Driving Simulation In Virtual Reality For Work Zone Design On Highway: A Validation Study

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SYNOPSIS

Interferences between work zones and vehicle flow can lead to a significant increase in accident probability. It is agreed that improving work zone design is necessary in order to provide optimal driver guidance. This paper reports on the outcomes of a survey aimed at measuring speeds on a highway in the proximity of a work zone; it, then, reports on the results of the successive experimental campaign conducted with a driving simulator rebuilding the real scenario in virtual reality.

The research activities were aimed at the calibration and validation of the virtual reality system for the simulation of travelling conditions near to work zones.

The surveyed work zone was located on highway A1, within Orvieto and Fabro, where a roadway was shut and the traffic diverted to the opposite roadway, according to the scheme of the Italian technical rules. Speed measurements were conducted with a laser speedmeter in the transition area, the activity area and the termination area, while in the advance warning area speeds were shot with a camera from an overpass. The images have been subsequently processed with a special software.

The virtual reality experiment was developed as follows: first, the real scenario for the driving simulator was reconstructed; next, a homogenous sample of drivers was selected; eventually, the driving tests with the simulator were carried out.

The field measurements highlighted that the speeds in all areas of the work zone are remarkably higher than those prescribed by the road signs. The speeds decrease below the limit only when drivers meet the physical constraint of the opening (which is only 30 m wide) for the change of roadway which compels them to adopt lower speeds.

The analysis of speeds of free vehicles in the various areas of the work zone, both in real situation and in virtual reality, led to the following results:

- The differences between the field speeds and the speeds from virtual reality vary from —7.6 km/h to + 5.6 km/h. In the activity area (travelling on a single road lane with opposite flow on the other lane) the percentage deviation is + 6,1%. The mean percentage deviation in the advance warning area is – 4,5%;
- the differences between the speeds observed in the real situation and those measured with the simulator resulted to be non-statistically significant for each measurement site. The bilateral Z test for non-matched samples, at the level of significance of 5%, led to accept the null hypothesis H_0: the field speeds and those from the simulation belong to the same population. That means that the simulator yields the same speeds as those observed in the real situations. The values assumed by the strength of the test highlight a very low probability to run into an error of type II in the advance area and in the activity area, higher in the transition and termination areas.

All these considerations enable us to validate the driving simulator of the Interuniversitary Research Center for Road Safety (CRISS) as a reliable tool for the analysis of the speeds adopted by the drivers on a highway, in several areas of a work zone.

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INTRODUCION

A work zone on highway causes interferences with the traffic flow as it reduces the cross section and forces the driver to perform several manouvres so as to adapt to the modified road configuration (narrowings, diversion, change of roadway). A number of researches demonstrate that this is the cause of a significant increase of car accidents (Rouphail et al., 1988) (Wang et al., 1996). Studies conducted on the Highways of California (Khattak et al., 2002) revealed that the total crash rate in the during-work zone period was 21.5% higher than the pre-work zone period. Such consideration is the reason of several researches in progress in the USA (TRB - National Cooperative Highway Research Program) and in Europe (COST - Transport 343) aiming to improve work zone design in order to provide optimal driver guidance and to improve work zone safety.

An innovative and useful technique to reach the goal mentioned above seems to be the driving simulation in virtual reality. Such a technique is more and more used to study the effect induced by particular road configurations on drivers' behaviour. A remarkable production of research activity has been carried out to analyse drivers' behaviour on a rural road (Klee et al., 1999) in a road-tunnel (Tornos, 1998), and to verify the effectiveness of perceptual countermeasures to high speed (transverse line, rumble strips, etc.)(Godley et al. 2002) (Fildes et al. 1996).

The use of the driving simulators presents a number of positive elements: experimental control, efficiency, low expence, safety and ease of data collection. Nonetheless the simulators must have appropriate validity to be a useful research tool.

It is usually made the distinction between two levels of validity: absolute and relative validity. The absolute validity refers to the numerical correspondence between behaviour in the driving simulator and in the real situation. Relative validity refers to the correspondence between effects of different variations in the driving situation. Tornos (1998) observed that, for a simulator to be a useful research tool, the relative validity is necessary, but the absolute validity is not essential. This is because research questions usually deal with matters relating to the effects of independent variables, rather than aiming to determine numerical measurements.

The objective of this paper is the calibration and validation of the CRISS (Interuniversitary Research Center for Road Safety) driving simulator in order to be able to use it for the project and for the verification of the effectiveness of the temporary traffic signs on highways. The simulator validation study has been conducted assuming driving as conditioned solely by the configuration of the work zone and the speed as the dependent variable.

An articulate research activity has been developed through the following steps:

1. a campaign of speed measurements on highways next to a work zone of medium duration;
2. reconstruction in virtual reality of the real situation, using the driving simulator of the CRISS and subsequent running of a series of driving tests in virtual reality;
3. statistical analysis of the field speeds and of the speeds from driving simulations for the validation of the simulator.

The detailed research plan is described in figure 1.

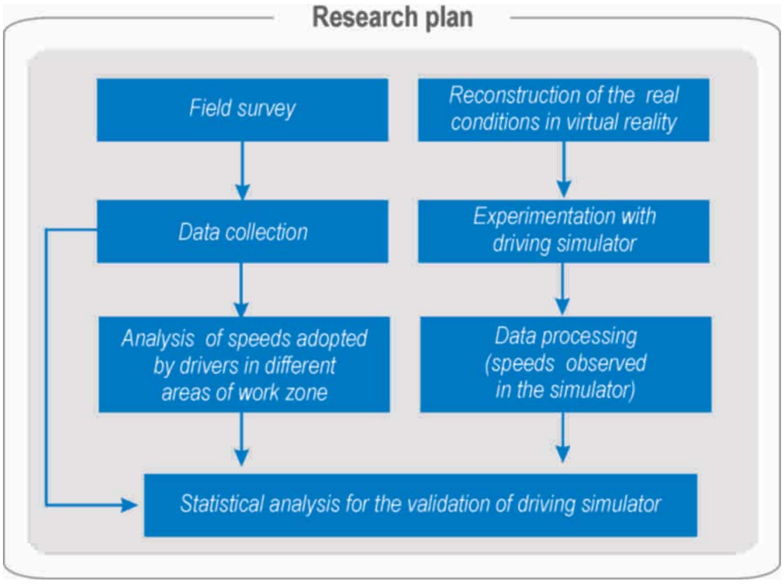

Figure 1: Research plan

FIELD MEASUREMENTS

To obtain the permission of collecting field data an official request was sent to Società Autostrade per l'Italia. In the request we outlined the following characteristics of the work zones necessary for the experiment:

- crossover: one roadway closed, the traffic, that normally uses that roadway, is crossed over the median, and two-way traffic is maintained on the other roadway;
- an overpass next to the advance warning area in order to place a video camera to shoot the images through which calculating the speed. In fact it is impossible, for safety reasons, to place a laser speedmeter in a car parked in the shoulder in the advance warning area.

The highway company indicated a work zone on highway A1 (Milano-Napoli) northward within the exits Orvieto and Fabro. The cross section of the roadway is composed by two lanes, each 3.75 m wide, and a 2.60 m large shoulder with a roadside barrier and a median barrier. The median is 3 m wide.
The work zone was set up for pavement maintenance works and developed from km 440 (beginning of signs) to km 347 (end of signs). The type of work zone is a crossover, the traffic northward is diverted to the opposite roadway where two traffic flows travel in opposite directions, each on one lane.
The signs are consistent with the instructions of the Italian technical rules for temporary signs (Ministero delle infrastrutture e Trasporti, 2002) (fig. 2).

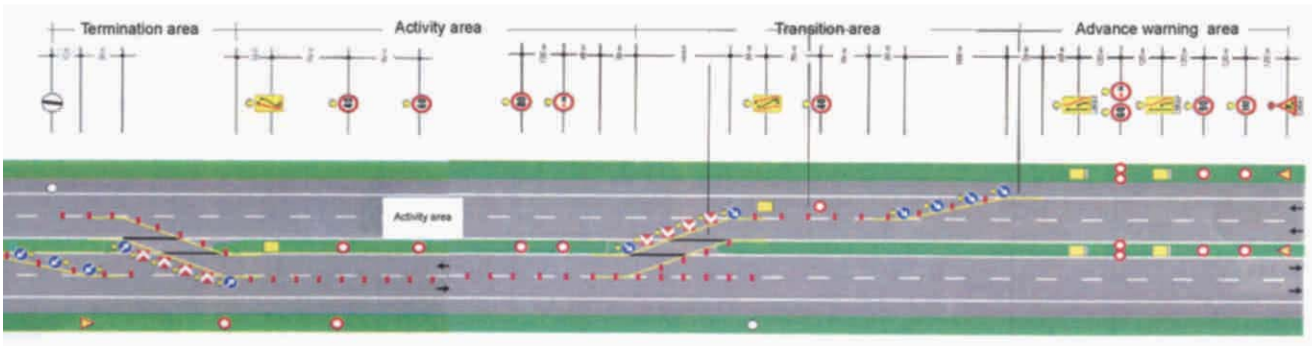

Figure 2: Scheme of the work zone where the measurements were taken

The advance warning area and the transition area are on a straigth with longitudinal grade of + 1%. The section of the roadway southward with two opposite flows (activity area) is 2 km long and is mainly a straight (except for a short section on curve, with radius of 800 m and a very narrow central angle). The longitudinal grade is constantly positive towards north in the range + 0.6% , +1,3%. The termination area is on a straight with longitudinal grade + 1%. The openings in the median to change roadway are about 30 m wide.

Data Collection

Speed measurements have been taken with a laser speedmeter in some work area zones (taper of transition area, activity area, taper of termination area) while in the advance warning area the speeds have been derived from the images shot with a video camera, from an overpass, and subsequently processed with a dedicated software.
Locations for the laser speedmeter were chosen so as not to interfere with the traffic flow. The laser speedmeter was installed on the rear windscreen of a private vehicle and connected to a computer in order to save the collected data. The vehicle was placed in such a way that drivers could not see the instrument in order to avoid biased behaviour of drivers, potential cause of accident, that could invalidate the measurements. The laser speedmeter was in fact hidden from drivers' sight by a service car of Società Autostrade per L'Italia (fig. 3).

Figure 3: A measurement site: the laser speedmeter placed on a private car is hidden from drivers' sight using a service car of Autostrade per l'Italia.

The speeds of vehicles driving northward were taken at the following locations of the work zone (fig. 4):

1. at km 439+300, immediately after the end of the taper (site 1);
2. at km 439+200, in the part of the roadway narrowed to a single road lane (site 2);
3. at km 439+020, at the point where vehicles cross the median and change roadway (site 3);
4. at km 436+980, at the point where vehicles cross back the median (site 4).

It was impossible to detect the speed of the flow northward between the two openings, where vehicles march in opposite directions on each road lane, because of the presence of the median. Only speeds of the flow southward were measured, thank to a parking lay-by at km 437+800 on the roadway southward (site 5).

As mentioned above, for safety reasons, the speeds in the advance warning area have not been detected with a laser speedmeter but through the procession of the images shot with a video camera. It was placed on an overpass, about 350 m from the merging taper of the transition area, more precisely within the sign of speed limit of 110 km/h and that of speed limit of 90 km/h.

The images allowed calculating the speeds in the following sites of the advance warning area:

A. sign of road work (site A)
B. sign of speed limit of 100 km/h (site B)
C. sign of speed limit of 90 km/h (site C)
D. warning sign of road narrowing (site D)
E. sign of speed limit of 60 km/h (site E)

Figure 4 shows the position of the video camera and the measurement locations: 5 sites for the laser speedmeter and 5 sites inside the warning advance area.

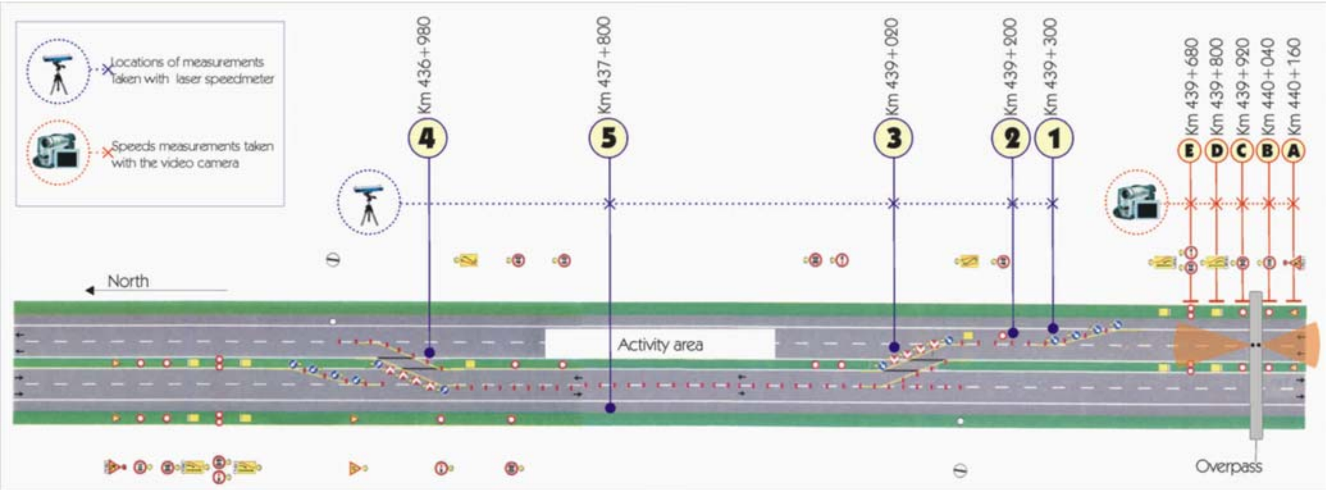

Figure 4: Locations of the measurements taken with the laser speedmeter (sites 1, 2, 3, 4 and 5), location of the video camera on the overpass and sites of the advance warning area (sites A, B, C, D and E) where speeds were calculated

Data Processing

About 3000 vehicles have been sampled with the laser speedmeter. For each one the following data have been acquired: speed, length, time (hour, minute and second). From these data those regarding free passenger cars, individuated as described below, have been extracted:

1. length equals to or shorter than 5 m
2. time headway equals to or greater than 5 seconds

282 vehicles fulfilling these requirements were individuated in direction north (121 in site 1, 91 in site 2, 39 in site 3 and 31 in site 4) and 58 in direction south. Despite the duration of the measurements being about the same in all sites (about 30 minutes), the number of free passenger cars individuated at each location varies depending on the interference of the traffic flow with the different work zone areas.

As far as the data collected with the video camera we proceeded spotting out first the free passenger cars, then calculating their speed as a function of travel time intervals, known the travelled distance. This distance is equal to 48 m which correspond to the sum of 4 modules, 12 m long each. Each module is made up by a white element of the centre line (4,5 m) and by the gap within two successive elements (7,5 m).

Using a video editing software we individuated five intervals, 48 m long each, so as that the axis of one interval pass throuhg one of the five measurement site. Then, knowkn the time taken by the vehicles to travel a 48 m interval we calculated the speed adopted at each site (fig. 5).

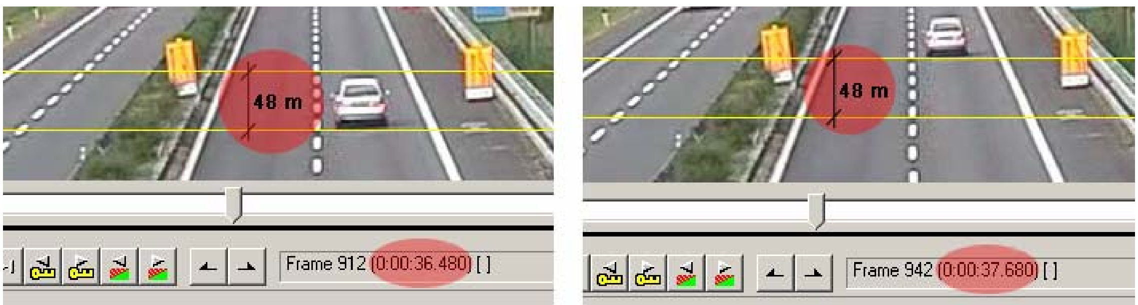

Figure 5: Determination of the speed from the video

Altogether, in the ten locations (5 sites for the laser speedmeter and 5 for the video camera) 636 speed measurements of free vehicle were taken (282 northward + 58 southward + 296 by the video camera).

For each location, the goodness of fit of the data to the normal distribution was preliminarily verified running the χ^2 test, with a level of significance of 5%. The outcomes of the test highlighted that the data fitted the Gaussian distribution.

Next figure (fig. 6) shows mean speed, 85th percentile, standard deviation and the number of measurements for each location.

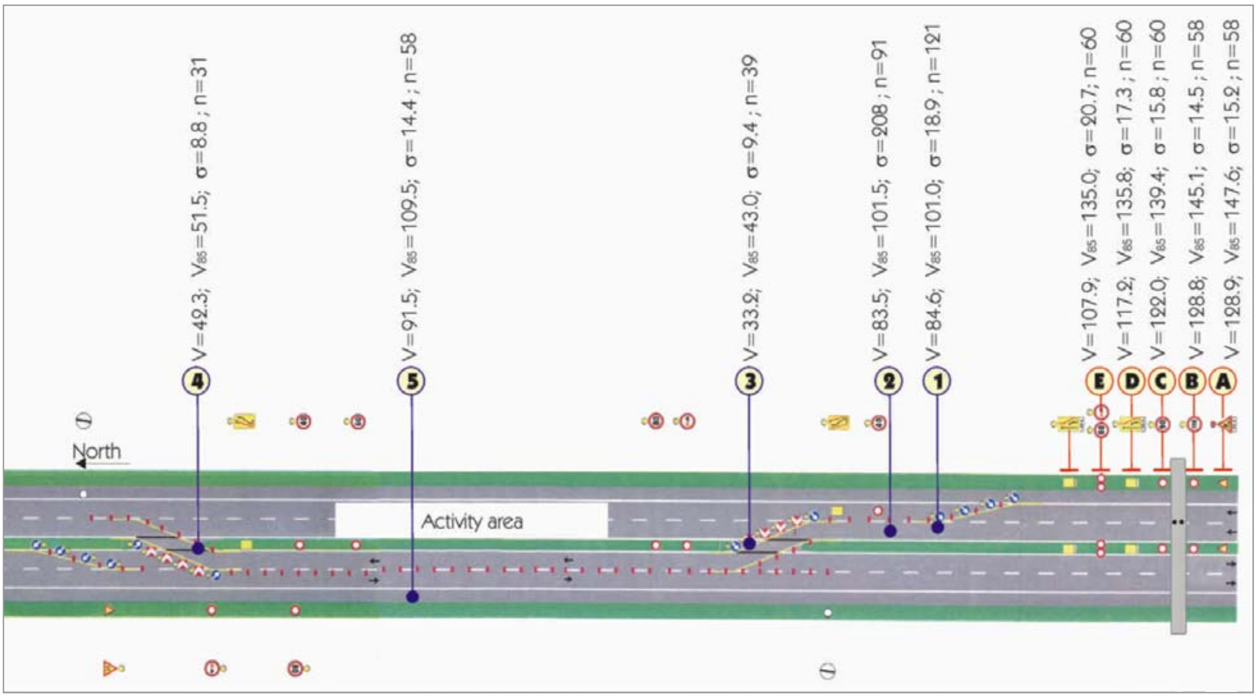

Figure 6: Characteristic parameters for free passenger cars

Data Analisys

The collected data allowed the study of the speeds adopted by the drivers in all work zone areas. The driver reaches where the first warning sign is posted (site A, sign "road work") at a quite high speed (mean value is 129 km/h, 85th percentile is 147 km/h) and maintains this speed in the first advance warning area (section A-B). In the following section he begins to slow down slightly and in site D, where the sign "closed right lane" is posted, he travels at V_{mean} 117,2 km/h (V_{85} is 138,5 km/h), which is much faster than the prescribed speed limt of 90 km/h.
In site E (sign of speed limit of 60 km/h) the driver adopts an mean speed greater than 107 km/h and a V_{85} of 135 km/h. Furthermore, in this section the standard deviation is greater (over 20 km/h) than those for the previous sections (mean of 16 km/h). This reveals a less homogeneous behaviour of drivers.
The speed is significantly reduced only when at the taper of the transition area (site 1 – where V_{mean} is 84,6 km/h and V_{85} is 101 km/h), though still well above the speed limit of 60 km/h. Standard deviation is quite high for this section, too, which means that speeds are distributed heterogeneously.

When the traffic flow is channelled on a single road lane (site 2), the speed is equal to those recorded at the taper of the transition area. Then it goes down significantly at the change of roadway (site 3) to reach the value of 32 km/h for V_{mena}, less than the speed limit of 40 km/h. The standard deviation at this site is 10 km/h, to mean a remarkable homogeneity of the speeds adopted by drivers, probably induced by the physical constraint of the opening for the change of roadway (opening little wider than 30 m).

A similar value for the standard deviation can be observed at the taper of the termination area (site 4), with a V_{mean} of 42,3 km/h slightly greater than the speed limit (40 km/h). This is probably due to the minor effort requested by the manouvre to go back to the roadway with two lanes in the same direction, with respect to the first change of roadway.
As it was not possible to detect the speed of the flow northward in the activity area, only the speed of the flow southward was measured (this flow travels in similar conditions as that northward: two lanes with flows in opposite directions), returning a V_{mean} of 91,5 km/h, much faster than the prescribed limit of 80 km/h, and a V_{85} of 109,5 km/h.

In conclusion it is possible to state that the speeds in all work zone areas are much higher than those prescribed by the signs of speed limit. The speeds are kept below the limits only when there is a physical constraint (a 30 m wide opening) due to the change roadway, which does not allow higher speeds.
When travelling on section A-B drivers do not alter their speed. They begin to reduce it slightly only when in the next section, and to reduce it more significantly, to values still well above the speed limit indicated by signs, only when in site D, at about 400 m from the merging taper.
In the end, the modification in driving behaviour seems to be suggested, rather than by signs, by the visual perception of the cause of the modification itself. This seems to confirm the outcomes of some researches conducted in the USA about the effectiveness of the changeable message locations too far from the work zone (McCoy et al., 2002). Drivers ignored the signs: they doubted the reliability of the signs as they could not see any reason to slow down.

EXPERIMENTATION IN VIRTUAL REALITY

In order to validate the driving simulator for the project and for the verification of the effectiveness of the temporary traffic signs, an experimentation was carried out with the driving simulator of the CRISS, following three main steps:
- preliminary reconstruction on the driving simulator of the real scenario observed on the highway A1;
- individuation of a homogeneous sample of drivers;
- drivings in virtual reality on the reconstructed road.

Then the resulting data from the simulator and the field measurements were analysed to ascertain whether the speeds adopted by drivers at the simulator were different from those observed in the real situation.

The Driving Simulator

The simulation system of CRISS is widely described in several previous works (Benedetto et al. 2002) (Bella et al. 2003) and we will omit here a further description. We only underline that in order to create a driving environment similar to the actual one, user interfaces (pedals, steering wheels, gear lever) are installed on a real vehicle and the road scenario is projected onto three big screens: one in the centre in front of the vehicle and two lateral ones angled at 60° with respect to the plane of the central screen (fig. 7). This set up provides a realistic view of the road and surrounding environment. The scenario is updated dynamically according to the travelling conditions of the vehicle, depending on the actions of the driver on the pedals and the steering wheel. It is integrated with a sound system to reproduce the sounds of the engine.
The system offers a very realistic simulation, recording the intensity of the actions of the drivers on the brake and the accelerator pedals and on the steering wheels, and providing many other parameters describing travelling conditions (vehicle barycentre, relative position with respect to the road axis, local speed and accelerations, steering wheel rotation angle, pitching angle, rolling angle, etc.) at time or space intervals of fraction of a second or of a meter, respectively.

Figure 7: Driving simulator of CRISS: the hardware, the driver's seat on a real vehicle and the screens to display the scenario

The Reconstruction of the Real Scenario

For the reconstruction of the horizontal and vertical alignments of the section of highway A1 occupied by the work zone, the geometrical parameters of the road axis have been found from the project provided by Società Autostrade per l'Italia.

In order to analyse in virtual reality both the interferences caused by the work zone on the traffic flow northwards (obliged to change of roadway) and on the traffic flow southwards, the alignment implemented on the simulator is composed by:

- an initial 1200 m long section (section 1), with horizontal and vertical alignment and cross section equal to those of the considered section of A1, while approaching the work zone, direction north;
- a section (section 2) exactly reproducing the geometry of the section of A1 within km 440+160m and km 436+050 m, direction north, and the same sign scheme as in the real work zone;
- a central section (section 3) with a cross section with two lanes, following the end of the work zone, on a straight with longitudinal grade equal to zero to put the driver back to normal travelling conditions, without interferences with the work zone;
- a section (section 4) with same horizontal and vertical alignment, cross section and sign scheme as those of the roadway southwards;
- a final section (section 5), past the work zone, on a straight with longitudinal grade equal to zero.

This allowed the drivers to perform the simulated drivings both in north and south directions without ever stopping the test. The alignment develops for about 12 km (fig 8).

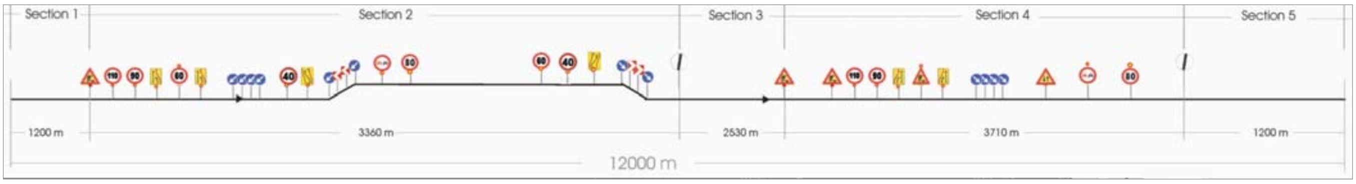

Figure 8: The scheme of the alignment reconstructed at the simulator

Particular attention has been placed on:

- fixed vertical signs and barriers
- temporary signs (flexible delineators, cones, etc.)
- two overpasses on the real alignment,

all rebuilt using a three dimensional software and introduced in the simulator scenario.
Eventually, to make the built scenario as much similar to the real one as possible, the background images are composed by photos of the real environment. Figure 9 shows some examples of the real scenario, as seen by the drivers during the simulation.

The experimentation has been carried out using dry pavement conditions in good state of maintenance. The simulated vehicle is an average passenger car, both for dimension and for mechanical performance, with an automatic gear. The data recording system acquires all the parameters at spatial intervals of 5 m.

The Sample of Drivers and the Driving Tests

35 drivers were selected to perform the drivings at the simulator according to the following characteristics: no experience with the driving simulator, at least four years of driving experience and an average annual driven distance in rural roads of at least 2500 km.

The procedure of the tests can be divided into the following steps:

- communication to the driver about the general modalities of the driving (duration of the driving, use of the steering wheel and pedals, automatic gear, etc.);
- filling in of a form with personal data;
- setting the driver inside the car and adjustment of the driver's seat;
- training on a specific alignment for approximately 10 minutes;
- car vacated by the driver for about 5 minutes in order to re-establish psycho-physical conditions similar to those at the beginning of the test;
- driving on the highway section of road occupied by the work zone;
- filling in of a questionnaire about the uneasiness perceived during the driving in order to eliminate from the sample the drivings carried out in anomalous conditions. The questionnaire consists of 4 questions, each for a kind of uneasiness: nausea, giddiness, weariness, other. Each question could be answered scoring 1 to 4, proportionally to the level of uneasiness experienced: null, light, medium and high. The level "null" for all four kinds of uneasiness is considered the condition of acceptability. No case of unacceptable driving was observed. All 35 drivings could be used for the purpose of the study.

Figure 10 shows a phase of the simulated driving, in proximity of the work zone.

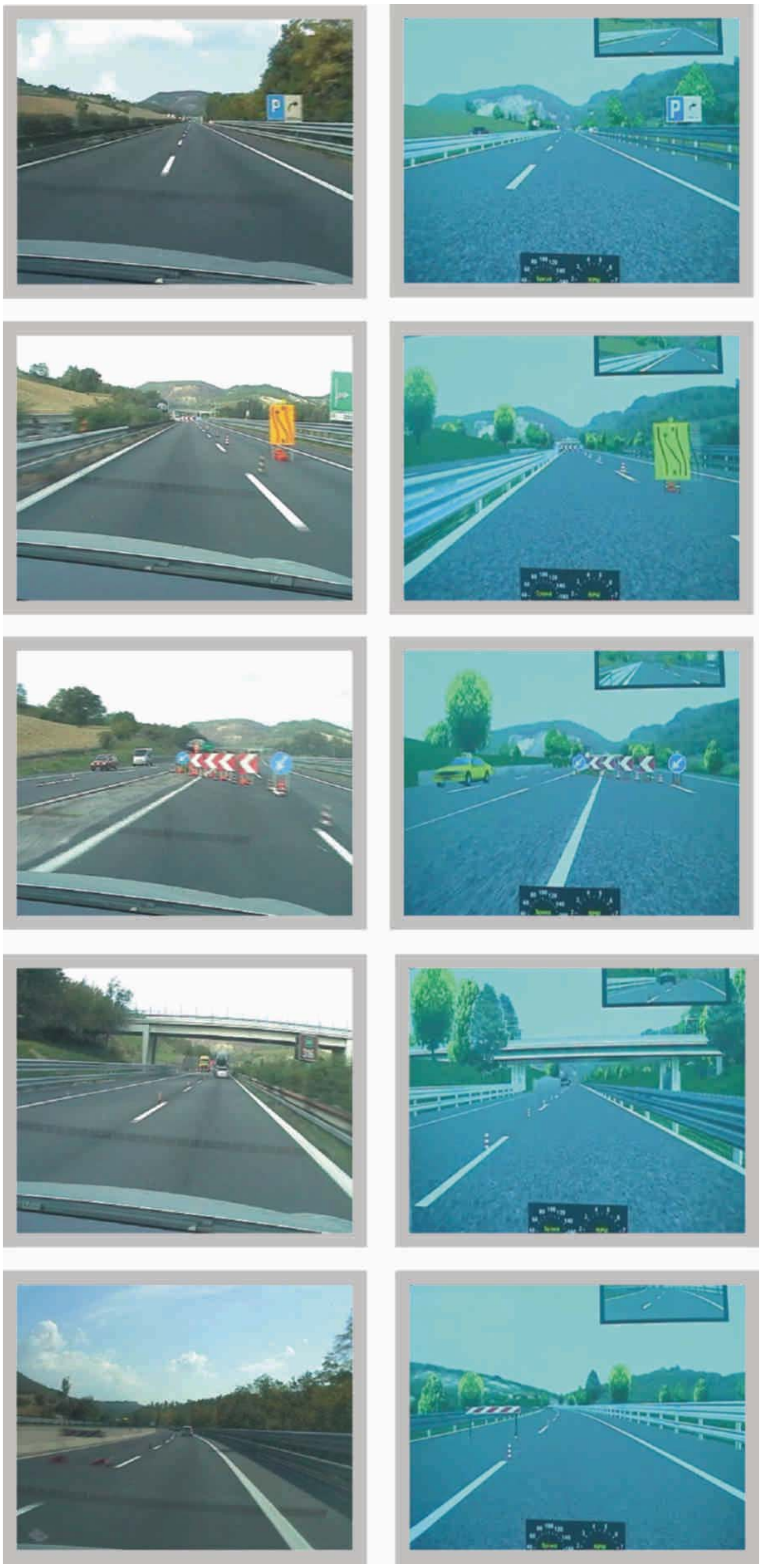

Figure 9: Examples of the real scenario of A1, for all areas of the work zone, as seen by the drivers during the driving simulation

Figure 10: A phase of the driving at the simulator approaching the work zone

Observed Speeds

A measurement of the speed was taken every 5 m and V_{mean} has been calculated for each measurement site. Measurements of the speeds have been taken along the rebuilt alignment in correspondence to the actual measurement sites, in order to compare the speeds from field observations to those from the simulation. As already done for the field data, for each measurement site the chi-squared test has been performed with positive results.

THE STATISTICAL ANALYSIS FOR THE VALIDATION OF THE DRIVING SIMULATOR

We obtained two samples of speeds, one from the field measurements, the other from the simulation. Both samples are normally distributed. We indicate their mean value respectively with Vr and Vs, their standard deviation with σr and σs and the amount of measures of the samples with nr and ns. At each measurement site the data acquired in virtual reality are 35, while the number of field observations ranges from 31 (site 4) to 121 (site1). Figure 11 shows the distributions of speeds obtained in the real situation and in the simulation at measurement site A.

Data from all measurement sites are in table 1. Figure 12 shows all V_{mean}s

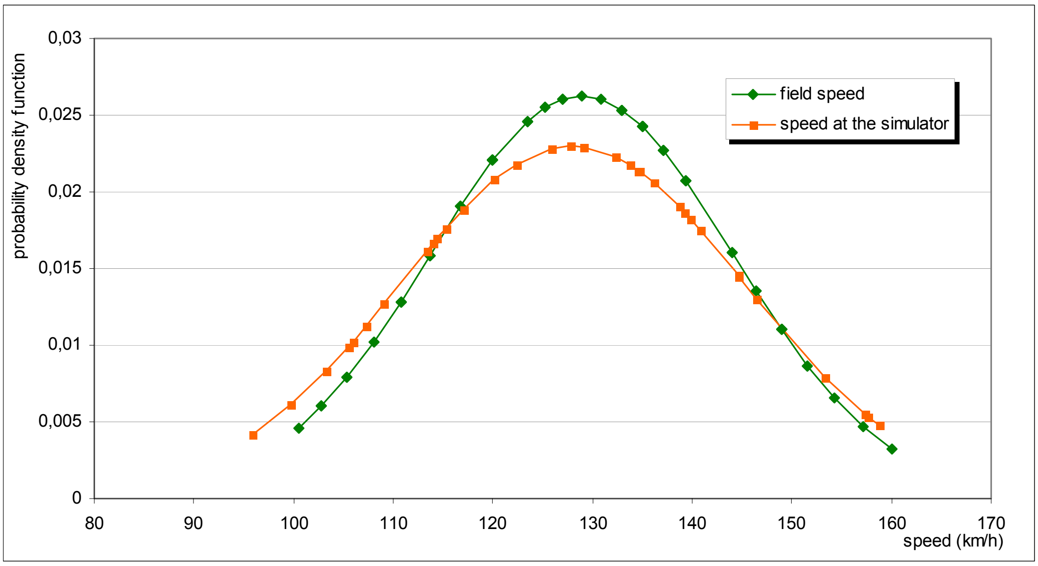

Figure 11: Distributions of speeds observed in the real situation and in the simulation at measurement site A

Table 1: Mean speeds, standard deviations and number of measures in the real situation and in the simulation at all 10 measurement sites.

	Real			Simulation				
measur-ment sites	mean speed Vr	number of measures	standard deviation	mean speed Vs	number of measures	standard deviation	Vs-Vr	Vs-Vr/Vr (%)
A	128,9	58	15,2	128,0	35	16,0	-0,9	-0,7
B	128,8	58	14,5	123,4	35	18,5	-5,4	-4,2
C	122,0	60	15,8	116,2	35	21,7	-5,8	-4,8
D	117,2	60	17,3	109,7	35	21,8	-7,5	-6,4
E	107,8	60	20,7	100,7	35	20,4	-7,1	-6,6
1	84,6	121	18,9	78,5	35	22,4	-6,1	-7,2
2	83,5	91	20,8	75,9	35	21,8	-7,6	-9,1
3	33,2	39	9,4	36,0	35	7,5	+2,8	+8,4
4	42,3	31	8,8	38,3	35	9,3	-4	-9,5
5	91,5	58	14,4	97,1	35	17,9	+5,6	+6,1

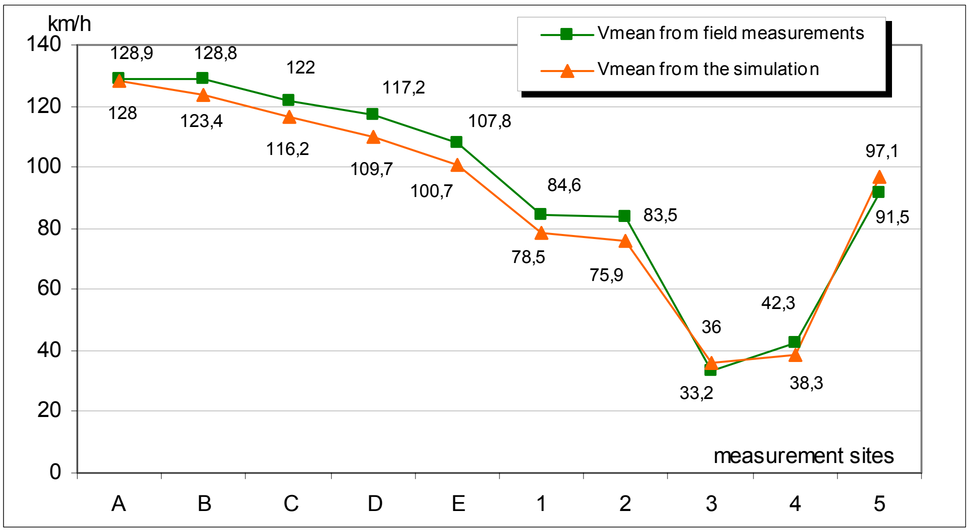

Figura 12: Mean speeds from field measurements and from the simulation

The mean speeds from the field measurements compared to those from the simulation seem to point to the reliability of the simulation. The relative validity seems to be high, as a good correspondence can be noted between the drivers' behaviours at the simulator and in the real situation (see fig. 12).

With regard to the numerical correspondence between the speeds at the driving simulator and those in the real situation it can be seen that in almost all measurement sites speeds from simulated drivings are slightly lower than those collected in the real situation. The differences between mean speeds (Vs – Vr) range from -0.9 km/h (in site A) to -7,6 km/h (in site 2).
In site 3 (change of raodway) and in site 5 (two lanes with opposite flows) the mean speeds from the simulation are slightly higher, + 2.8 km/h and + 5,6 km/h respectively, than those from the real situation.
The percentage deviation

$$\frac{(V_s - V_r)}{V_r} * 100$$

is equal to - 0,7% at site A. At sites 3 and 4 the absolute differences between the speeds are quite small (+ 2,8 km/h at site 3 and - 4 km/h at site 4) but the percentage deviations are equal to + 8,4 % and - 9,5%, respectively, because of the low value of Vr. At site 5 the percentage deviation is + 6.1%.
The mean percentage deviation on the advance warning area (from A to E) is - 4,5%.

The outcomes of the comparison within mean field speeds and mean speeds from the simulation are consistent with previous studies also aimed to the validation of driving simulators. Such studies were carried out on a road with a tunnel (Tornos, 1988), a road with transverse rumble strips (Godley et al. 2002) and on a

road inside a university campus (Klee et al., 1999). The first two studies demonstrated the reliability of the simulator in relative terms, but not in absolute ones. Goodley also observed that the speeds at the simulator were lower than those in the real situation.
Klee, too, observed a tendency of drivers to travel at slower speeds at the simulator but, differently from the first two studies, found that the mean speeds in simulation, except for few sites, resulted not to be significantly different from those in the real situation.

In order to verify statistically the reliability of the simulator we performed a statistical comparison analysis of the mean speeds from the real situation and from simulation. A bilateral Z-test, for non-matched samples was used for the analysis. The test was used to ascertain whether the differences between the mean speeds of the two populations of speeds from the real situation and from the simulator are statistically significant.

For each measurement site the following hypothesis are formulated:

- null hypothesis H_0: field speeds and speeds from simulation belong to the same population, i.e. the driving simulation yields the same speeds as those observed in the real situation;
- alternative hypothesis H_1: field speeds and speeds from simulation do not belong to the same population, i.e. the driving simulation yields different speeds from those observed in the real situations.

Such hypotheses can be written as follows:

H0: $\mu_r - \mu_s = 0$

H1: $\mu_r - \mu_s \neq 0$

where:
μr and μs are the means of the populations of the field speeds and the speeds from the simulation, respectively.

The test is run at a level of significance (α) of 5%. This means to accept the probability of 5% that an error of type 1 may occur, that is to reject, mistakenly, a true null hypothesis. The test also foresees an error of type II, conventionally known as β, .which is the probability to accept a false null hypothesis.
To test the hypotheses we consider the distribution of the differences between the speed of the samples (Vr – Vs) represented by the mean value $\mu_{V\,r-Vs}$ and by the standard deviation $\sigma_{V\,r-Vs}$, obtained from the following equations:

$$\mu_{V\,r-Vs} = \mu_r - \mu_s$$

$$\sigma_{\mathrm{Vr\,-\,Vs}} = \sqrt{\frac{{\sigma_r}^2}{n_r} + \frac{{\sigma_s}^2}{n_s}}$$

where :
σ_r and σ_s are the standard deviations of the samples of speeds from the real situation and from the simulator, respectively
nr and ns are the numbers of measures of the samples of field speeds and speeds from the simulator, respectively

Z statistic was calculated according to the following:

$$Z = \frac{(V_r - V_s) - (\mu_r - \mu_s)}{\sqrt{\frac{{\sigma_r}^2}{n_r} + \frac{{\sigma_s}^2}{n_s}}}$$

where Vr and Vs are the means of the samples of the field speeds and the speeds from the simulator, respectively.

When hypothesis H_0: $\mu_r - \mu_s = 0$, Z becomes:

$$Z = \frac{(V_r - V_s)}{\sqrt{\frac{\sigma_r^{\ 2}}{n_r} + \frac{\sigma_s^{\ 2}}{n_s}}}$$

The calculated Z was compared to the critical value (Zc) correspondent to the level of significance of 5% (Zc = 1,96). The latter value defines the acceptance region of the null hypothesis. If

Z < Zc = 1,9 then H_0 is rejected
Z > Zc = 1,96 then H_0 cannot be rejected

The confidence interval, at probability α, of the difference of the means (μv – μs = 0) was determined according to the following:

$$\bar{d}c = 0 \pm Zc\sqrt{\frac{\sigma_r^{\ 2}}{n_r} + \frac{\sigma_s^{\ 2}}{n_s}}$$

The null hypothesis H_0: μv – μs = 0 cannot be rejected when the difference between the samples' means (Vv- Vs) falls inside the confidence interval; that is when the following relation is true:

$$-Zc\sqrt{\frac{\sigma_r^{\ 2}}{n_r} + \frac{\sigma_s^{\ 2}}{n_s}} <= Vv - Vs <= Zc\sqrt{\frac{\sigma_r^{\ 2}}{n_r} + \frac{\sigma_s^{\ 2}}{n_s}}$$

For each site, the results of the test were such that the null hypothesis H_0 was accepted ; in fact for each site it was found that $|Z| < |Z_C|$ and then the difference Vr-Vs always falls inside the confidence interval (See table 2.)

In the end, the hypothesis that the simulator yields the same speeds as those observed in the real situation can be accepted, at the level of significance of 5%.

Accepting the null hypothesis involves an inherent probability β to run into a type II error. The value 1-β represents the strength of the test, that is the probability to reject (correctly) a null hypothesis when it is false.

To assess the probability of an error of type II we need to define the alternative hypothesis H_1: $\mu_v - \mu_s \neq 0$ assuming a value (Δ) of the differences between mean speeds.

Then the alternative hypothesis becomes

H_1: $|\mu_v - \mu_s| \geq \Delta$

The probability β to make an error of type II is determined as a function of the value Zβ, defined as follows:

$$Z\beta = Zc\sqrt{\frac{\sigma_r^{\ 2}}{n_r} + \frac{\sigma_s^{\ 2}}{n_s}} - \Delta) * \frac{1}{\sqrt{\frac{\sigma_r^{\ 2}}{n_r} + \frac{\sigma_s^{\ 2}}{n_s}}}$$

which corresponds to the value of probability β.

The probability β is a decreasing function of the difference Δ. It is useful to choose Δ as equal to the maximum acceptable (for the purpose of the study) difference between mean field speeds and mean speeds from simulation.

Assuming, for each measurement site, this difference equal to 10% of the real speed (i.e. assuming that an approximation smaller than or equal to 10% for the mean speeds obtained with the simulator compared to the real ones does not invalidate the behavioral analysis of drivers), accepting the null hypothesis $\mu_r - \mu_s = 0$, which is in fact false, would lead to errors of type II and the strengths shown in table 2.

Table 2: Results of the test of hypotheses

Measurement sites	Vr	Δ (10% Vr)	Vr-Vs	σ_{Vr-Vs}	I Z I	I z_c I	confidence interval (upper and lower limits)		β	Strength 1-β	
A	128,9	13	0,90	3,37	0,27	1,96	-6,6	6,6	0,03	0,97	H_0 accepted
B	128,8	13	5,41	3,66	1,48	1,96	-7,2	7,2	0,06	0,94	H_0 accepted
C	122,0	12	5,81	4,20	1,38	1,96	-8,2	8,2	0,18	0,82	H_0 accepted
D	117,2	12	7,46	4,32	1,73	1,96	-8,5	8,5	0,21	0,79	H_0 accepted
E	107,8	11	7,12	4,37	1,63	1,96	-8,6	8,6	0,29	0,71	H_0 accepted
1	84,6	8,5	6,17	4,16	1,48	1,96	-8,2	8,2	0,47	0,53	H_0 accepted
2	83,5	8,5	7,65	4,29	1,79	1,96	-8,4	8,4	0,49	0,51	H_0 accepted
3	33,2	3,3	-2,82	1,97	1,43	1,96	-3,9	3,9	0,39	0,61	H_0 accepted
4	42,3	4,2	3,93	2,23	1,76	1,96	-4,4	4,4	0,48	0,52	H_0 accepted
5	91,5	9,2	-5,58	3,57	1,56	1,96	-7,0	7,0	0,12	0,88	H_0 accepted

null hypothesis H_0: $\mu_r - \mu_s = 0$

alternative hypothesis H_1: $|\mu_r - \mu_s| \geq 0{,}10 * Vr$

level of significance α = 5%

In sites 1, 2 (transition area) and 4 (termination area) the strength of the test is slightly over 50%, while in other sites it is very high, indicating the high probability to reject correctly the null hypothesis when false.

Therefore, from the statistical analysis it is possible to say that for each measurement site the results of the Z test, at the level of significance of 5%, admit the acceptance of the null hypotesis. Therefore the driving simulation yields to the same speeds as those collected in the real situation. The strength values spot out a very low probability to make an error of type II in the advance warning area and in the activity area, higher in the transition and termination areas.

CONCLUSION

The survey carried out on the section of highway A1 between Orvieto and Fabro, measuring the speeds of free passenger cars in different areas of a work zone, highlighted that the speeds in all areas are remarkably faster than those indicated by the road signs.
Speeds decrease below the prescribed limits only when drivers meets a physical constraint represented by the opening in the median to change roadway (only 30 m wide) which compels the drivers to adopt low speeds.

The comparison between field speeds and the speeds obtained from the simulation led to the validation of the driving simulator of the Interuniversiary Research Center for Road Safety as a reliable tool for the analysis of the speeds in several areas of a work zone on a highway. In particular, it was found that:

- the speeds from the simulation are slightly different from the field speeds. The maximum negative difference (Vs – Vr) is -7,6 km/h, while the maximum positive difference is +5,6 km/h;
- the percentage deviation is equal to +0,7% at site A. At sites 3 and 4 (change of roadway), though the absolute speeds differences are quite small (+2,8 km/h at site 3 and –4 km/h at site 4), the percentage deviations are +8,4% and –9,5% respectively, because of the low value of Vr. At site 5 (two lanes with opposite flows) the percentage deviation is + 6.1%. The mean percentage deviation on the advance warning area (from A to E) is - 4,5%.
- the differences between the speeds observed in the real situation and those measured with the simulator resulted non-statistically significant, at each measurement site. The bilateral Z test for non-matched samples at the level of significance of 5%, led to the acceptance of the null hypothesis for all sites: the field speeds and those from the simulation belong to the same population. This means that the simulator yields the same speeds as those observed in the real situation. The values assumed by the strength of the test spot out a very low probability to run into an error of type II in the advance warning area and in the activity area, higher in the transition and termination areas.

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