DRIVERS' SPEED BEHAVIOUR AT RURAL INTERSECTIONS: SIMULATOR EXPERIMENT AND REAL WORLD MONITORING

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ABSTRACT

While drivers' speed behaviour has been widely studied, only marginal attention to the speed behaviour at intersections has been dedicated and more research is needed. Aim of this study was: (1) to evaluate if the intersections significantly affect drivers' speed along the major road; (2) to quantify this interaction in terms of both speed change at the center of the intersection and speed profile approaching and departing the intersection; and (3) to develop a procedure to integrate the existing operating speed profile models in order to take into account the presence of the intersections.

The study was performed by a driving simulator experiment and a real world speed monitoring. The presence of the intersection in the simulator study produced a statistically significant mean speed reduction in the center of the intersection equal to 12%, while in the real world experiment it produced a mean speed reduction equal to 22%. Furthermore, a statistically significant mean speed reduction was observed also 150 and 75 m before the intersection. Similar reductions in the operating speeds were observed. Both simulator and real world results showed that that intersections significantly affect drivers' speed behaviour, even though some differences between the two experiments were observed.

Keywords: rural intersections, operating speed profile, driving simulator, speed monitoring.

INTRODUCTION

The speed-profile is an useful tool for road safety both in the design process and in the evaluations of existing roads because the availability of the operating speed on each point of the alignment can be used for several safety considerations. While drivers' speed behaviour has been widely studied, only marginal attention to the speed behaviour at intersections has been dedicated and more research is needed (Montella et al., 2010). Indeed, the existing operating speed-profile prediction models do not take into consideration the presence of intersections along the road (Perco et al., 2010). The intersections create a higher momentary mental workload. Driving on open roads requires less cognitive demands than stopping for an intersection or performing change maneuvers, thus the speed generally decreases as the driver gets closer to the intersections (Teasdale et al., 2004). In some cases, the operating speeds of the adjacent roadway segments are appropriate for an intersection while in other cases a reduced speed may be desirable (Ray et al., 2008).

Despite the importance of the role of speed at intersections, the available research on the subject is surprisingly sparse (Haas et al., 2004; McLean et al., 2010), little data exist that isolate the effects of speed on overall intersection performance (Ray et al., 2008). Most studies focused on relationship between speed and crash severity (McLean et al., 2010) and focused on infrastructure-based research that has been conducted on human cognition, perception, and behavior in the areas of intersections, speed management, pedestrians and bicyclists, and visibility (Kludt et al., 2006).

In Italy, speed measurements were carried out on two-lane rural highways at major approaches of four intersections (Canale et al., 2004). The speed measures were collected along approach and departure tangents in the daylight, dry paving, good weather, good sight distance, and in free flow conditions. The results showed speed reductions ranging between 20 and 25 percent even though statistical significance of the results was not evaluated. On the other hand, the geometric design standards (Italian Ministry of Infrastructures and Transports, 2001, 2006) provide rules which do not take into account the intersections in the design speed profile. That is, according to the Italian standards the speed profile along the main road is not affected by the presence of the intersections. To shed lights on the drivers' speed behavior along approaching the intersections along the major road, aim of this study was: (1) to evaluate if the intersections significantly affect drivers' speed along the major road; (2) to quantify this interaction in terms of both speed change at the center of the intersection and speed profile approaching and departing the intersection; and (3) to develop a procedure to integrate the existing operating speed profile models in order to take into account the presence of the intersections.

DATA COLLECTION METHODOLOGY

The study was performed by two complementary methodologies: (1) a driving simulator experiment and (2) a real world speed monitoring.

Driving simulators have become an increasingly widespread tool to understand evolving and novel technologies. Study made in a controlled environment, like driving simulator, helps provide insights into situations that are difficult to measure in a naturalistic driving study such as differences in visual search as influenced by day, night, and rain while controlling for roadway demands or differences in driving performance (Boyle and Lee, 2010).

Even if the results of the driving simulator experiment were very accurate and were investigated with sound statistical techniques, the use of driving simulators has some possible shortcomings, including validity (Yan et al., 2010; Godley et al., 2002; Shinar et al., 2007; Van der Horst et al., 2007). Many validation studies have shown that drivers have similar speed performances in driving simulators as those measured in the real-world, but the investigation of drivers' speed behaviour in a real-world setting produces data with the greatest validity. Thus, real-world speed monitoring was carried out to integrate and validate results of the driving simulator experiment. Speed data were collected along the approach and departure tangents of major roads of 5 at-grade intersections located in two-lane rural roads in the province of Naples using high resolution video cameras.

Driving Simulator Experiment

Apparatus

The VERA (Virtual Environment for Road sAfety) dynamic-driving simulator (Figure 1), operating at the TEST (Technology Environment Safety Transport) Road Safety Laboratory located in Naples (Italy), was used.

Three flat screens (3.00 × 4.00 m) are fixed at the simulation room floor in order to surround the motion platform. The visual scene is projected to an high-resolution three channel 180° × 50° forward field of view with rear and side mirror views replaced by 6,5" LCD monitors. The visual system allows a resolution equal to 1400 × 1050 for each channel and a refresh rate equal to 60 Hz. To minimize the flickering effect and enhance the image quality of the driving scenarios, an 8X antialiasing and an 8X anisotropic filtering are enabled. The cockpit is one half of a real Citroen C2. The audio system can reproduce various sounds that can normally be heard while driving, including the rolling, engine, and exhaust noise produced by the driving vehicle as well as the surrounding sound field from other vehicles and wheels-pavement interaction. Feedback is provided by a force feedback system (SENSO-Wheel SD-LC) on the steering and a six degrees of freedom electric motion platform. The torque feedback at the steering wheel is provided via a motor fixed at the end of the steering column. The motion system consists of an hexapod with six electric actuators, able to reproduce most of the accelerations that real car occupants feel, in particular those arising from turning and braking maneuvers and from dynamic interaction between the vehicle and the pavement surface unevenness. The driving simulation software used in VERA is SCANeR®II r2.22 from Oktal company.

Figure 1 The VERA driving simulator

The use of driving simulators offers a number of positive elements, but simulators must have appropriate relative validity to be useful as research tools aimed at testing new measures. To obtain relative validity, in our study the following precautions were taken: (a) the road scene was accurately modeled, providing realism in the simulation of all the main elements, such as road environment, cross section, road markings and signs (all conforming to the current Italian legislation), and perceptual cues; (b) data from a random sample meeting specific selection criteria were used; and (c) the order of the design conditions was counterbalanced for all the drivers to minimize the presentation order effect. To test absolute validity, comparison between real-world and driving simulator speed data was performed in a previous study (Galante et al., 2010). The study was carried out in Italy on a two-lane rural highway and the comparison showed that there were not significant differences between the real and the simulated speed samples.

Procedure

Thirty participants were recruited for the experiment, basing on a selection questionnaire. The questionnaire allowed to select drivers meeting the following criteria: (a) ownership of an active driving license from more than five years; (b) adequate driving experience in rural area (more than 3,000 km per year); (c) non proneness to motion sickness; (d) good physical shape, i.e. absence of any diagnosed ailments, diseases, conditions, or physical handicaps that would adversely affect driving ability; and (e) absence of the influence of drugs or alcohol that could alter perception, cognition, and attention. Finally, thirty participants, balanced for gender and age, were randomly drawn from the list of people meeting the selection criteria.

Upon their arrival in the laboratory, each participant was briefed on the requirements of the experiment and all read and signed an informed consent form. Each subject drove 10 minutes a learning route. After a rest, each participant drove two times the experimental route. A two-lane rural highway with lane width equal to 3.50 m and shoulder width equal to 1.25 m was simulated. The experimental route consisted of the succession of 20 tangents with length equal to 1,000 m and curves with radius equal to 400 m and deflection angle equal to 35 degrees. The tangent-to-curve transition was carried out by spiral curves with length equal to 55 m, which corresponds to 2.0 s at 100 km/h. During the route the drivers ran through ten different tangent configurations: (a) a tangent without intersections; (b) two tangents with a four leg intersection located in the middle of the tangent (Figure 2); and (c) and seven tangents with a four leg intersection located in the middle of the tangent and speed reducing measures approaching the intersection. To test the behaviour of drivers familiar with the treatments, the first run was used as the adaptation route and the second run was used as the test route. The order of the ten design alternatives was counterbalanced for all the drivers to minimize the presentation order effect.

Figure 2 The simulated intersection

Seven subjects, 5 women and 2 men, exhibited simulator sickness and did not complete the experiment. Twenty-tree participants, 13 men and 10 women with age ranging between 23 and 55 years (mean = 35.2 years; s.d. = 9.3 years) and valid Italian driving licenses from more than five years (mean = 15.5 years; s.d. = 10.0 years), completed the experiment. The instantaneous speeds were recorded during the experiment with a frequency equal to 20 Hz.

Real World Speed Monitoring

Data were collected in the main road of five intersections (Figure 3) of two-lane local rural highways owned by the Province of Naples (in Italy).

These intersections were selected basing on the following features: (a) rural area; (b) level terrain; (c) tangent alignment of the main road; and (d) carriageway width not less than 6 m. Candidate sites were selected by reviewing plans and/or computerized alignment records. Potential sites were marked on maps, and adequate distance between the sites was a deciding factor in site selection. Final selection of the study intersections was carried out after site visits. Minor roads were stop controlled. Main differences between simulated and real intersections were the followings: (a) the simulated road width was 9.50 m, whereas the real world road width ranged between 6 and 6.50 m; (b) the simulated approach tangent was 500 m long, whilst the approach tangent of the real intersections was shorter; and (c) in the simulation the distance from the previous intersection was 1300 m, whereas in the real world it was shorter.

Speed data were collected along approach and departure tangents, in seven stations: -250m, -150m, -75m, 0, +75 m, +150 m, +250 (Figure 4). Speed were not recorded simultaneously in the seven stations.

Int. 1 SP Nola Piazzolla - Via Cinquevie - Via Curti (Saviano)

Int.2 SP Masseriola - Via Ponte dei Cani - SP275 Via Padula (Marigliano)

Int. 3 SP177 Calabricito - SP23 Gaudello (Acerra)

Int. 4 SP58 Santa Maria a Cubito SP54 Via Quadrelle Ischitella (Giugliano in Campania)

Int. 5 SP25 Madonna del Pantano - Via Signorelli a Patria (Licola)

Figure 3 Study intersections

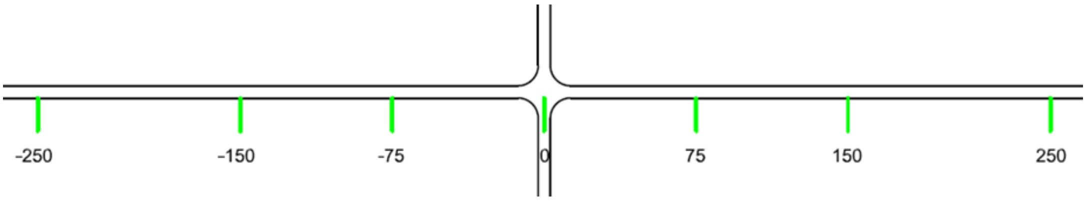

Figure 4 Measurement stations in real-world experiments

Two high resolution video cameras with built-in timers were used to record the traffic and to collect the speed data. Each camera was unobtrusively hided between poles or trees.

The first video camera was used to record the vehicles passing through the station and was placed perpendicular to the road axis, according to the layout reported in Figure 5. The second video camera was placed in the intersection area to detect the vehicles' maneuvers.

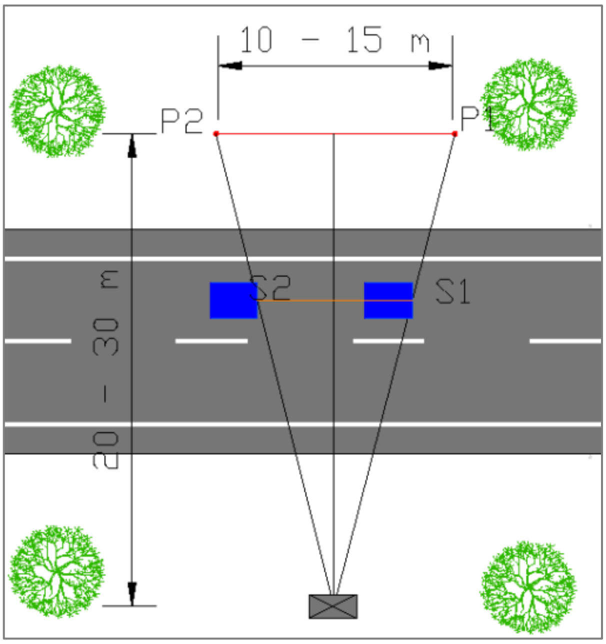

Figure 5 Layout of the first video camera placement

By the combined use of two cameras, vehicles were classified in relation to: (a) four types (car, powered two-wheelers, heavy vehicles, and other types); (b) two main road traffic conditions (free flow with headway greater or equal to 6 seconds and non free-flow); (c) two secondary road traffic conditions (vehicles stopped or entering in the main road, or no vehicle in the secondary road); and (d) two maneuvers types in the main road (crossing or turning).

All recordings were made in daytime, clear weather conditions, and dry pavement. At each station, about 2 hours of speed measures were collected (about 9–11 a.m.) during February 2011. To investigate speed behaviour of drivers' unconditioned by other traffic and by turning maneuvers, only cars crossing the intersections in free flow traffic without vehicles visible at the crossroads were used for the subsequent analyses. Sample size was greater than 100 unconditioned vehicles at each station.

DATA ANALYSIS

Real world and simulator speed data were analyzed in the seven sections (figure 4): -250m, -150m, -75m, 0, +75 m, +150 m, +250. The normality assumption of the speed data distribution was verified using the Shapiro-Wilk, Anderson-Darling, Lilliefors, and Jarque-Bera tests. The homoscedasticity assumption of the speed data distribution was verified using the Fisher's test. According to the tests, both the normality and homoscedasticity assumptions cannot be rejected at the 5% level of significance.

Speed Data

Speed reductions approaching the intersection were observed both in the real world and in the driving simulator (Table 1, Figures 6 and 7).

In the real world, mean speed (V_m) reduction from – 250 m to the center of the intersection was 18 km/h, whereas in the driving simulator the mean speed reduction was 12 km/h. Operating speed (V_{85}) reduction was 14 km/h in the real world and 11 km/h in the simulator experiment. Student's two-tailed paired t-test results (Table 2) showed that the speed changes between the stations were statistically significant ($\alpha < 0.001$) both in the real world and in the simulator. Thus, the intersection presence significantly affected speed behaviour of drivers' unconditioned by other traffic and by turning maneuvers.

Table 1 Real world and driving simulator speed data

Station	Mean Speed [km/h]		Operating Speed [km/h]		Standard Deviation [km/h]	
	Simulated	Real	Simulated	Real	Simulated	Real
-250 m	109.20	84.71	129.80	96.93	17.25	13.31
-150 m	104.62	78.40	123.48	93.10	17.28	14.65
-75 m	100.65	72.30	117.51	87.50	18.01	14.41
0	96.96	66.38	118.37	82.44	20.91	15.57
75 m	99.99	69.90	121.50	86.40	18.52	15.44
150 m	103.05	75.12	122.94	90.00	16.68	14.97
250 m	104.70	80.94	124.95	94.04	17.16	14.45

Table 2 Speed data: results of the t-tests

	Simulator						
	-250 m	-150 m	-75 m	0	75 m	150 m	250 m
-250 m	1.00	<0.001	<0.001	<0.001	<0.001	<0.001	0.09
-150 m		1.00	<0.001	<0.001	<0.001	0.28	0.30
-75 m			1.00	<0.001	0.49	0.07	<0.001
0				1.00	<0.001	<0.001	<0.001
75 m					1.00	<0.001	<0.001
150 m						1.00	<0.001
250 m							1.00
	Real world						
	-250 m	-150 m	-75 m	0	75 m	150 m	250 m
-250 m	1.00	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
-150 m		1.00	<0.001	<0.001	<0.001	<0.001	<0.001
-75 m			1.00	<0.001	<0.001	<0.001	<0.001
0				1.00	<0.001	<0.001	<0.001
75 m					1.00	<0.001	<0.001
150 m						1.00	<0.001
250 m							1.00

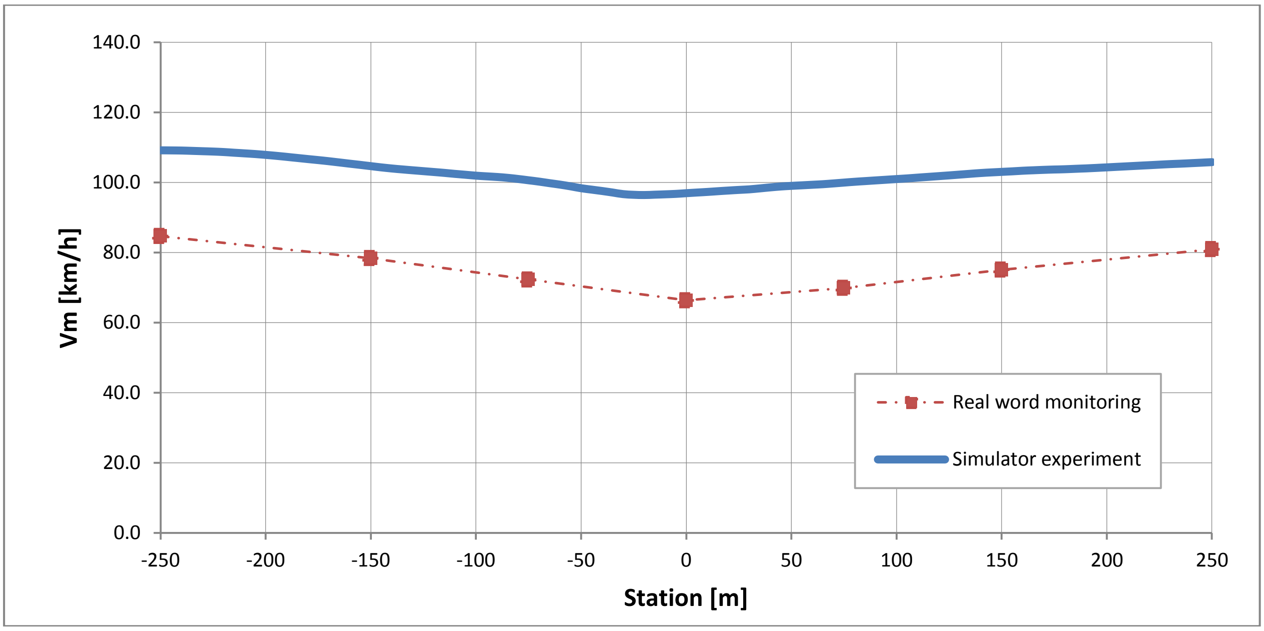

Figure 6 Mean speed profile

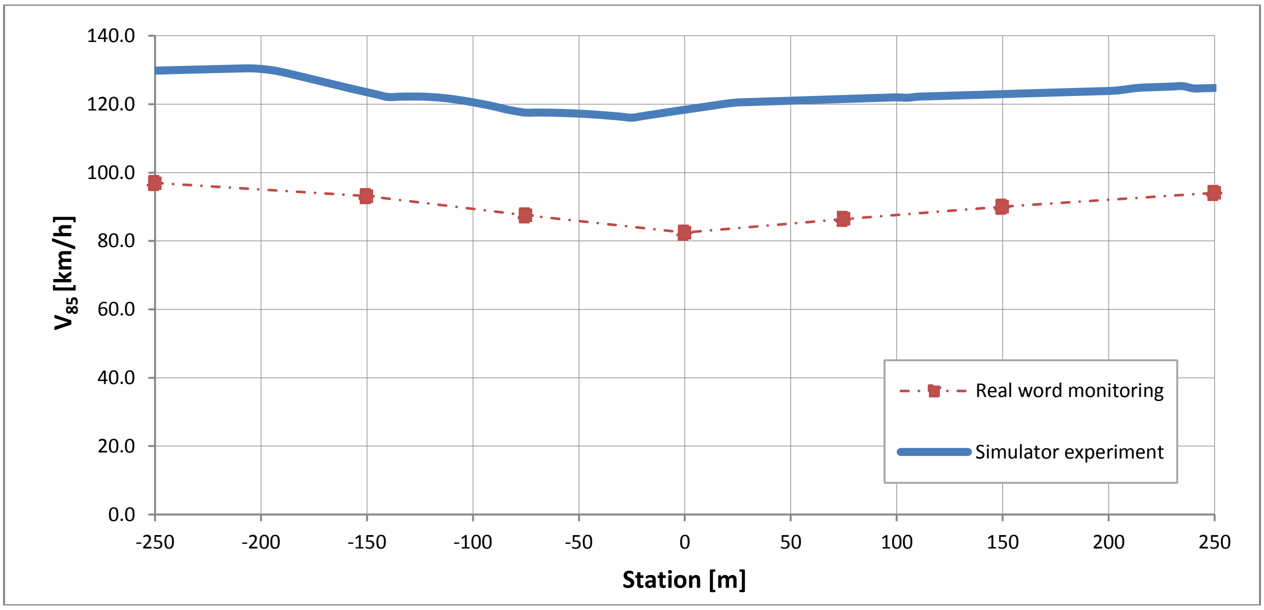

Figure 7 Operating speed profile

Simulator speeds were substantially greater than the real world speeds. Several reasons explain this difference: (a) in the simulator experiment a route with more than 25 km in rural area was simulated, while the real world intersections were located in local roads not far from urban area; (b) the simulated road width was 9.50 m, whereas the real world road width ranged between 6 and 6.50 m; (c) the simulated approach tangent was 500 m long, whilst the approach tangent of the real intersections was shorter; and (d) in the simulation the distance from the previous intersection was 1300 m, whereas in the real world it was shorter. However, aim of the study was the evaluation of the relative effect of the intersections on the speed behaviour. Both in the simulator and in the real world a significant speed reduction approaching the intersection was observed.

To compare the speed reductions, the ratio between the speed in the study section and the speed in the approach tangent (- 250 m) was calculated (Table 3). In real world mean speed reduction at the intersection center was 22% while in the simulator it was 11%. Similarly, real world speed reduction at the intersection center was 15% while in the simulator it was 9%. Overall, the speed reducing effect of the intersections was greater in the real world than in the simulator experiment.

To compare relative speed data in the simulator and in the real world, the homoscedasticity assumption of the speed data distribution was verified using the Fisher's test. According to the test, the homoscedasticity assumption is not satisfied at the 5% level of significance. Hence, speed data were compared using the following nonparametric methods: (a) the Mann–Whitney test and (b) the Kolmogorov-Smirnov test. Nonparametric methods do not rely on assumptions and use less information contained in the data. The Mann–Whitney test is one of the most powerful nonparametric tests and was used to test the equality of two population means. The Kolmogorov-Smirnov test tries was used to determine whether the two independent samples were drawn from populations with the same distribution. The null hypothesis was rejected for both the mean and the operating speeds (Table 3). The real world greater relative effect of the intersections in the real probably mainly depends on two aspects: (a) the risk perception is greater in the real world than in the simulator; and (b) in the simulator experiment there were not cues of the intersections presence whereas in the real world there were some cues (e.g., trees or commercial activities) which induced a better perception of the intersections.

Table 3 Real world and driving simulator relative speed data

Station	$V_m/V_{(m\ -250)}$ [%]		$V_{85}/V_{(85-250)}$ [%]		Test	
	Simulated	Real	Simulated	Real	Mann-Whitney	Kolmogorov-Smirnov
-250 m	100.00	100.00	100.00	100.00	< 0.001	< 0.001
-150 m	95.81	92.55	95.13	96.06	< 0.001	< 0.001
-75 m	92.17	85.35	90.53	90.28	< 0.001	< 0.001
0	88.79	78.36	91.19	85.06	< 0.001	< 0.001
75 m	91.57	82.51	93.61	89.14	< 0.001	< 0.001
150 m	94.37	88.69	94.71	92.85	< 0.001	< 0.001
250 m	95.88	95.55	96.26	97.02	< 0.001	< 0.001

Deceleration and acceleration rate

The deceleration and acceleration rates were evaluated using the mean and operating speed variations ($\Delta V_{ms21} = V_{ms2} - V_{ms1}$; $\Delta V_{85s21} = V_{85s2} - V_{85s1}$) along the study sections assuming a uniformly decelerated or accelerated motion (Table 4). Similar rates were assessed in the simulator and in the real world. The deceleration approaching the intersections ($\Delta V_{85}/\Delta t$ between – 250 m and 0) was around 0.40 m/s^2 and the acceleration departing the intersections ($\Delta V_{85}/\Delta t$ between 0 and 250 m) was around 0.30 m/s^2.

Table 4 Deceleration and acceleration rates

	$\Delta V_m/\Delta t$ [m/s^2]		$\Delta V_{85}/\Delta t$ [m/s^2]	
	Simulated	Real	Simulated	Real
[-250 m; -150 m]	-0.38	-0.40	-0.62	-0.37
[-150 m; -75 m]	-0.42	-0.47	-0.74	-0.42
[-75 m; 0]	-0.38	-0.42	0.10	-0.41
[-250 m; 0]	-0.39	-0.43	-0.43	-0.40
[0; 75 m]	0.31	0.25	0.39	0.26
[75 m; 150 m]	0.32	0.39	0.18	0.32
[150 m; 250 m]	0.13	0.35	0.19	0.34
[0; 250 m]	0.24	0.33	0.25	0.31

Operating speed profile

The development of a procedure to predict the operating-speed profile in proximity of an intersection requires an important preliminary consideration. The procedure has to be integrated into the construction rules of the existing operating speed models. The easiest way to guarantee this integration is to consider the intersection as an element of the horizontal alignment. To effectively consider the intersection as an element of the horizontal alignment, it is necessary to define the operating speed of the intersection and the deceleration and acceleration rates approaching and departing from the intersection.

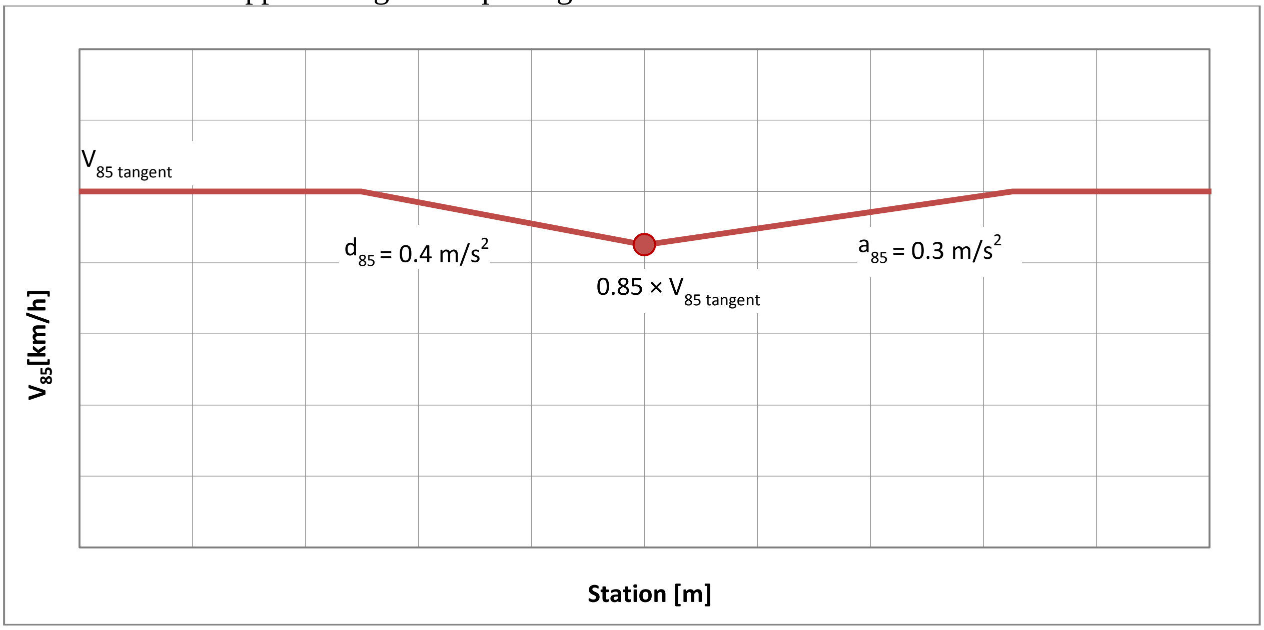

Figure 8 Example of operating speed-profile

The results of our study suggest these assumptions: (a) the operating speed at the intersection center might be assumed equal to 0.85 the operating speed at the approach tangent (calculated with the model suitable for the site conditions); (b) the deceleration approaching the intersection might be assumed 0.4 m/s^2; and (c) the acceleration departing the intersection might be assumed 0.3 m/s^2.

CONCLUSIONS

Statistically significant speed reductions approaching the intersection were observed both in the real world and in the driving simulator experiment. In the real world, mean speed reduction from – 250 m to the center of the intersection was 18 km/h, whereas in the driving simulator the mean speed reduction was 12 km/h. Operating speed reduction was 14 km/h in the real world and 11 km/h in the simulator experiment. Overall, the speed reducing effect of the intersections was greater in the real world than in the simulator experiment. To integrate the existing operating speed models which do not take onto account the presence of the intersections, study results suggest these assumptions: (a) operating speed at the intersection center equal to 0.85 the operating speed at the approach tangent (calculated with the model suitable for the site conditions); (b) deceleration approaching the intersection equal to 0.4 m/s^2; and (c) acceleration departing the intersection equal to 0.3 m/s^2. Overall, study results clearly show that it is important to consider the presence of the intersections in the speed profile models. However, further research is needed to increase the validity of the speed profile models at intersections and to separately evaluate the several factors that affect speed reduction at intersections.

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