 2008.
25. Ministry of Environment, Regional Planning and Public Works. Guidelines for the Design of Road Projects, Part 3, Alignment (OMOE-X), Greece, 2001.
26. Ministerio de Fomento. Instrucción de Carreteras, Norma 3.1 – IC “Trazado”, Spain, 2000.
27. Yannis G., Papantoniou P., Nikas M., (2015) Comparative analysis of young drivers behaviour in normal and simulation conditions at a rural road, Proc. of the 5th Int. Conf. on Road Safety and Simulation
28. Bella F. (2008). Assumption of Operating Speed-Profile Models on Deceleration and Acceleration Rates: Verification in the Driving Simulator, 87th Annual Meeting of the Transportation Research Board, Washington, D.C
29. Montella A., Pariota L., Galante F., Imbriani L.L., Mauriello F. (2014). Prediction of Drivers' Speed Behaviour on Rural Motorways Based on an Instrumented Vehicle Study. Transportation Research Record, n. 2434, pp. 52–62.
30. Montella A., Galante F., Mauriello F., Aria M. (2015). Continuous Speed Profiles to Investigate Drivers' Behavior on Two-Lane Rural Highways. Transportation Research Record, n. 2521, pp. 3–11.
31. Pérez Zuriaga A. M., García García A., Camacho Torregrosa F.J., D’Attoma P. (2010). Modeling Operating Speed and Deceleration on TwoLane Rural Roads with Global Positioning System Data. Transportation Research Record, n. 2171, pp. 11–20.

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Establishing the minimum routing decision distance for express lanes

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Abstract

Congestion Pricing is increasingly becoming a common strategy for congestion management, often requiring microscopic simulation during planning and operational stages. One of the microscopic simulation issues that has not yet been addressed is the required minimum routing decision distance upstream the ingress point. Decision distance is an optimal upstream distance prior to the ingress at which drivers decide to use express lanes and change lanes to orient on a side of express lanes ingress. To answer this question, this study used a VISSIM model for I-295 proposed express lanes in Jacksonville, Florida, varying the routing decision point at regular intervals from 500 feet to 7000 feet for different levels of service input. Three measures of effectiveness (MOEs); speed, the number of vehicles changing lanes, and following distance, were used for the analysis. These MOEs were measured in the 500 feet zone prior to the ingress. The results indicate that as the level of service (LOS) deteriorates, speed decreases, the number of vehicles changing lanes increases, and the following distance decreases. When the LOS is constant, the increase in the routing distance from the ingress point was associated with the increase in the speed at the 500 feet zone prior to the ingress, less number of lane changes, and the increase in following vehicle gap. However, the MOEs started to be constant after reaching a certain routing decision distance. LOS D was used to determine the minimum routing decision distance to the ingress of the express lanes. The determined minimum distances were 4000 and 3000 feet for six and three lane segments prior to the ingress point, respectively.

Keywords – decision distance, express lanes, VISSIM

1. Introduction

In the United States (U.S), nearly ninety percent (90%) of people drive to work [1], with a considerable proportion of commuters using freeways. Urban freeways are characterized by congestion [2] due to recurring incidents, mainly caused by peak hour traffic and non-recurring incidents. Every year, traffic congestion costs billions of dollars. For example, time lost due to congestion is about 91 million hours, which is worth $2.4 billion annually [2]. Congestion also leads to a loss of 35 million gallons of fuel per year, pollutes the environment by adding 740 million pounds of CO_2, and leads to 9,800 crashes [2]. A recently released report by the USDOT, Beyond Traffic [3], indicates that America's population will grow by 79 million by 2045, and by 2050, emerging mega regions could absorb 75% of the U.S. population, as rural populations continue to decline. Subsequently, this will increase traffic demand on urban freeways, resulting in more congestion. Increased congestion in urban highway facilities has caused transportation agencies to implement congestion pricing initiatives across the country. Florida is no exception. One of the

Transportation Systems Operations and Management (TSMO) strategies used by several states is introducing dynamic tolling facilities, also known as managed lanes or express lanes. Under the new Florida Department of Transportation (FDOT) policy [4], all additional capacity on the interstate shall be express lanes.

Any freeway facility whose operational strategies are implemented and managed in response to changing conditions such as increase freeway efficiency, maximize capacity, and manage demand, falls under the broad rubric of ‘managed lanes’ [5]. Managed lanes include high occupancy toll lanes (HOT), express lanes, truck lanes, bus lanes, and other special use lanes. Express lanes are exploited in this study.

As express lanes are becoming more pronounced, more studies are done to mimic its operation. The advantages of express lanes, such as increasing freeway efficiency by providing predictable trips with little to no congestion, have been well documented by previous studies including a Texas study by Grant and Ginger [6]. The operation of express lanes can be bi-directional or reversible with reduced number of entry and exit to ensure better flow. The establishment of express lanes have proved to be successful. A good example of successful express lanes is documented in the Florida I-95 Express lane annual report [7] which shows improvements in the overall performance. According to the report, travel speeds of express lanes have increased by 20 mph and are about 63 mph and 56 mph for southbound and northbound, respectively. Whereas for the general-purpose lanes, 20 mph average speed increase for northbound and 15 mph for southbound, resulting in average speeds of 50 mph and 42 mph for southbound and northbound, respectively.

Since express lanes are gaining popularity, more work on microscopic simulation of proposed and existing corridors is being conducted. One of the issues that have neither been addressed nor modeled is the determination of minimum routing decision distance to express lane ingress. Decision distance is an optimal upstream distance prior to the ingress at which drivers decide to use express lanes and change lanes to orient on a side of express lanes ingress. This distance allow drivers to initiate lane change maneuvers and reach express lanes ingress with minimal or no conflicts. Drivers are supposed to make an early decision to use express lanes so that they can easily access the lanes. This helps to avoid last minute rush which can lead to conflicts. The decision to change lanes and align on the lane to managed lanes ingress comes wherever the signs are placed. A cursory review of developed simulation models for Florida dynamic tolling facilities by various consulting firms shows inconsistency in coding the routing decision distance. To the authors’ knowledge, no research has been done focusing on the influence of decision distance upstream the ingress point on operational characteristics of dynamic tolling facilities. Therefore, this study intends to establish decision distance thresholds necessary for a smooth traffic operation at the proximity of the express lane ingress points.

2. Literature review

Traffic microscopic simulation modeling has long been recognized as a useful and important tool for planning and operational analysis of transportation infrastructure. There are several traffic simulation models including VISSIM, Paramics, Intergration, CORSIM, and SimTraffic. These models differ in simulation capabilities and limitations. In the U.S, for express lanes in particular, the two most commonly used models are CORSIM and VISSIM [4, 8, 9]. A dynamic tolling module was added in version 5.30 of VISSIM and since then, most agencies have been using it for modeling express lanes with dynamic tolling. In the current model, the decision to use express lanes in lieu of general-purpose lanes is determined by the tolling algorithm that uses base, cost, and time coefficients as user inputs. A pricing algorithm plays a key role in the analysis of express lanes. Since express lanes are dynamically managed, a dynamic toll algorithm that reacts to real-time traffic change conditions [10], computes the new toll price based on real-time information. Specifically, these computations are conducted at given interval, typically 15 minutes.

Dynamic tolling algorithm has been a focus of many studies for the last decade. The study by Zhang et al. [11] developed a dynamic tolling algorithm for HOT lane operations in VISSIM because at that time VISSIM could only simulate static tolling conditions. Michalaka et al. [12] developed three sets of modeling components to demonstrate HOT lane operation. The first component implements responsive pricing. While the second component mimics drivers change behavior in presence of toll, the third represents toll structure for multi-segment HOT facilities. The existing dynamic tolling algorithm in VISSIM is not without limitations. It uses only speed as the congestion performance measure to vary tolling cost and likelihood of drivers using the managed lanes [13]. In an effort to improve the existing model, PTV America, a vendor for VISSIM software, was contracted by the Florida Turnpike Enterprise to develop a script that incorporates density in the existing module. The aforementioned script was used in a recent study [14] that developed a verification tool for dynamic traffic assignments on I-95 managed lanes. The tool compares the theoretical number of drivers who decide to use managed lanes based on the logit dynamic assignment model and the VISSIM output.

At the time when this study was being undertaken, there was no literature on minimum decision distance prior to managed lane ingress. This distance relates to routing decision distance on express lanes in VISSIM. Perhaps the closest scenario to decision distance from the ingress point is the minimum weaving distance to the express lanes, i.e., distance from the closest on-ramp upstream the ingress point. For the decision distance scenario, drivers using the inside lanes and do not intend to utilize express lanes have to move to the outside lanes to avoid entering the express lanes. On the other hand, drivers who are in the outside lanes and need to use the express lanes would need to change lanes to access the express lanes. For the weaving maneuver that starts from the on-ramp upstream of the ingress point, drivers would need to change several lanes to access the express lanes located adjacent the median. For weaving sections, the State of California guidelines [15] allow a minimum distance of 800 feet per lane change on an intermediate opening of managed lanes and also an opening of an intermediate access that is not less than 2000 feet.

Another scenario that is somehow similar to the managed lane decision distance is the placement of notification signage prior to the managed lane ingress. Here, the assumption is that drivers will start taking action after they read the sign, similar to the assumption made in simulation, i.e., drivers will decide whether or not to use managed lanes at the predefined decision distance from the ingress. According to Chrysler et al. [16], advanced sign should be placed at a distance of at least 800 meters (2625 feet) prior to the ingress. On the other hand, the Manual on Uniform Traffic Control Devices (MUTCD) [17] requires managed lanes guidance signs to be placed approximately 0.5, 1, and 2 miles in advance of entry point from a general-purpose lane. The Washington State guidelines [18] have minimum weaving distance requirements based on different traffic composition (truck percentages) and desired level of service (LOS), with a minimum recommended weaving distance of 500 feet per lane.

3. Methodology

This section summarizes the information on project site, data source, and modeling process of the simulated scenarios. Specifically, these scenarios are decision distance from 500 to 7000 feet (10 scenarios) with variable volume inputs giving different LOS from LOS A to E (5 scenarios).

These scenarios are simulated with 10 variable random seeds (from 35 to 53 at an increment of 2) in the VISSIM software (10 Scenarios). This makes a total of 10*10*5 = 500 scenarios. Three measures of effectiveness i.e. number of lane changes, following or trailing distance, and speed, were used to compare the aforementioned scenarios.

3.1. Project site

The project site is a 4.3 and 3.1-miles stretches for the northbound and the southbound respectively, of I-295 proposed managed lanes in Jacksonville, Florida. This section extends from San Jose Boulevard (SR 13) to I-95 (Figure 1). It is part of an interstate beltway around the city of Jacksonville that serves as an important route for moving people and goods to different parts of Jacksonville. The express lane segment of I-295 within Duval County is a closed access facility with barrier separation which was proposed for the purpose of adding capacity and improving travel time on I-295 from west of SR 13 to the I-95/I-295 south system to system interchange. The express lanes will use dynamic tolling, which will vary with traffic volume to maintain the optimum number of vehicles so that the usage cannot compromise speed and travel times.

3.2. Data source

Simulation models require accurate and detailed data so as to replicate the actual traffic condition and operation. In the I-295 express lanes project, models were developed to reflect the actual site condition and features including alignments, weaving sections, and number of lanes. A microscopic traffic simulation model, VISSIM, is used in this study. A simulation period of two (2) hours with 30 minutes seeding time and 30 minutes dissipating time, specifically an AM eastbound peak hour from 8:00 to 10:00 AM is used. One year weekly traffic data were used to create a model. Traffic data input is varied to obtain different levels of services (LOS). Speed profiles (Table 1) which plays a significant role in network setting in VISSIM are used in modeling.

Fig. 1 - Location of the I-295 express lane project (Source: Google Earth 2016)

Tab. 1 - Speed percentiles for express lanes and general-purpose lane

Percentiles, %	0	10	20	30	40	50	60	70	80	90	100
GP (mph)	9	32	52.5	58.8	61.1	62.3	63.4	64.7	66.4	70	77.4
EL (mph)	40.6	63.8	65.2	66.3	67.4	68.6	70.8	75	76.8	78.3	89