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Pedestrian crossing situations: Quantification of comfort boundaries to guide intervention timing

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ABSTRACT

Introduction: Technical systems that warn or brake for vehicle–pedestrian encounters reduce injuries more effectively the earlier an intervention is initiated. However, premature intervention can irritate drivers, leading to system deactivation and, consequently, no injury reduction whatsoever. It has been proposed that no intervention should be initiated as long as attentive drivers are within their comfort zones. This study aims at quantifying driver comfort boundaries for pedestrian crossing situations to offer guidance for the appropriate timing of interventions.
Methods: Sixty two volunteers drove through an intersection on a test track at 30 and 50 km/h. A pedestrian dummy was launched from behind an obstruction towards the driving path of the approaching car. Brake onset indicated discomfort. Time to collision (TTC), longitudinal and lateral distance were measured at brake onset.
Results: TTC was independent of driving speed ranging from 2.1 to 4.3 s with a median of 3.2 s. Longitudinal distance ranged from 19 to 48 meters with an apparent difference between driving speeds. Lateral distances differed slightly, but significantly between driving speeds. The median was 3.1 m (3.2 m for 30 km/h and 2.9 m for 50 km/h) and values ranged from 1.9 to 4.1 m. Lateral distance in seconds ranged from 1.9 to 4.3 s with a median value of 3.1 s (3.2 s for 30 km/h and 3.0 s for 50 km/h).
Discussion: TTC was independent of driving speed, trial order and volunteer age. It might be considered suitable to intervene in situations where, for example, 90% of drivers have exceeded their comfort boundary, i.e. when drivers have already initiated braking. This percentile value translates to intervention at a TTC of 2.5 s (95% confidence 2.4–2.7 s). The study was limited to Swedish nationals, fully aware drivers, and two driving speeds, but did not investigate behavioural changes due to system interaction.
Conclusion: This study showed that TTC at brake onset was a suitable measure for the quantification of driver comfort boundaries in pedestrian crossing situations. All drivers applied their brakes prior to 2.1 s TTC.

1. Introduction

Vehicles are becoming increasingly well-equipped with technical systems to detect pedestrians and predict the likelihood of a collision. They warn the driver for dangerous situations, and the vehicle's brakes can be applied automatically. These systems offer a considerable potential for pedestrian injury reduction (Coelingh et al., 2010; Grover et al., 2008; Jermakian and Zuby, 2011; Lindman et al., 2010; Robinson et al., 2011; Rosén et al., 2010; Rosén, 2013).

Intervention timing, either in the form of warnings or automatic braking, requires modulation. The later the intervention, the less time for speed reduction or other evasive manoeuvres. The earlier the intervention, the greater the chance the situation deemed critical will not evolve to a collision. The driver or pedestrian may resolve the situation without the need of an intervention. In a strict sense, these interventions are false positives. Early intervention might be experienced as a nuisance to drivers, and thus lead to switching off a technical system or ignoring it altogether. Late interventions will leave potential for injury reduction unused as shown by Lee et al. (2002). Hence, system designers need to

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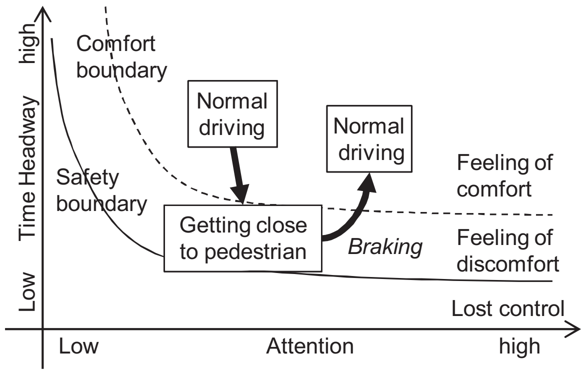

Fig. 1. Comfort boundaries (adopted from Ljung Aust and Engström, 2011).

find a balance between system effectiveness and false positive interventions. There are various approaches to this problem (Brännström, 2012; Seiniger et al., 2013; Tiemann et al., 2010). For warning systems, Källhammer (2011) argued that, since collisions are rare, a certain amount of relevant false positives are needed for drivers to learn how to react to a warning. Irrelevant false positives, that cannot be related to a critical situation, for example originating from sensor noise, are likely to always be a nuisance and are best to be avoided using accurate technical systems. Learning will be enabled by false positive interventions that can clearly be related to a situation deemed critical by the driver. However, for automatic braking no such learning is needed. Nevertheless, automatic braking interventions may still be appreciated in critical situations by the driver. Hence, by allowing some false positive interventions, both system effectiveness and driver appreciation of the technical system may be increased compared to a system intervening at a later stage.

Furthermore, Källhammer et al. (2007) found that alerts issued for pedestrians are more welcome than alerts to other traffic encounters. This finding indicates that an intervention for pedestrian encounters could occur earlier than for other traffic situations.

Ljung Aust and Engström (2011) suggested a framework for active safety evaluation by describing driver comfort boundaries (Fig. 1). These boundaries describe thresholds above which drivers feel comfortable and are engaged in normal driving activity, and below which drivers have a sense of discomfort, that is, they will take action to leave the situation perceived as risky to return to normal driving (Summala, 2007). These risky situations might not only be related to predicted stopping distances and potential collisions but also to the drivers' intention to achieve a smooth ride, to comply with traffic rules and manners and other driving objectives.

Consequentially, active safety interventions should not occur as long as attentive drivers are in their comfort zone, as the driver perceives any intervention as unnecessary (see, e.g., Ljung-Aust and Dombrovskis, 2013). Once comfort boundaries are passed by inattentive drivers, an intervention might be appreciated for return to the comfort zone, as they would have felt discomfort had they been attentive to the threat. A quantification of comfort boundaries can guide a distinction between false positive interventions appreciated by drivers, and unacceptable false positives. This, in turn can guide the development and assessment of technical systems. Intervention timing for a system that warns the driver for pedestrians or applies the brakes automatically may be deduced from driver comfort boundaries.

This study aimed at an objective quantification of comfort boundaries defined by brake onset. The influence of driving speed on TTC, longitudinal and lateral distance measured at brake onset was analysed to determine an appropriate metric and to quantify it. This can give important cues to desired system intervention timing for development and assessment.

2. Method

Comfort boundaries were quantified measuring brake onset of 62 volunteers on a test track. Volunteers were on average 42 years old (range: 20–61), had been in possession of a driver's licence for an average of 23 years (range: 3–41), and drove an annual average mileage of 18,000 km (range: 500–100,000). Females accounted for 42% of participants.

Volunteers drove through an intersection. They were in control of longitudinal and lateral dynamics, i.e. were instructed to use the accelerator to maintain a specific speed. The oncoming lane was blocked by a stationary balloon car to prevent steering reactions (Fig. 2). No particular instructions were given for steering.

Tests were conducted twice per volunteer, once at the 50 km/h instructed driving speed (measured actual average 1 s before brake initiation: 47 km/h) and once at the 30 km/h instructed driving speed (measured actual average 1 s before brake initiation: 30 km/h) in random order. The purpose of the study was not revealed to participants.

Driving speeds were chosen based on the test set-up as an urban intersection. These intersections usually have a speed limit of 30 or 50 km/h, thus these speeds felt natural to volunteers. Pedestrian starting position and speed were determined to provide early visibility of the dummy at TTC 4.0 s. As building walls could not be moved, this was achieved by adjusting the pedestrian speed to 1 m/s, which is somewhat below average walking speed.

Tests were conducted at Carson City, an outdoor facility for active safety testing at Autoliv Sweden (Rosén et al., 2012). The layout of Carson City is based on a real intersection and includes side-scenes resembling real buildings. All tests occurred in daylight on dry asphalt. Drivers were instructed as follows:

"Your task is to drive through the intersection at 30/50 km/h. A realistic traffic situation will be reproduced and we want you to react to any events as you would normally. The car you are driving is an ordinary car with no additional equipment. There are pedestrian dummies and balloon-cars in the test area so try to regard them as normal pedestrians and cars. We would like you to reach the correct speed when passing the two orange cones".

While volunteers were driving towards the intersection, a pedestrian dummy was launched from behind an obstruction towards the path of the car. Dummy motion was triggered when a reflector (mounted on the car, 1.5 m from the bumper) reached a photo-cell at 64 or 39 m from the pedestrian crossing at 50 or 30 km/h. This occurred at a time to collision (TTC) equal to 4.5 s if the car maintained the correct speed. In this paper, TTC is indicated for an unbraked car, i.e., defined as the distance between car and predicted collision point divided by the car's speed. Other definitions exist in which, e.g., car acceleration is taken into account. Approximately 150 ms later, the dummy was accelerated by 2 m/s^2 until it reached 1 m/s. It was judged that the dummy was visible to the driver after having moved 0.2 m. As seen from the sketch in Fig. 2, the dummy's center of gravity was then still 0.1 m behind the building walls. However, one leg was clearly visible, and because the dummy was propelled by a gantry with visible wires, the dummy was judged visible at this point (Fig. 3). This occurred at TTC = 3.9 s if the car was driven at the correct speed. Measured actual TTC at dummy visibility ranged from 3.0 to 5.0 s with a median of 4.0 and 4.2 s for 30 and 50 km/h, respectively, i.e., actual driving speeds were a bit too low. If neither the dummy nor the car would have stopped and the car was driven at the correct speed in the center of the lane, the collision point would have been at the center of the car front end. However, the dummy only walked a total distance of 3.5 m (in less than 4.5 s) and then stopped 0.6 m before the centerline. Dummy acceleration at startup was 2 m/s^2 and speed was 1 m/s. The car had therefore not reached the virtual collision point when the dummy stopped. The driver was expected to have