Impact of Narrower Lane Width

Comparison Between Fixed-Base Simulator and Real Data

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This driving simulator study investigated differences in the influence of lane width reduction on speed profiles and lateral positions in real-world and simulator conditions. The use of driving simulators has been expanding in transportation research. This use raises the question of the simulators' validity. The study was developed in two steps. In the first step, an experiment was conducted with the INRETS (French National Institute for Transport and Safety Research) driving simulator. Forty-three drivers drove in the simulator. Two configurations of lane widths (3.5 m and 3 m) were tested, both chosen in reference to a previous French field study carried out on a rural road to assess the impact of lane width reduction and the provision of a hard shoulder on driver behaviors (speed, lateral positioning). In the second step, results were compared with the results of the French field study. The comparison showed that, as in the field study, reducing the lane width had no impact on speeds but did induce the participants to drive closer to the center of the road. It also showed that oncoming vehicles induced subjects to move toward the right side of their lanes. Finally, the results showed a relative behavioral validity.

Rural roads are more dangerous than other roads. In Europe, more than 80% of all fatal crashes occur on rural roads. Rural roads account for 60% of road fatalities (*1, 2*) compared with 10% for motorways (*1, 3*). Three accident types are reported in crashes on rural roads: single-vehicle accidents (e.g., runoffs against culverts and utility poles), head-on collisions, and collisions at intersections. Single-vehicle runoffs and head-on collisions (which relate to trajectory control) account for 48% of all crash types (*4*). Studies found that roadway cross sections (width, number of lanes, etc.) had the strongest influence on drivers' perceptions of safety and travel speeds (*5, 6*). Fildes et al. (*5, 6*) argued that making the driving environment appear less safe for drivers (i.e., using narrow walled settings) could help reduce travel speeds.

Reducing lane width leads to lower speeds and accident frequency (*7, 8*), but the effects depend on lane widths and road types (*9*). However, results found in these studies are inconsistent. For example, in Denmark, a study showed that as the lane width increases, the relative accident frequency decreases; for road widths less than 6 m, there was an increase in the risk of both severe accidents and accidents with injuries (*10*). TRB Special Report 214 (*11*) noted that accident rates decrease with increases in lane and shoulder widths and that widening lanes provides a greater safety benefit than widening shoulders. A recent French literature review (*12*) of the impact of lane width on driver behaviors in field studies underscores the inconsistency of the results. This inconsistency could result from the differences between the contexts (e.g., field versus driving simulator, road type, and the like). Furthermore, most studies focus on the impact of both lane and shoulder width and not the impact of lane width only.

A previous field study (*13*) evaluated the impact of lane narrowing with subsequent provision of a hard shoulder on driver behaviors on a rural road. This study gave two results. First, the lane narrowing with a wider hard shoulder had no influence on speeds and drivers traveled closer to the center of the lane. Second, the lateral position of the vehicle is largely influenced by oncoming vehicles.

For this study, in collaboration with the CETE Normandie-Centre (CETE-NC), a center for technical studies reporting to the French ministry for transport, the authors focused on speed and lateral positioning according to the lane reduction. The first purpose was to verify that the rural road lane narrowing, built in virtual reality in the driving simulator, had not influenced speed choice and had influenced lateral position as shown in the field study. The second purpose was to go further into the use of driving simulators as useful tools and validate them in the evaluation of traffic engineering issues such as roadway design and traffic management.

The benefits of using driving simulators include experimental control, efficiency, low cost, safety, and ease of data collection (*14, 15*). Furthermore, driving simulators provide an ethical tool, and to test perceptual treatments, they appear to be ideal (*16–18*). Nonetheless, driving simulators raise the problems of result replications between different simulators and the problems of driving simulator validity (i.e., differences between behaviors in driving simulators and those in real environments). However, Keith et al. (*19*) and Bella et al. (*20*) confirmed the usefulness of driving simulators in the road design process, which was one of the aims of this study.

This driving simulator study is part of the French national multidisciplinary research project PREDIT-SARI. This national project aims to inform drivers and road managers more effectively about the higher risk of loss of control on rural roads. In this context, the authors carried out a driving simulator study to evaluate the effects perceptual treatments have on lateral control during driving on crest vertical curves (CVCs). This study showed that drilling rumble strips on both sides of the centerline and providing a hard shoulder are effective treatments that direct drivers toward the center of the lane [for further details about this study, see work by Rosey et al. (*21*)].

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Transportation Research Record: Journal of the Transportation Research Board, No. 2138, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 112–119.
DOI: 10.3141/2138-15

METHOD

The main part of this study describes the experimentation in virtual reality with the driving simulator of INRETS (French National Institute for Transport and Safety Research). This paper describes this experimentation and also provides a concise description of the field study performed by CETE-NC.

The authors used the virtual three-dimensional database used in a previous driving simulator study [i.e., reconstruction in virtual reality of the real rural two-lane road (D961), in Maine-et-Loire, Department 49, France]. The two cross sections under scrutiny were a lane width of 3.5 m and a lane width of 3 m with a hard shoulder of 0.5 m.

Participants in Driving Simulator Study

Forty-three participants with full French driving licenses (i.e., not learners or those with restricted licenses) were called in. They all were required to have had a driving license for at least 2 years and normal or corrected vision. One subject stopped the test because he felt sick, leaving 16 women and 26 men ranging in age from 22 to 58 years (average age 38.6 years; standard deviation = 10.83 years). They had been driving 12,373 km/year on average, ranging from 5,000 to 30,000 km. Once in the laboratory, each participant was briefed on the requirements of the experiment and all read and signed an informed consent document.

Apparatus

The study was conducted using the INRETS-MSIS SIM^2 driving simulator (Figure 1), which is an interactive fixed-base simulator with a complete Citroën Xantia car, which hosts the user interface. The hardware is composed of four networked computers: one processes the motion equations and three generate the images.

The data recording system collected all the objective parameters (e.g., relative position with road axis, local speed and accelerations, steering wheel rotation angle, pedal actions) at a frequency of 60 Hz. The simulator presented three-dimensional driving scenes in panorama across three screens (150 degrees horizontal, 45 degrees vertical), one in the center and two on each side in a semicircle. This setup provides a realistic view of the road and surrounding environment (*14*). The resolution of the visual scene was 1,024 × 768 pixels and the refreshing rate was 60 Hz. The simulator was placed at 2.8 m in front of the central screen from the driver's head. The simulated road surface was high friction, corresponding to dry asphalt, and scene visibility corresponded to clear daytime conditions. The control devices were the steering wheel, the manual gearbox, and pedals (brake, accelerator, and clutch) of the complete Citroën Xantia car. The driving simulator provided sound feedback about the speed of the car (i.e., as speed increased, engine noise increased), and haptic feedback with a force feedback steering wheel. Velocity was displayed on the front screen in kilometers per hour.

FIGURE 1 Fixed-base INRETS-MSIS SIM^2 driving simulator.

From the driver's point of view, the simulator vehicle was used and reacted in the same way as a real car. Even the ignition key was used to "start" the engine, resulting in engine noises similar to a normal running vehicle.

Simulator Scenario

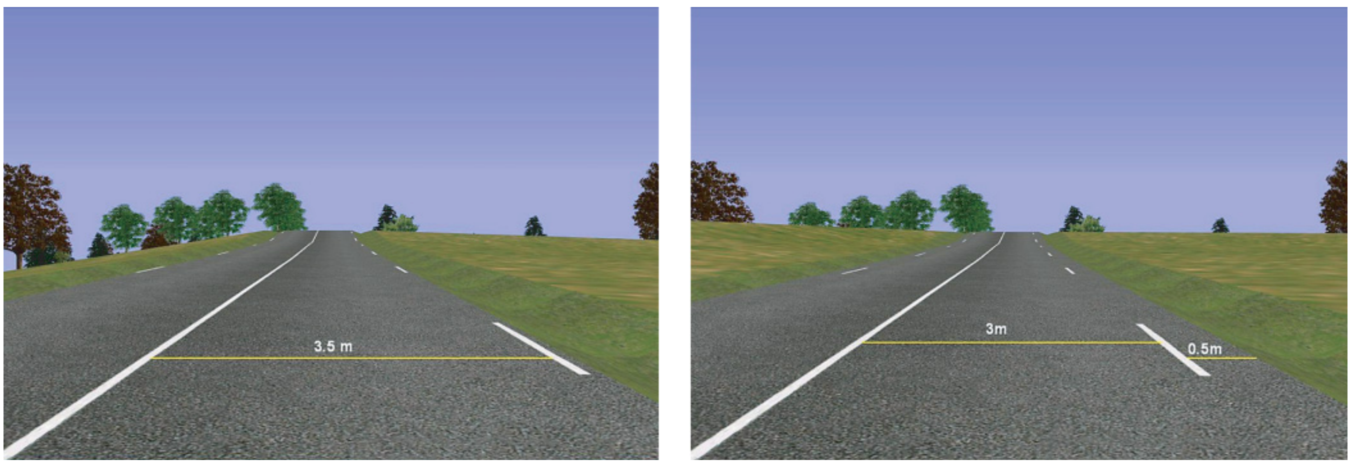
The roadway geometry of the simulated road was a reconstruction in virtual reality of the real rural two-lane road (D961) in Maine-et-Loire (Department 49, France). This reconstruction was based on the real-world topographic layout, which consists of a bidirectional straight road that is 3.5 km long with a lane width of 3.5 m and two CVCs. Lane widths, road markings, sight distances, and other road design characteristics were incorporated in the simulation to obtain similar road perception. Figure 2*a* shows a photograph of one section of the real road (left) with an image of the same section as it appeared in simulation (right). For both experimental situations (lane width of 3 m and 3.5 m), the road markings (edge and center) and the horizontal alignment and landscape were identical. The lane width of 3 m was obtained by relocation of the road markings (Figure 2*b*).

Procedure

Each participant was tested individually and the procedure used for each was as follows:

1. On arrival, participants were briefed on the requirements of the experiment. All read and signed an informed consent document and were asked to complete a form containing basic information (age, gender, etc.).
2. Participants then went on board the driving simulator and were shown the vehicle commands.
3. They were familiarized with the simulator in a neutral condition (i.e., they drove on the reconstruction of a three-dimensional virtual reality of the D961 rural road in the south direction, Marans to Segre. They had to go through a roundabout, which allowed for familiarization with the tactile feedback through the torque in the steering wheel.
4. Participants were informed that they would drive on a rural road until they reached the roundabout and then they had to stop at the entry of the roundabout. They were instructed to "drive like they would drive in the same situation in the real world, up to the roundabout where you would have to stop at the entry." The participants were also told that some disturbances could occur during the simulation and that they could stop the experiment at any time.
5. Participants drove on two separate random runs. Each run corresponded to one of two cross sections (i.e., 3 m or 3.5 m). For each driving condition, there was a low concentration of oncoming traffic from the opposite lane.

(a)



(b)

FIGURE 2 One section of road and two lane widths: (*a*) photograph (*left*) and reconstruction (*right*) of one section of road and (*b*) lane width from centerline to edge line of 3.5 m (*left*) and 3 m with hard shoulder of 0.5 m (*right*). For both roads, roadway widths were identical (i.e., 3.5 m).

The purpose of the traffic in the opposite lane was twofold: first, to remind participants that they could meet oncoming traffic (at the end of the road), and second, to determine the impact when participants met vehicles (i.e., cars or heavy trucks) according to the lane width. This option was taken because the lane reduction raised the problem of oncoming traffic. Indeed, on narrow roads (i.e., 3 m), drivers tend to drive close to the centerline (*22–24*). Furthermore, the size of the oncoming vehicle has an effect on lateral positioning. Rasanen (*25*) found in a field study that drivers steer closer to the edge line when meeting oncoming traffic. Thus, on narrow roads, drivers can either collide with an oncoming vehicle on the opposite lane or drift toward the road edge when meeting a larger vehicle such as a truck.

Participants were expected to choose a position on the road further away from the centerline when they met a heavy truck than when they met a car. They were also expected to lower their speed more when meeting a heavy truck than when meeting a car.

To assess the impact of oncoming traffic, a car and a heavy truck were simulated at the end of road, on the flat straight segment. The order of appearance of the simulated vehicles was either a car and a heavy truck or a heavy truck and a car. The cars were a Modus (Renault) and a C4 (Citroën), and the heavy truck (cabin and trailer) was 12.85 m long.

The authors chose not to create heavy traffic to avoid influencing participants' speed and lateral positioning, in reference to Lewis-Evans and Charlton's study (*26*).

The participants drove twice: one run for each lane width. They met at the end either a car and a heavy truck or a heavy truck and a car. A repeated measures design was used for the study.

Analysis

The lateral position measurements and speed measurements were continuously recorded with a sampling frequency of 60 Hz. For both conditions (i.e., 3.5 m and 3 m + 0.5 m), to estimate the influence of lane width only, size of the vehicle met, and road geometry on lateral position and speeds, four sections of 300 m were analyzed (Figure 3):

1. A section of reference (SR, yellow) without oncoming traffic to identify the impact of lane width only;

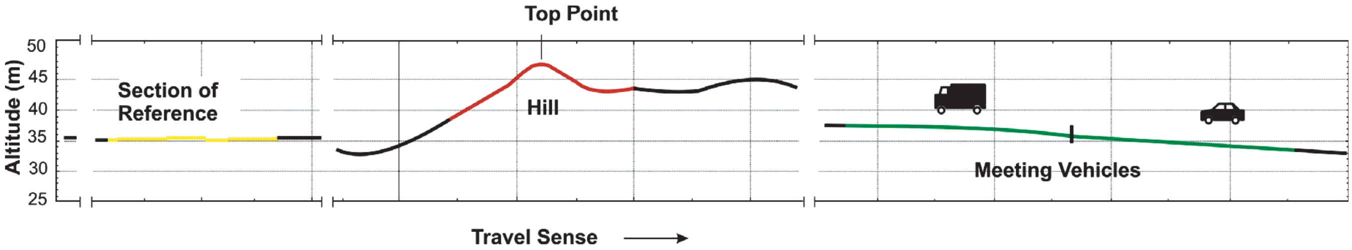


FIGURE 3 Profile of reconstructed road with three sections studied (not to scale).

2. A test hill section (TH, red) of 300 m of the second CVC (i.e., 200 m before the top of the hill and 100 m after it) to assess the impact of road geometry according to the lane width; and
3. Two sections on which the participants met oncoming vehicles (MV, green), to assess their impact according to their size and the lane width: 300 m for meeting the heavy truck (MHT) and 300 m for meeting the car (MCar).

Each section was divided in two parts to assess the influence area of the CVC and the possible influence of oncoming vehicles met (i.e., car or heavy truck).

The lateral position of the participant's car corresponded to the distance (in millimeters) of the front right wheel of the vehicle to the center of the road (Figure 4), to be in the same configuration that was used for the field study. A lane position of 0 mm was obtained when the vehicle was straddling the center of the road.

Lateral position and speed measures were analyzed using analysis of variance (ANOVA) to repeated measures with the three sections (reference, test hill, and oncoming vehicles). Each repeated measures ANOVA was followed by a post hoc Newman-Keuls test. The threshold for statistical significance was set at .05.

RESULTS

The results of the driving simulator study are reported first in this section, followed by the summarized results of the field study performed by the CETE-NC (*13*).

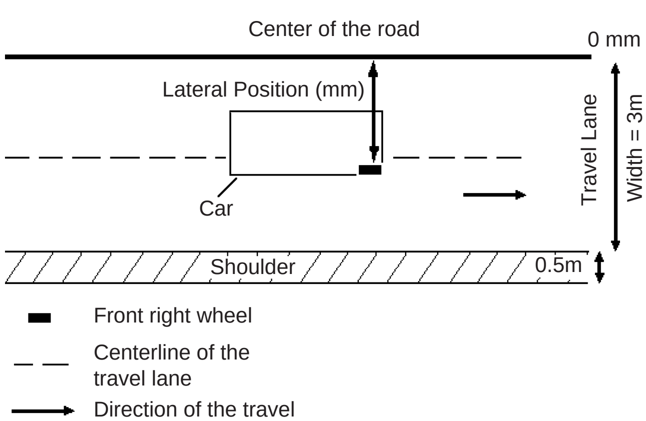


FIGURE 4 Example of method used to determine lateral position.

Driving Simulator Study

Each section (i.e., SR, TH, and MV) was divided in two parts to assess the influence area of the CVC and the possible influence of oncoming vehicles met (i.e., car or heavy truck). This influence has been reported as the "influence area" factor.

Speed

The ANOVA indicated a main effect of the section [$F(3, 123) = 36.53$, $p < .0001$], of the influence area [$F(1, 41) = 8.87$, $p < .004$], but not of the lane width [$F(1, 41) = 3.21$, $p = .08$]. Thus, the participants drove at a higher speed before the middle of the sections than after it. The ANOVA indicated only a section *x* influence area interaction [$F(3, 123) = 64.59$, $p < .0001$]. The other interactions were not significant: lane width *x* section interaction [$F(3, 123) = .78$, $p = .50$]; lane width *x* influence area interaction [$F(1, 41) = 1.26$, $p = .27$]; and lane width *x* section *x* influence area interaction [$F(3, 123) = 1.96$, $p = .12$].

Post hoc analyses indicated the following:

1. The participants drove with similar speeds on the section of reference (SR: 102 km/h) and when meeting the car (MCar: 99 km/h, $p = .80$), and they drove at higher speeds on the SR than on the CVC (CVC: 90 km/h, $p < .0001$) and when they met the heavy truck (MHT: 97 km/h, $p < .05$). Furthermore, the participants drove with lower speeds on the CVC than when they met the car ($p < .0001$) and the heavy truck ($p < .0001$). They drove faster when meeting the car than when meeting the heavy truck ($p < .05$).
2. The participants drove the SR and each time the car was met with similar speeds ($p = .80$ and $p = .55$, respectively). They drove faster when going uphill than going downhill ($p < .0001$) and after meeting the heavy truck than before meeting it ($p < .0001$).

Lateral Position

The ANOVA indicated a main effect of the lane width [$F(1, 41) = 30.59$, $p < .0001$], of the section [$F(3, 123) = 33.85$, $p < .0001$], of the influence area [$F(1, 41) = 6.94$, $p < .01$]. Thus, the participants drove, on the lane width of 3 m (m = 2,658 mm), significantly closer to the center of the road than on the lane width of 3.5 m (m = 2,798 mm), and before meeting the vehicle than after meeting it.

The ANOVA indicates a lane width *x* section interaction [$F(3, 123) = 5.60$, $p < .001$]; section *x* influence area [$F(3, 123) = 5.04$, $p < .002$], but not lane width *x* influence area interaction [$F(1, 41) = 3.09$, $p < .09$] or lane width *x* section *x* influence area interaction [$F(3, 123) = .89$, $p < .45$].

Post hoc analyses indicated the following:

1. Participants drove on the section of reference closer to the center of the road than on the other sections for the two lane widths: the test hill (SR * TH, $p < .001$) and the section with oncoming traffic (SR * MHT, $p < .001$ and SR * MCar, $p < .001$).
2. For the lane width of 3.5 m, the participants drove with similar lateral positions on the CVC and when they met the heavy truck (CVC * MHT, $p = .92$) and on the MV whatever the vehicle met (MHT * MCar, $p = .10$), but they drove closer to the center of the road on the CVC than when they met the car (CVC * MCar, $p < .04$).
3. For the lane width of 3 m + 0.5 m, the participants drove with similar lateral positions on the CVC and the MV (CVC * MHT, $p = .20$ and CVC * MCar, $p = .66$).
4. For the lane width of 3.5 m, the participants drove closer to the center of the road before meeting the vehicles than after meeting them (before * after, $p < .007$), but not for the lane width of 3 m (before * after, $p = .73$). Before meeting a vehicle and after meeting it, participants drove closer to the center of the road for the lane width of 3 m + 0.5 m than for the lane width of 3.5 m (3 m * 3.5 m, $p < .0001$).

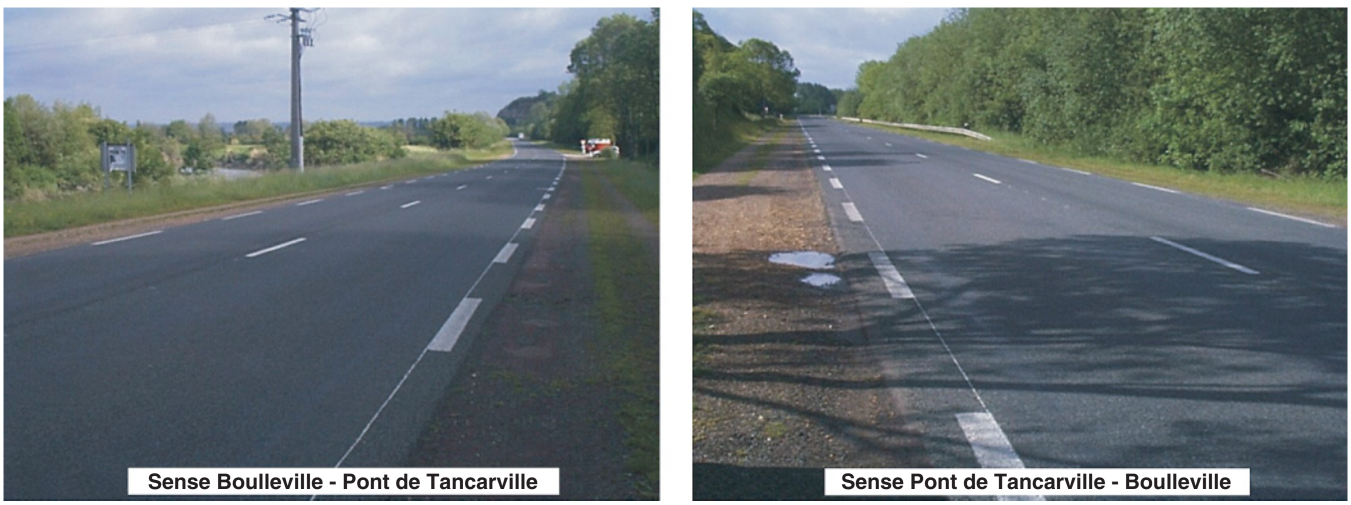
Comparison with the Field Study of CETE-NC

For more details, the reader can refer to the CETE-NC report (*13*).

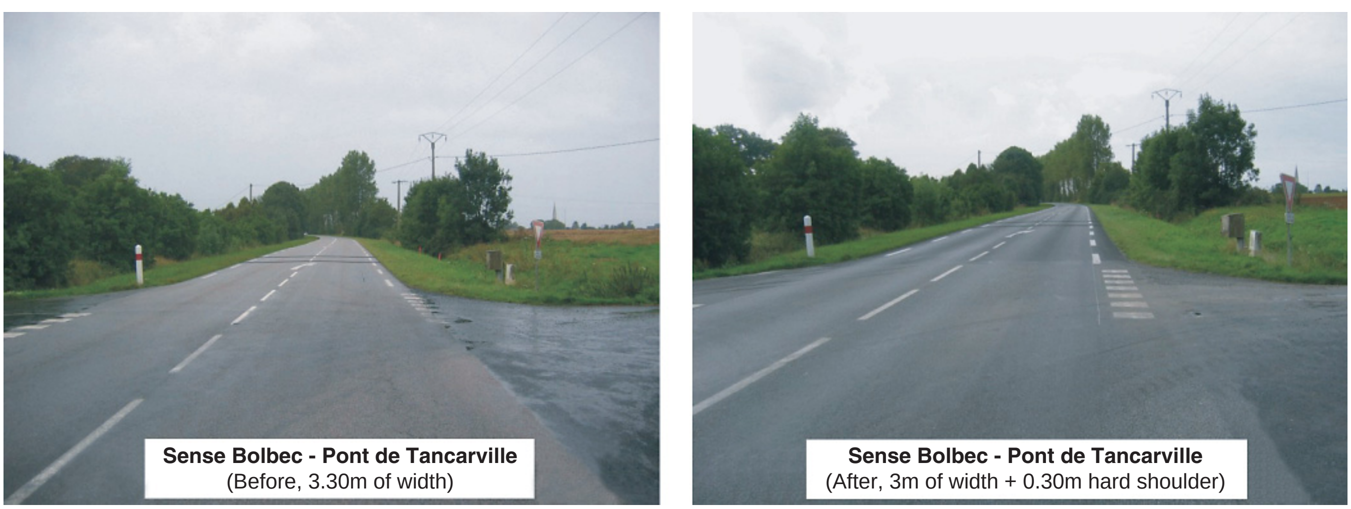
Summarized Protocol

The purpose of this study was to evaluate the impact of a lane narrowing (i.e., 3.3 m before reduction) with provision of a right hard shoulder (i.e., 3 m + 0.3 m after reduction) on driver behaviors on a rural road. The field site was a two-lane road (D910) in Seine-Maritime (Department 76, France). In this study, drivers were unaware that they were subjects in an experiment.

On the two sites [i.e., control and experimental (see Figure 5)], the measurements (i.e., lateral position and speed) were carried out



(a)



(b)

FIGURE 5 Control site and one of two experimental sites: (*a*) two travel directions of control site and (*b*) view of one of two travel directions of the experimental site.

in October and November 2004 before the lane width reduction, and in October and November 2005 after the lane width reduction. Each measurement period addressed free-moving vehicles in both directions.

Control Site To obtain a standard of comparison for determining the effects of the treatment, CETE-NC chose a site on which no change in lane width has been performed (see Figure 5*a*). This control site corresponded to a section of the RD178 (Department 76, France). On this control site, only speed measurements of free-moving vehicles were carried out. The mean speeds were 92 km/h ($n = 3{,}390$) for October and November 2004 period and 90.5 km/h ($n = 3{,}197$) for the October and November 2005 period.

Experimental Site The experimental site corresponded to a section of the RD910 (Department 76, France) (Figure 5*b*). On this site, speed and lateral position measurements of free-moving vehicles before and after lane width reductions were carried out.

Speed measurements were carried out with a SIREDO traffic counting station (i.e., automatic traffic counter loop in pavement, thus not visible). The lateral position measurements were carried out with pneumatic tubes and completed with video recordings. The camera was installed in a nacelle (about 5 m above the ground) mounted on a truck parked at the roadside. Vehicles with headways lower than 5 s were not considered as free-moving vehicles and thus, they were not taken into account in this analysis. Note also that in the comparison, the authors focused on the car driver data.

Comparison of the Driving Simulator Study Results with the Field Study Results

The results showed the following:

1. Speeds were not affected by the lane narrowing (Tables 1, 2, and 3).
2. Drivers drove more toward the center of the lane after the lane narrowing (Figure 6).
3. On the lane width of 3.3 m, the drivers were mostly on the left side of the lane, whereas on the lane width of 3 m, the drivers shift toward the center of the lane but one driver out of two remains on the left side of the lane.
4. Drivers drove more on the right side of the lane when they met oncoming vehicles.

Furthermore, for the two driving conditions, speeds in virtual reality are higher than those in field measurements.

TABLE 1 Overall Speed Means (Smean, km/h) by Studies (Driving Simulator and Field) for Two Lane Widths

	Lane Widths	
Field Study	3.30 m ($n = 176{,}117$)	3 m + 0.30 m ($n = 140{,}060$)
Experimental site Smean	95	92
Simulator study ($n = 42$)	3.50 m	3 m + 0.50 m
Smean	96	98

TABLE 2 Speed Means (Smean, km/h) for Field Study for Two Lane Widths

	Field Study (i.e., experimental site)			
	Lane Widths			
	3.30 m		3 m + 0.30 m	
Direction of Travel	Smean	*n*	Smean	*n*
Pont de Tancarville → Bolbec	95	91,797	93	67,940
Bolbec → Pont de Tancarville	95	84,320	91	72,120

NOTE: $n = 42$.

DISCUSSION OF RESULTS

In this study, the authors assessed the impact of narrower lane width on lateral positions and speeds on rural roads. Experiments were conducted on a fixed-base driving simulator and on real roads. The lane narrowing was obtained by delineation marking.

As reported in the field study, the driving simulator study showed that the lane reduction with subsequent provision of a hard shoulder leads the driver to drive more toward the center of the lane but has no influence on speeds. Furthermore, results showed that as in the field study, for both lane widths, they drove more toward the right side of the lane when they met a vehicle. In the study that concerned driver behavior in function of the road type, the authors obtained a relative validity (i.e., correspondence between effects of different variations in the driving situation on simulated and real roads). For Törnros (*27*), this kind of validity is needed for a driving simulator to be a useful research tool.

The speed results showed that the speed was higher in the simulated roads than in the real roads, consistent with those of other studies (*14, 20, 27, 28*).

Nevertheless, after the reduction in lane width, on the simulated roads, the drivers were more centered (i.e., 38% of lateral position less than 2.6 m from the road axis) than on the real roads (i.e., 13%). Furthermore, speeds used during simulated driving after the lane narrowing were higher than speeds used during the field study. One

TABLE 3 Speed Means (Smean, km/h) for Driving Simulator Study for Two Lane Widths

	Lane Widths	
	3.5 m	3 m + 0.5 m
Section	Smean	Smean
SR	99	101
CVC	89	91
MV		
Heavy truck	96	99
Car	99	100
All sections	96	98

NOTE: Speed means are given by sections. SR = section of reference, CVC = crest vertical curve, MV = section on which participants met oncoming vehicles (i.e., a car or a heavy truck).

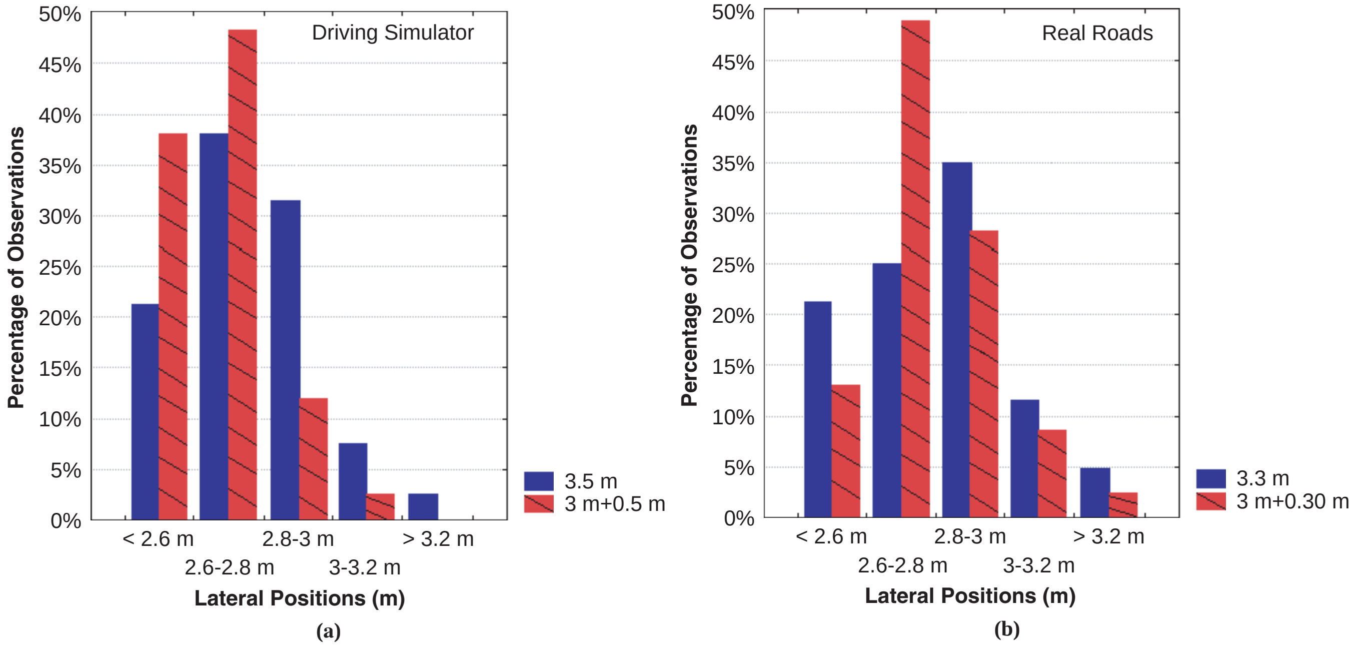


FIGURE 6 Histogram of lateral positions before the lane narrowing (blue bars) and after (red hatched bars): (*a*) driving simulator study and (*b*) field study.

explanation can be that on this type of French road, the posted speed limit is 90 km/h. During the field study of CETE-NC, some participants were asked to express their feelings about the lane width reduction. They felt a lane widening. Furthermore, studies have shown that wider lanes increase travel speeds (*5*, *6*). From these elements, the authors suggest that the participants who took part in the driving simulator study could have implicitly perceived a lane widening. Thus they used speeds in the reduced lane width condition corresponding to their own perception of the road (i.e., impression of wider lane). This wrong perception led the participants to drive over the speed limit. The explanation of the impact of lane width on lateral positioning could be that a narrower lane could have implicitly affected the participants. Indeed, in a previous study, Rosey et al. (*21*) found that the rumble strips on both sides of the centerline affected the drivers' trajectory even though 30% of drivers had not previously seen them.

In conclusion, the relative behavioral validity found in this study corroborates the driving simulator as a reliable tool for the analysis of driver behavior in roadway design in the sense that it allows researchers to predetermine, in a safe and controlled environment, treatments or impact environment modifications on driver behaviors. Furthermore, practitioners (e.g., safety engineers and road engineers) are always looking for roadway and roadside improvements to reduce the probability and severity of crashes, and they look to design roads that reduce driving errors and their associated risks. A better understanding and quantification of the safety implications of geometric improvements and countermeasures is necessary, especially with regard to the impact of any change to the cross section. The driving simulator offers considerable benefits in terms of prevention. From various situations with low-cost objectives, the virtual environment can allow the practitioners to visualize the impact of different designs on driver behaviors (e.g., rumble strips, hard shoulders, no road marking on CVC) (*21*) and to estimate the level of acceptability to the road users. Consequently, they can set up a first scheme and design to facilitate future road accommodations and operations. The use of a driving simulator allows a better understanding of the physical space that is being designed without danger for the drivers, an increase in the number of facilities to be used virtually, and quantitative evaluation of the safety of alternative designs, which enables the selection of the most appropriate before initiating real designs.

ACKNOWLEDGMENTS

The research presented in this paper was performed as part of the French national project PREDIT-SARI, sponsored by the Department of Ecology, Energy, Sustainable Development and Regional Development. The authors thank Olivier Bisson, Dominique Delouis, and Peggy Subirats for their helpful comments.

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The Simulation and Measurement of Vehicle and Operator Performance Committee sponsored publication of this paper.