Dynamic traffic management on a familiar road: Failing to detect changes in variable speed limits

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Abstract
Variable speed limits (VSL) are used more commonly around the globe lately. Although on a macroscopic level positive effects of VSLs have been reported, the caveat is that the impact of VSLs is very sensitive to the level of driver compliance. Thus far it is unknown whether all individual drivers are actually able to notice when a speed limit changes into another speed limit; a prerequisite for purposeful speed limit compliance in the first place. To simulate regular driving conditions, twenty-four participants were familiarised with a particular route by driving the same route in a driving simulator nineteen times on five separate days. Part of the route consisted of a motorway where VSL signs were regularly displayed above every driving lane. At drive nineteen, speed limits changed from 80 km/h to 100 km/h on four out of eight consecutive signs. After passing all signs, one expects 6.25% of the participants still to be unaware that the speed limit had increased (based on chance), while the results showed most participants had failed to notice the speed limit change (58.3%). Instead, they saw what they expected to see: a speed limit of 80 km/h. If the speed change had been vice versa, in other words from 100 km/h to 80 km/h, this would immediately result in speed offences, though not deliberately at all.

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1. Introduction

Speed limit compliance plays an important role in road safety. Over the last couple of years a new type of speed limits has been introduced: speed limits which can vary based on local conditions. These variable speed limits (VSLs) are mainly used on motorways, in Western (oriented) countries. Changes in speed limits represent real-time changes in local conditions. The aim is to influence driver behaviour more swiftly to improve both traffic safety, traffic circulation and in some cases air quality. As a result, most research on VSLs has been focussed on the effects they have on traffic safety and traffic flow (e.g. Corthout, Tampère, & Deknudt, 2010; Lee & Abdel-Aty, 2008; Nissan, 2010; Papageorgiou, Kosmatopoulos, & Papamichail, 2008; Stoelhorst et al., 2010). While researchers agree on the positive effects regarding traffic safety, results concerning traffic flow remain inconclusive. Nevertheless, the outcomes of Hellinga and Mandelzys’ microscopic traffic simulator study (2011) emphasised that the impact of VSLs is very sensitive to the level of driver compliance. Drivers’ willingness and ability to comply with speed limits is affected by factors such as speed limit credibility and the design of speed signs. A study by van Nes, Brandenburg, and Twisk (2010) indicated that appreciation of VSLs by drivers in terms of usefulness and acceptance is higher compared to their static counterpart. Research on the design of signs for VSLs pointed out that they are best displayed...
on electronic signs per driving lane on overhead gantries, as this is where they are expected and how they attract most attention (Chang & Li, 2008; Hoogendoorn, Harms, Hoogendoorn, & Brookhuis, 2012; Rämä, 2001). For example electromechanical VSLs and roadside electronic signs on high poles on the contrary, are less conspicuous and less effective in terms of driver behaviour (Hoogendoorn et al., 2012; Rämä, 2001).

In a recent traffic management pilot programme in the Netherlands, VSLs were used to test their potential to adjust real-time driver speed to the circumstances of the road condition. Although on average it appeared that changes in speed limits resulted in changes in drivers’ speed (Burgmeijer et al., 2010), close examination of minute-to-minute loop data of one of the pilot roads showed that not all drivers changed speeds. When the speed limit was increased during calm traffic conditions, the average speed did not increase for car drivers who were on the pilot track while the change occurred (Harms & Brookhuis, 2010). This made us wonder why drivers failed to comply with a speed limit increase.

1.1. Route familiarity

When studying speed limit compliance for VSLs it is important to look into how VSLs are generally encountered. In daily life, drivers prefer the same route over and over again, hence becoming increasingly familiar with this particular route (Dicke-Ogenia, 2012). Moreover, drivers tend to frequent these routes – such as the route from home to work – at approximately the same hours a day (Pendyala, 1999; Schönfelder, 2006). On roads with VSLs, this means drivers will normally encounter one speed limit far more frequently than another. This is an important notice, as previous experiences play an important role in driver behaviour. With repeated experience, expectations are built and task-performance becomes increasingly automated (Schneider & Shiffrin, 1977). In other words, drivers drift into a form of habit. Thus far, research on how route familiarity influences the detection of changes in infrastructural and/or traffic management measures, such as a speed limit increase on VSLs, is still scarce; and to our knowledge studies on the effects of route familiarity on variable traffic management measures are non-existent. Martens and Fox (2007) found that drivers who are familiar with a particular road tend to reduce their glance duration at traffic signs. This suggests less time is needed to process the information presented, provided the information has not changed. High levels of route-familiarity may also increase sensitivity for detecting changes to road features associated with vehicle guidance (Charlton & Starkey, 2013). On the downside, strong habituation may also obscure what can actually be seen. For example, when a traffic sign is changed into a less expected sign most route-familiar drivers may not notice this change (Charlton & Starkey, 2011; Charlton & Starkey, 2013; Martens, 2011; Martens & Fox, 2007). Instead they see what they expect (Martens, 2007).

1.2. Change blindness

Based on a literature review, Harms (2011) proposed that because of its properties, it is likely that dynamic traffic management information – which includes VSLs – is subject to change blindness. Change blindness is characterised by ‘the inability to detect changes to an object or scene’ (for a review see Simons & Levin, 1997). Normally, changes are accompanied by transient motion signals which aid change detection. When these signals are lacking it is increasingly difficult to detect the change, leaving people ‘change blind’ (Zheng & McConkie, 2010). As VSLs are presented on subsequent intermittent roadside displays, any transient motion signals involved in a speed limit change will be masked by a temporal gap. This feature is reminiscent of the flicker paradigm commonly used for studying change blindness, in which two – generally slightly different – scenes are separated by a brief flicker which disrupts any transient motion signal. On the other hand, VSLs also have a feature that may aid change detection. Changes in visual information which is considered meaningful or useful for the task at hand, result in higher detection rates (O’Regan, Deubel, Clark, & Rensink, 2000; Pearson & Schaefer, 2005; Rensink, O’Regan, & Clark, 1997; Wallis & Bülthoff, 2000). Standard speed limits, contrary to other types of traffic signs, have proven to be considered meaningful, relatively well observed and relatively well recollected by drivers (Johansson & Backlund, 1970; Johansson & Rumar, 1966; Lajunen, Hakkarainen, & Summala, 1996; Luoma, 1991; Rämä, 2001). To find out whether the above reported findings play a role in speed limit compliance, the current study focuses on the perception of VSLs: do drivers notice when a VSL speed limit changes into another speed limit along a familiar route?

2. Method

2.1. Experimental design

In a driving simulator, participants drove the same route twenty times on five separate days over an average period of 1.2 months (between five and hundred and twenty days), with slightly varying traffic conditions. This method to promote habituation in driving is derived from studies by Martens and Fox (2007) and Charlton and Starkey (2011). Modifications were made due to constraints in participants’ availability. The method was used because it closely resembles real-life driving on familiar routes, for example, the route to work, to the shopping mall or to friends. To prevent any interference from participants who might expect ‘something’ to happen on the last, 20th, drive, the change was introduced in the 19th drive instead. The change consisted of a speed limit increase from 80 km/h to 100 km/h on consecutive VSLs.
The experimental design and the timing of all manipulations are explained in Table 1. The “meaningfulness questionnaire” – which indicated participants’ perceived meaningfulness of various on-road and roadside objects – was used to assess participants’ preferences for traffic signs, specifically speed signs. The “recollection task” in the 20th drive involved recollecting which speed limits had been in place in drive 19 (the change session). Change detection was measured in six different ways, of which the outcome was used to designate drivers as change-aware or change-unaware.

2.2. Participants and procedure

Twenty-four participants completed the experiment successfully. Three more participants were unable to participate due to simulator sickness and the data of another participant had to be excluded as it had accidentally been overwritten during the experiment. Participants were recruited through advertisements in a local supermarket and on the internet. Their ages varied from 23 to 57 years ($M = 34.4$, $SD = 10.4$) and both male and female Dutch drivers participated (16 males and 8 females). Participants held their driving licence for at least five years and had driven over 4000 km in the past twelve months prior to the experiment ($M = 13,200$, $SD = 7,900$). All participants reported normal or corrected to normal eyesight and were paid for their participation.

Participants were told that the aim of the experiment was to gain more insight into what people look at while driving. They were not explicitly told that anything could change; neither were they told to expect changes in speed limits. Participants were instructed to drive as they normally would. To become comfortable with the driving simulator participants drove two practice laps for 10 min. Each experimental drive took participants approximately 15 min to complete. In between consecutive drives were short breaks of two to five minutes in which participants were allowed to get out of the car for a stretch. The experiment took approximately 1.5 hours per day. The study had been approved by the Ethical Committee of the Department of Psychology of the University of Groningen.

2.3. Materials

2.3.1. Questionnaires

The meaningfulness questionnaire – which was used at the start of the experiment – consisted of rating eighteen consecutively displayed pictures. Each picture consisted of a snapshot of the route that participants would later drive in the driving simulator. The eighteen snapshots covered nine categories of objects – two snapshots per category – including fixed speed limit signs, electronic speed limit signs and route signage. The object of interest was marked by one yellow circle per picture. The question was to express the amount of importance one attached to the circled object when driving a route for the first time by rating it on a five-point Likert scale (ranging from 1, very unimportant, to 5, very important). The questionnaire was conducted with E-Prime software which randomised the pictures.

The questionnaire finalising the experiment contained questions on the speed limits participants had encountered in the driving simulator. Successive topics were recollection (had one noticed anything special about the speed limits in drive 1–19?); expectation (what expectations had one held concerning possible variability in speed limits while driving for both the standard traffic signs and the electronic signs on the overhead gantries?); and finally recognition (had one seen the change?). As participants may be inclined to say they have seen the change (even if they have not), the recognition question also included a plausible alternative. For this, it was suggested that there had been two groups: one group for whom the speed limit on the gantries had always been 80 km/h and another group for whom the speed limit on the gantries had increased from 80 km/h to 100 km/h. While in fact all participants belonged to the second group, they were asked to which group they thought they belonged and how confident they were of their decision.

2.3.2. Driving simulator

The current study was conducted using the Delft University of Technology’s STSoftware driving simulator. It consists of a fixed base car mock-up, allows participants a 210° view of the driving environment and is capable of simulating fully interactive traffic (see Fig. 1). Both the software and the simulator are described in more detail by van Winsum and van Wolffelaar (1993) and Hoogendoorn et al. (2012), respectively. The simulated vehicle’s dashboard displayed accurate speed and engine RPM data as well as a navigation device. This indicated the route both visually by means of an arrow as well as verbally by means of spoken instructions. Information on participant’s speed, lane position, time headway and headlight signalling switch usage was collected at a rate of 10 Hz.

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<td>Overview of the experimental design. Q1,2 = demographic questionnaire succeeded by a meaningfulness questionnaire. P = two practice drives. N = speed limits do not change. C = variable speed limits change. R = recollection task. Q3 = final questionnaire including expectations, recollection and recognition.</td>
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<td>Day 1</td>
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<td>Q1,2</td>
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The simulated route was 20.9 km long. It consisted of driving on a rural road and a motorway. To promote familiarity the route contained prominent landmarks such as windmills. The second half of the motorway was equipped with eight gantries displaying VSLs for traffic management purposes. Drivers could never see two gantries at the same time, hence leaving a temporal gap between displayed speed limits. The VSL speed limits were displayed on electronic signs per driving lane on overhead gantries as can be seen in Fig. 2, because – as mentioned earlier – this sign design attracts most attention (Chang & Li, 2008; Hoogendoorn et al., 2012; Rämä, 2001). In drive 1–18 all these speed signs displayed a speed limit of 80 km/h. During drive 19 – the change session – the second half of the drive had the last four overhead speed signs showing 100 km/h instead of 80 km/h (see Table 2). The driving simulator was programmed to minimise the effects other traffic may have on detection of the VSL change. To this end – to avoid obstructing the view on the VSLs themselves – there were no trucks driving in the same direction as the participant. The other traffic driving in this direction was programmed to keep time headways closely to or above three seconds when driving near gantries by changing speed based on the participant’s speed. This was done to ensure changes in drivers’ speed could be attributed to the speed signs rather than to speeds of other traffic. When time headway exceeds 2.5 s, drivers refrain from car-following behaviour (Lewis-Evans, De Waard, & Brookhuis, 2010).

2.4. Measures

In this study, change detection is regarded as ‘the apprehension of change in the world around us’ (cf. Rensink, 2002). Underlying processes that may prevent this apprehension include the failures of not visually selecting and not sufficiently processing the change. These processes are described in detail by Martens (2007). Discerning between these failures was not part of this study. To detect whether participants noticed the speed limit change which occurred in drive 19, change detection was measured in six ways. The first and second measure were part of drive 19 itself. Similarly to Charlton & Starkey’s participants (2011), participants were instructed to report anything interesting, unusual, or hazardous during drives 1–19. It was pointed out that the objective was not to see how much could be reported, but merely to find out what people notice when they drive. When participants wanted to report anything, they had to flash their headlights and say out loud what they had seen. All verbal reports were logged. For drive 19, these reports were used to reveal detection of the speed limit change (measure 1). Driving speed was also monitored for drive 19 (measure 2). The third and fourth measures were part of an
embedded recollection task which participants performed in drive 20. For this, they drove the same route they had driven before, though this time all speed limits were deleted. When passing points where a speed limit sign used to be present, a computer voice asked participants what the speed limit had been in the previous drive. Answers were logged (measure 3). Additionally, before engaging in drive 20 participants were instructed to maintain the speed in accordance with the speed limit present in drive 19 during the whole drive. These speeds were monitored as well (measure 4). The fifth and sixth measure were part of the final questionnaire, which included the question about recollection concerning the speed limits (measure 5) and the recognition question which explicitly asked participants whether they had seen the change (measure 6).

As an indication of alertness, drivers’ responses to a separate and explicit detection task were measured. Participants were instructed to report any time they noticed a red Volvo truck. The truck appeared a random amount of times per drive and at irregular intervals in the opposing traffic stream during the first 19 drives. Once participants reached the motorway section equipped with gantries, the detection task ended so by drive 19 it would not interfere with change perception concerning the VSLs. To report the red Volvo truck, participants flashed their headlights and said ‘truck’. Participants were asked to react with the headlights, as responses using switches or handles of the car are considered a ‘more ecologically valid manipulan-

2.5. Data analysis method

When referring to the participants’ speed in this article it concerns only the speed measured at the 38 hectometre long gantry-equipped part of the motorway. As the data sampling rate of the driving simulator was set at 10 Hz, speed data per participant showed nearly all fluctuations in the pressure participants applied on the accelerator. To be able to compare speed between drives within subjects, speed samples have been aggregated to averages per hectometre. To compare the habituation process for change-aware drivers and change-unaware drivers, driver speeds have been aggregated to averages per drive for both groups.

3. Results

3.1. Detection of the changed speed limit

The six different measures which were used to detect whether participants noticed the speed limit had changed yielded different outcomes. Therefore, a combination of measures was used to designate participants as “change-aware drivers” or “change-unaware drivers”. Table 3 provides an overview of these results, which are described in more detail below. In this study, “change awareness” is defined by at least two measures indicating a participant has seen the change, including at least one measure representing a conscious awareness of the change (measure 1, 3, 5 or 6). Hence, ten participants (41.7%) are considered to be “change-aware drivers”. The other fourteen participants are referred to as “change-unaware drivers”.

The outcome of “having seen the change” is the result of apprehension of the change on at least one of the four electronic signs. As per sign there is a 0.5 chance of apprehension (50%), it is expected that at the end of the experiment 6.25% of the participants have failed to see what changed (as $(0.5)^4 = 0.0625$). Based on chance, the remaining 93.75% is expected to have seen the new speed limit. A binomial test compared this percentage with the actual results. It showed that only 41.7% of the participants being aware of the speed limit change by the end of the experiment, is significantly less than what may be expected, $p < 0.001$.

In drive 19, reports of the changed speed limit and adjusted driving speeds (measures 1 and 2, respectively) indicated that some change-aware drivers needed to pass more than one changed speed sign before noticing that the speed limit had changed. This was also reflected in recall concerning any peculiarities about the speed limits one had encountered (measure 5). Two third of the change-aware drivers proved to have some difficulties with the recollection task in drive 20 – in which dri-

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to the – non-existent – group for whom speed limits in drive 19 remained at 80 km/h, did so with an average confidence rate of 3.3 on a 5-point Likert scale (SD = 1.1).

Fig. 3 shows that in drive 19 on average change-aware drivers increased their speed according the prevailing speed limit (measure 2). As shown in Table 3, one change-unaware driver also adjusted her speed according to the changing speed limit. However, this might as well have been coincidental as none of the other measures supported detection of the change. In drive 20 (measure 4) change-aware drivers drove a similar speed as in drive 19 (measure 2). Though the speed difference is not exactly the same, the effect size reveals a strong association, \( t(38) = 2.68, p = 0.011, r = .830 \). Change-unaware drivers, on the contrary, drove significantly more slowly during drive 20, \( t(38) = 80.49, p < 0.001, r = .139 \). They maintained an average speed of 86.7 km/h (SD = 2.2) and continued driving at an average speed of 87.6 km/h (SD = .5) on the road section at which the speed limit had been increased, indicating that they recollected a speed limit of 80 km/h rather than 100 km/h (see Fig. 3).

3.2. Habituation: driver speed

All participants displayed clear signs of habituation; as they gained more experience with driving the route, their speed initially increased and stabilised after a certain number of drives, suggesting that participants have familiarised themselves with the route (see Fig. 4). There was a clear difference in driving speed for all drives between change-aware drivers (\( n = 10 \)) and change-unaware drivers (\( n = 14 \)); participants who were unaware of the changing speed limit in drive 19 drove significantly faster in drives 1–18, \( t(21.2) = -10.74, p < 0.001, d = 4.667 \). Age, driving licence possession, the number of kilometres

![Fig. 3. Average driving speed in drive 19 (speed limit change) and drive 20 (recollection task) near the point where the speed limit increases. Change-aware drivers increase their speed near the speed limit increase, in both drive 19 and drive 20. Change-unaware drivers on the contrary fail to increase their driving speed in drive 20 and remain driving at a continuous pace reflecting the speed limit they expect (which is 80 km/h).](image-url)
driven in the past twelve months prior to the experiment and the number of days necessary to finish the experiment did not differ significantly between change-aware and change-unaware drivers. Effects of gender could not be tested due to the small sample size of both groups.

3.3. Meaningfulness of speed limits

Change-aware and change-unaware drivers differed in rating and ranking of object meaningfulness. The ten change-aware drivers rated fixed speed limit signs ($M = 4.2, SD = 1.2$) and electronic speed limit signs ($M = 4.1, SD = 1.1$) as the most meaningful objects when driving a new route. Whereas the fourteen change-unaware drivers considered fixed speed limit signs ($M = 4.1, SD = 0.7$) and warning signs ($M = 4.1, SD = 0.9$) to be most meaningful. Electronic speed limit signs were ranked fifth with a 3.8 ($SD = 1.0$). However, the meaningfulness scores for both fixed as well as electronic speed limit signs did not differ significantly between change-aware and change-unaware drivers; $t(26.8) = .423$, ns, and $t(46) = 1.158$, ns, respectively.

3.4. Expectations

Four participants indicated that the standard traffic signs could change, although the signs had not changed. Nine participants had expected that the speed limits on the electronic signs on the overhead gantries could change. Five of them were change-aware drivers who noticed when the speed limits on these signs had actually changed; the other four participants did not.

3.5. Alertness: verbal reports and truck detection task

The amount of verbal reports about anything that caught participants’ attention decreased over the course of the experiment. The first drive resulted in a total of 150 reports of anything regarded as interesting, unusual, or hazardous. By drive 19 this was reduced to 72 reports (excluding reports on the changed speed limit). Most reports were comments on how other drivers behaved on the road (Participant 9, drive 7 “Blinking indicator, though not changing lanes”; Participant 27, drive 2 “Again someone driving in the left lane unnecessarily”). When reports on other road users were excluded, the amounts changed to 60 reports at the start of the experiment to 5 at the end. Participants reported objects such as landmarks, traffic signs and delineation, or they commented on the 80 km/h zone on the motorway (Participant 5, drive 4 “Unnecessary speed restriction of 80 km/h”; Participant 17, drive 4 “I really don’t understand why one has to drive 80 here”).

Contrary to the verbal reports, the amount of correct truck detections increased from 69% in the first drive to a detection rate of 98% at drive 19. The increase was fast, mainly occurring in the first four drives. By drive 5 the average detection rate was already at 95% and fluctuating between 93% and 99% for the remaining drives. The truck detection rate stabilises once participants appear to have accommodated to the task and familiarised themselves with the route and its surroundings, indicated by their driving speed. Once familiarised after extended practice, the detection of the irregularly appearing truck may be viewed as a measure for alertness. The high truck detection rate in drive 19 indicates that participants are still alert and aware of the task situation. Detection rates did not differ significantly for change-aware and change-unaware drivers (see Fig. 5). This was also the case for drive 19. It shows that although general alertness while driving is high, drivers may still be unaware of changes in variable speed limits.
4. Discussion

This study clearly shows that not all drivers are equally able to comply with VSLs on familiar roads, simply because they fail to notice when the speed limit changes. Even some participants who indicated to expect that the electronic signs could display various speed limits, failed to notice when the signs finally did. A positive meaningfulness level for speed limits did not result in correct detection either. Instead, the change-unaware drivers reported seeing what they expected to see, i.e. the 80 km/h limit which they had encountered before. As based on chance 6.25% of the drivers on a road failing to detect when speed limits change is expected, a percentage of 58.3 is unacceptable.

So, why is it that all participants quickly became proficient in the embedded truck detection task, whilst 58.3% of them failed to consciously notice the changed speed limit? A possible explanation is given by Charlton and Starkey (2013). They proposed a tandem model of skilled performance, discerning between a process of conscious, intentional task engagement (the operating process) and an unconscious monitoring process. For parts of the driving task, repeated experience allows drivers to switch from an attention-consuming mode of conscious processing of stimuli to a mode of unconscious monitoring. Similar to Martens and Fox (2007) and Charlton and Starkey (2013), an increase of participants’ driving speed was observed in our study, reflecting habituation of participants’ driver behaviour. In other words, their increased route-familiarity allowed participants to broaden and refine their cognitive templates of this route to a point that little or no involvement of the operating process was needed. On the one hand, this allowed participants to detect the trucks more effortlessly as the experiment continued. On the other hand, it made more than half of the participants blind to unexpected changes in traffic signs; either because they failed to visually select the sign or failed to process it sufficiently. Since transient motion signals were lacking when speed limits changed in our study, there was no environmental cue to increase attention to the level of the conscious operating mode. Instead, to detect the change cues concerning speed limits should be part of the monitoring process. Charlton and Starkey noted that not all changes went unnoticed for route-familiar drivers; for example, changes in delineation were detected well. Therefore they proposed to discern between aspects of the driving environment which are and those which are not necessary for moment-to-moment vehicle control. Still, in this light, speed limits may well be considered necessary input for the continuous task of speed control, though perhaps not for all drivers.

For all but the 20th drive in our study, it should be noted that in general, participants who failed to notice the speed limit change drove considerably faster than those who were change-aware. Demographic differences did not explain this finding and neither did the level of alertness. A possible explanation is that the change-unaware drivers were less interested in looking at the variable speed limits. This hypothesis is only partly corroborated by the meaningfulness scores for variable speed limits as on average change-unaware drivers still score their meaningfulness on the positive half of the Likert scale. That change-unaware drivers did not disregard variable speed limits completely is also reflected in the fact that during drive 20 (recollection drive) they proved to be perfectly able to reproduce the speed limit of 80 km/h, which had been on display in drives 1–18. Therefore it appears as if change-unaware drivers are interested in variable speed limits, though less so on a subconscious level. In terms of Charlton and Starkey’s tandem model (2013): perhaps drivers who are more inclined to comply with the current speed limit – even in a driving simulator environment – are more likely to unconsciously consider speed limits necessary for their moment-to-moment vehicle control.

Regardless of the underlying processes involved, the outcome of continuously offering the same speed limit is that it habituated drivers so solidly to the “regular” speed limit, that most of them missed the apparently not so obvious change. At some point, this may put many familiar-route drivers in a position of a serious traffic offence. In our study, the speed limit was increased from 80 to 100 km/h. In actual traffic, the consequences of missing this might still be small. Missing a change in speed limit could...
from 100 to 80 km/h, however, will immediately turn drivers into serious speed offenders, speeding with 20 km/h though not deliberately at all.

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