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The effects of lane width, shoulder width, and road cross-sectional reallocation on drivers' behavioral adaptations

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ABSTRACT

Previous research has shown that lane-width reduction makes drivers operate vehicles closer to the center of the road whereas hard-shoulder widening induces a position farther away from the road's center. The goal of the present driving-simulator study was twofold. First, it was aimed at further investigating the respective effects of lane and shoulder width on in-lane positioning strategies, by examining vehicle distance from the center of the lane. The second aim was to assess the impact on safety of three possible cross-sectional reallocations of the width of the road (i.e., three lane-width reductions with concomitant shoulder widening at a fixed cross-sectional width) as compared to a control road. The results confirmed that lane-width reduction made participants drive closer to the road's center. However, in-lane position was affected differently by lane narrowing, depending on the traffic situation. In the absence of oncoming traffic, lane narrowing gave rise to significant shifts in the car's distance from the lane's center toward the edge line, whereas this distance remained similar across lane widths during traffic periods. When the shoulders were at least 0.50 m wide, participants drove farther away from both the road center and the lane center. Road reallocation operations resulted in vehicles positioned farther away from the edge of the road and less swerving behavior, without generating higher driving speeds. Finally, it is argued that road-space reallocation may serve as a good low-cost tool for providing a recovery area for steering errors, without impairing drivers' behavior.

1. Introduction

Humans are highly skilled at controlling locomotion. However, while individuals commonly experience efficient locomotor adaptations in complex and dynamic environments (Warren and Fajen, 2004), lane keeping during driving remains a critical safety task. Almost one third of all road-accident fatalities (31.4%) in the European Union during the decade 2004–2013 occurred in single vehicle accidents (ERSO, 2015), most of which were related to lane departure (see Najm et al., 2007). Furthermore, only 33% of these single-vehicle fatalities occurred in the dark, whereas 51% occurred in daylight or twilight (ERSO, 2015). The large number of crashes involving run-off-road collisions without third-party involvement or severe perceptual impediment indicates that drivers are often confronted to inadequate lateral control issues. Keeping a proper distance from the lane boundaries along a road thus appears to merit further research. The present work was aimed at investigating the relationship between drivers' lateral positioning and a road's cross-sectional dimensions, in particular lane width and shoulder width.

1.1. Lane width

Despite the lane width is a basic factor in accident analysis research (e.g., Hadi et al., 1995; Karlaftis and Golias, 2002), a few studies, whether on a driving simulator (Dijksterhuis et al., 2011; Godley et al., 2004; Green et al., 1994; Lewis-Evans and Charlton, 2006) or in real-world conditions (De Waard et al., 1995), have investigated its effects on steering control and lateral position. The findings have consistently indicated that lane narrowing results in less variability of the vehicle's lateral position (De Waard et al., 1995; Dijksterhuis et al., 2011; Godley et al., 2004; Green et al., 1994) and speed reduction (De Waard et al., 1995; Godley et al., 2004; Lewis-Evans and Charlton, 2006). As an explanation of why lateral-position variability decreases with lane-width reduction, evidence indicates that driving in a narrow lane requires more steering effort on the part of the driver. Larger steering-wheel angle deviations were found for narrow lanes as compared to wider ones in Godley et al. (2004), while subjectively experienced mental workload was increased by exposure to narrow lanes in Dijksterhuis et al. (2011). The lateral-position variability has also been

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shown to be negatively correlated with workload ratings (Green et al., 1994). Concerning travel speed, an influential hypothesis for speed choice in narrow lanes is based on models of steering control. As supported by a number of experimental results, drivers use time-to-line-crossing – i.e., the time needed by the vehicle to reach a lane boundary, assuming the steering wheel angle remains the same – as a critical cue to controlling the lateral safety margin (Van Winsum and Godthelp, 1996). In this view, narrowing lane width causes drivers to reduce their speed so that time-to-line-crossing remains constant and safety margin is not jeopardized (Godthelp, 1988).

The lane width was also shown to influence drivers' lateral positions (De Waard et al., 1995; Dijksterhuis et al., 2011; Green et al., 1994; Lewis-Evans and Charlton, 2006). By defining a vehicle's lateral position as the distance between the car and the center of the road, it has been shown that narrow lanes produce lateral positions that are significantly closer to the road center than do wider lanes, both in simulation (Green et al., 1994) and in real-world studies (De Waard et al., 1995). However, according to Green et al. (1994), this observation may not necessarily reflect different in-lane positioning if drivers systematically keep their offset from lane center constant, regardless of its width. When a vehicle's lateral position is computed as its distance from the lane's center, empirical evidence suggests, on the contrary, that drivers use different in-lane positioning strategies that depend on lane width (Dijksterhuis et al., 2011; Lewis-Evans and Charlton, 2006). Lewis-Evans and Charlton (2006) showed that participants drove closer to the road's axis in a narrow (3.00 m) lane (i.e., with a 0.37 m shift to the left of the lane's center, when driving on the right-hand side of the road), while a wide lane (4.60 m) caused vehicles to drive closer to the edge line (i.e. with a 0.26 m shift to the right of the lane's center). The findings for different in-lane positions when lane width was varied were marginally replicated by Dijksterhuis et al. (2011), who reported a significant effect of lane width on lateral position but no significant pairwise comparisons in a-posteriori analyses. This study also revealed a significant interaction between lane width and traffic density. While an increase in oncoming traffic from low to high density led to a lateral displacement of the vehicle toward the right side of the lane in the four lane–width conditions (3.00, 2.75, 2.50 and 2.25 m), the largest effect of traffic condition was found in the 2.75 m lane (Dijksterhuis et al., 2011). Lastly, lane-width effects on drivers' positioning do not appear to result from conscious steering control – most participants did not notice changes in lane width – but rather from implicit processing of the road environment (Lewis-Evans and Charlton, 2006; see also Coutton-Jean et al., 2009). Narrowing the driving lane can therefore be regarded as a powerful way to influence road-user behavior, since the effect occurs at an implicit perceptual level that lowers driving speed and lateral-position variability while producing a lateral position closer to the center of the road.

1.2. Shoulder width

Another cross-sectional feature of the road is the shoulder adjacent to the driving lanes which may serve multiple purposes, including providing a recovery area for driver errors (Hall et al., 1998). As for lane width, the effects of shoulder width on crash rate have been investigated (e.g., Hadi et al., 1995; Wang et al., 1998; Zegeer and Council, 1995) but studies aimed at understanding its effects on driver behavior are scarce. Recently, two driving-simulator studies revealed significant shoulder-width effects on speed and lateral position (Bella, 2013; Ben-Bassat and Shinar, 2011). The results showed that drivers drove at higher speeds when shoulders were present (Bella, 2013) or became wider (Ben-Bassat and Shinar, 2011). Regarding lateral position, Ben-Bassat and Shinar (2011) highlighted that in the presence of guardrails, participants drove in the left side of the lane when the shoulder was narrow (0.50 m), but shifted toward the middle of the lane and toward the right side of the lane when the shoulder was enlarged (1.20 and 3.00 m, respectively). This outcome is supported by the results obtained by Bella (2013), who showed that the presence of a 0.50 m shoulder produced a lateral position that was 0.20 m farther away from the road's center than without a shoulder, regardless of the roadside configuration. Thus, shoulder widening gave rise to effects opposite to lane-width reduction, since it produces higher speeds and lateral positions closer to the edge line.

1.3. Road cross-sectional reallocation

For nearly a decade now, a low-cost safety plan consisting of reconfiguring the combination of lane and shoulder widths by moving the location of the edge line toward the center of the road has been in effect in France. In this system, each lane (defined by road markings) is reduced in width and the width of the shoulder is increased without changing the cross-sectional dimension of the road. This provides a larger recovery area to drivers. This reallocation of the total paved width thus combines the effects of two road operations (lane narrowing and shoulder widening) on drivers' lateral positioning and speed, known to work in opposite directions when taken separately. Examples in the literature include a simulator study conducted on a road with a 7 m cross-section and two lanes 3.50 m wide reduced to create 0.50 m shoulders, and a real-road study conducted on a road with a 6.60 m cross-section and two 3.30 m lanes reduced to create 0.30 m shoulders (Rosey and Auberlet, 2012; Rosey et al., 2009). The results of these two studies showed that lane narrowing by relocating the edge line caused participants to drive closer to the road's center, but it increased lateral-position variability and had no impact on driving speeds (Rosey and Auberlet, 2012; Rosey et al., 2009). While the lane-reduction effect on lateral position generated by relocating the edge lines is in line with what was observed when the entire road (or physical lane) was reduced, the results for lateral-position variability and speed were clearly at variance with those found in the physical lane-reduction literature (De Waard et al., 1995; Dijksterhuis et al., 2011; Godley et al., 2004; Green et al., 1994; Lewis-Evans and Charlton, 2006). Although one could assume that lane-width reduction has a greater influence on drivers' behavior than shoulder-width enlargement, the systematic covariation of lane and shoulder widths due to the fixed roadway width found in existing reports (Rosey and Auberlet, 2012; Rosey et al., 2009) precludes drawing any clear conclusions about the respective effects of these two cross-sectional characteristics when road space is reallocated.

1.4. The present study

The present study was carried out on a fixed-base driving simulator to find out how speed and lateral position are affected by different lane-width and shoulder-width combinations when the road's cross-sectional width was reallocated. While the primary research goal was to assess the effectiveness of lane–shoulder combinations given a fixed road width, lane and shoulder widths were manipulated separately to combat the above-mentioned covariation issues. Driving behavior was examined at fixed and variable pavement width on rural two-lane roads, which account for around two-thirds of the single vehicle accident fatalities in France (68%) and Europe (62%) (ERSO, 2015). Based on the earlier results, it was hypothesized that lane-width reduction would induce shorter vehicle distances from the road center, lower lateral-position variability, and slower driving speeds than would wider lanes. This study was also aimed at documenting the effects of lane width on in-lane positioning strategies (i.e., the vehicle's distance from the center of the lane), since available findings have not made it entirely clear what behavioral results can be expected on this issue. A second hypothesis was that shoulder widening would have effects opposite to lane-width reduction and would make participants drive faster and closer to the edge line. Regarding cross-sectional reallocation, it was expected that lane-narrowing effects at a fixed pavement width would be mitigated by an increase in the shoulder width. Lastly,