A basis for driver state estimation

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In order to design systems, aiming at assisting the driver in his manoeuvering task, there is a need to understand the interaction between driver and vehicle. The most simple model for analysis of lateral closed loop behaviour is the path tracking control model, depending on preview length, feed-back steering gain and driver delay time. This paper examines the dependency of the first two parameters on vehicle properties, selected path, vehicle speed and driver characteristics. It is shown that driver and path characteristics play a minor role in the selection of preview length and steering gain. In addition, gain and preview length cannot be chosen independently. Within certain boundaries, a driver can follow a path with almost the same minimum path error with different preview lengths, as long as the gain is adapted according to an optimal relationship between these two parameters, which depends on vehicle properties and speed. It means that gain and preview length may well vary along a certain path, and this has been examined, experimentally, for a double lane change, for different drivers. We observe a distinct difference between an inexperienced and an experienced driver. The lower boundary of the acceptable preview length is mainly related to the closed-loop stability, and an explicit expression is presented, describing the sensitivity of the closed loop stability boundary in terms of vehicle parameters, vehicle speed and driver delay time. For the upper boundary, the path and vehicle properties are the most dominating factors.

Topics / Vehicle Dynamics, state estimation and system identification, driver behaviour and driver model, driver-vehicle system

1. INTRODUCTION

In recent years, the interest in active safety measures in vehicles has strongly increased. Such active safety measures, indicated as driver support systems, serve to prevent the driver to enter potentially dangerous conditions or to have an accident. In case of safety critical driver support systems, the driver plays a critical role in the sense that he (or she) should not misinterpret this driver support, or accept higher risk because of the availability of the support systems. Different drivers may respond in different way, and driver characteristics may change in time (drowsiness, learning effect,…).

It means that the driver’s ability to accept, understand and react appropriately to support systems should be accounted for in the design of such systems.

This suggests that present driver states should be an input to support systems, to allow these systems to effectively adapt to the specific driver, vehicle and surrounding traffic conditions. Such driver states could be workload or performance related, based on steering information, physiological information, or head position and eye motion, see also [7], [8], [9]. Another approach is to exploit driver models and to identify the model parameters on-line. Model parameters could be gains, preview length or delay time. A change in these model parameters implies that the driver model and therefore the driver has changed his driving characteristics in response to road layout or traffic conditions, and the support may be adjusted in order to be more effective.

This paper is restricted to driver models describing the driver lateral control behaviour, in general also referred to as tracking control models. A basic and one of the best known models of driver closed loop performance was first given by McRuer et. al, see for example [5] and [6]. The driver is assumed to observe deviations from the intended manoeuvring conditions at some distance ahead of the vehicle (the preview length L), and to correct proportionally in steering (with a certain gain K) after some delay. Kuriyagawa and Kageyama [4] have used these driver parameters to estimate the (elderly) driver state in relationship to potentially safety critical conditions.

We will demonstrate that K and L are related, with the (K, L)-values satisfying an almost hyperbolic relationship. Hence, different (K, L) combinations may lead to almost the same path error, and (K, L) values may therefore vary along the path without affecting the tracking performance. Several authors have examined varying driver parameters along a path, such as Salvucci and Gray [10] with distinction between a 'near preview point' and a 'far preview point'. We also refer to Edelmann et. al. [2] where a feed forward part in driver response is combined with a McRuer based compensatory part, being activated by changes in path curvature.

The paper is organized as follows. The next section will address experimental assessment of the driver preview length and steering gain, which motivated further research on the identification of the driver state. In section 3, we will present more theoretical considerations on the optimal relationship between these model parameters. The lower and upper boundaries of this relationship are treated in section 4 for varying vehicle properties and vehicle speed. Experimental results on (K, L) variation along the optimal (K, L) relationship during non-extreme lane change path tracking are discussed in section 5. Conclusions are drawn in section 6.

2. PATH TRACKING

We refer to figure 1 for a layout of a vehicle, tracking a path. At time t, the vehicle has a lateral deviation y(t) in local y-direction, and a yaw angle ψ. The preview length L is measured from the vehicle centre of gravity. The orientation of the intended position along the path at L meter ahead of the vehicle with respect to the path location at time t is denoted by yaw angle Ψ_p as indicated in figure 1. This angle depends on the vehicle position as well as on the preview length L.

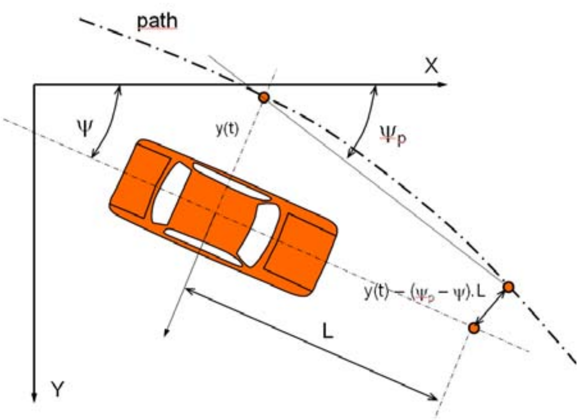

Figure 1.: Path tracking

Assuming the driver to respond with a lag time τ, the vehicle steering angle will satisfy the following first order differential equation:

$$\tau.\dot{\delta}(t) + \delta = K.\big(L.[\psi_p(t;L) - \psi(t)] - y(t)\big) \qquad (1)$$

with gain K.

Students from the HAN Master in Automotive Systems have carried out experiments, with the intention of identifying L and K during a double lane change, for varying vehicle speed (30, 50, 70 km/h) and the cruise control being switched on and off. For some tests, the heart rate has been varied by pre-test physical exercises, and the view distance has been limited to 10, 15, 20 m.

The delay time was set at a fixed value, and preview length L as well as driver gain K were determined from the test results. Path deviation was determined by matching the test results for position with closed loop simulation results such that the path error:

$$J_p = \left(\frac{1}{T_2 - T_1} . \int_{T_1}^{T_2} [Y_{test} - Y_{simulation}]^2 \, dt \right)^{\frac{1}{2}} \qquad (2)$$

was minimal for some combination of K and L.

This path error is depicted in figure 2 as a function of K and L, with the area in the middle of the figure corresponding to small error. We have als shown the (K, L) – values for minimum J_p as derived for several specific tests. The (K, L) values appear to satisfy an almost hyperbolic relationship, meaning that smaller

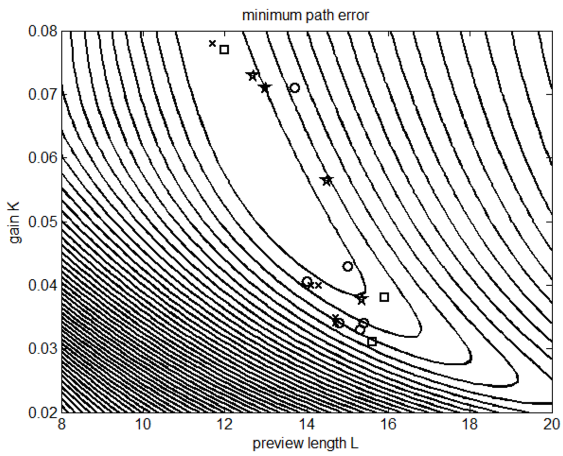

Figure 2.: Contour plot of the function J_p (K, L)

preview lengths correspond to larger gains. Clearly, the criterion of minimal J_p is not very discriminating. It means, in this specific case, that a similar path error can be obtained for (K, L) = (0.03, 17) as for (K, L) = (0.07, 12). Increasing the preview length beyond 18 m along this hyperbolic curve will increase the path error, but at a much smaller rate compared to variation of (K, L) away from this curve.

This raises some questions. When describing driver behaviour, do we need to select a fixed set of gain and preview length for a certain manoeuvre, or should we take the K-L characteristics as a starting point? And if we follow this last approach, what does this K-L relationship depend on? What happens if we vary the path, the speed, the vehicle parameters? And how does the driver 'move' along the K-L curve in response to driving conditions, and why?

3. THEORETICAL CONSIDERATIONS.

We have examined the hyperbolic curve of optimal (K-L) values for both steady state conditions and transient conditions. We assume that the vehicle can be described by a linear one-track model. Figure 3 shows a vehicle following a circular path (steady state conditions).

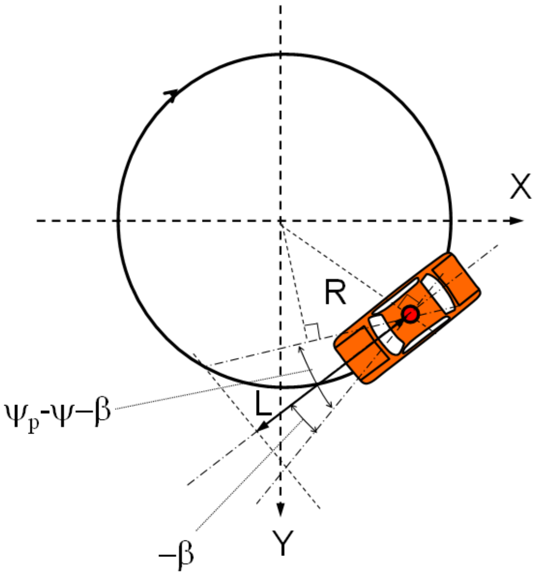

Figure 3.: Vehicle following a circular path

The body slip angle can be derived from the vehicle front axle steering angle δ as follows (see for example [3]):

$$\frac{\beta}{\delta} = \frac{b - B.V^2}{l.(1 + K_s.V^2)} \qquad (3)$$

with vehicle speed V, wheel base l, and (stability factor K_s , understeer gradient η):

$$K_s = -\frac{m.(a.C_1 - b.C_2)}{l^2.C_1.C_2} = \frac{\eta}{g.l}; \quad B = \frac{a.m}{l.C_2} \qquad (4)$$

with front and rear axle cornering stiffnesses C_1 and C_2, vehicle mass m, distances a and b from centre of gravity to front and rear axle, and acceleration of gravity g. The steering angle for a steady state circular path with radius R and vehicle speed V is known [3] to be expressed by:

$$\delta = \frac{l}{R} + \eta.\frac{V^2}{g.R} \qquad (5)$$

According to figure 3 the following expression is correct up to first order in $\Psi - \Psi_p$ (difference in yaw angles):

$$\psi_p - \psi = \arcsin(\frac{L}{2R}) + \beta \qquad (6)$$

Substitute (5) and (6) in (1) neglecting the first derivative of δ. Accounting for the expression for β, and assuming the preview length L to be much smaller than the curve radius R, one arrives at the following relationship between K and L:

$$LK.\left[A_1 + \frac{L}{2}\right] = A_2 \qquad (7)$$

with

$$A_1 = A_2.\frac{b - B.V^2}{l.(1 + K_s.V^2)} \quad ; \quad A_2 = l + \eta.\frac{V^2}{g} \qquad (8)$$

Note that A_1 and A_2 only depend on speed and vehicle parameters. Consequently, in order to follow the circular path in an ideal way (no path error), gain K and preview length L satisfy a hyperbolic-type of relationship as indicated in (7).

A larger preview length for a given steering angle (which is determined by circular path) will increase the path deviation and therefore reduce the required gain K. Increasing the speed V beyond a certain value will increase the body slip angle in absolute sense, and therefore reduce the path deviation, suggesting a larger gain. But the steering angle will increase as well (for an understeered vehicle), resulting also in a larger gain. The dependency on the vehicle parameters is related to both the body slip angle gain, being directly depending on the front and rear axle stiffnesses and vehicle CoG position. The relationship (7) is shown in figure 4 for three different speeds. Figure 5 shows the gain vs preview length for reduced axle slip stiffness, front or rear.

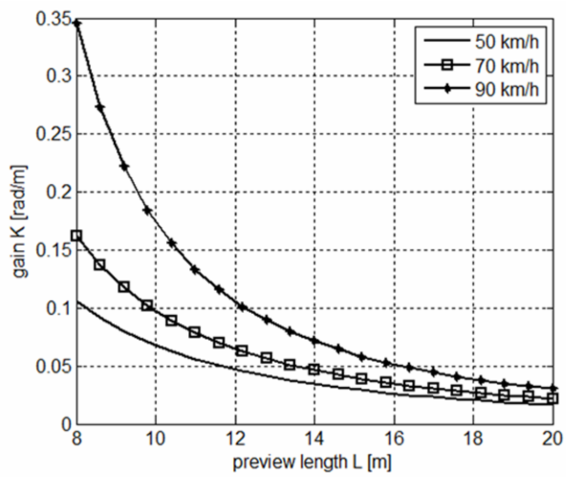

Figure 4.: Gain vs. preview length for various vehicle velocities

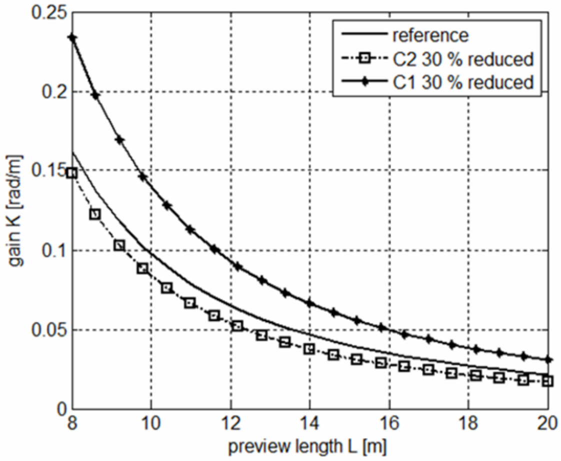

Figure 5.: Optimal (K, L) values for different axle slip stiffnesses

So far, we have assumed linear vehicle behaviour under steady state conditions. With nonlinear axle characteristics, the K-L relationship will change as well. Extreme driving, close to saturation of the tyres, may result in increased understeer or even oversteer. In the first case, the K-L curve will move up and in the second case, the K-L curve will move down. In this paper, we will restrict ourselves to linear axle behaviour.

Dynamic behaviour can be analysed by assuming a periodic steering input in time:

$$\delta = A.\sin(2.\pi.f.t) \qquad (9)$$

with the vehicle, in average, driving in X-direction. This steering input leads to a path, which is then used as the desired path in a closed loop analysis. The frequency f is varied between 0.05 Hz and 0.25 Hz with amplitude A chosen such that the oscillatory path has an amplitude of 2 m. The lateral acceleration increases with the frequency up to a level of 0.5 g for 0.25 Hz, see also table 1.

Frequency [Hz]	Amplitude [rad]	Latac [g]	Wavelength [m]
0.05	0.0035	0.020	277.8
0.1	0.0139	0.080	138.9
0.15	0.0312	0.181	92.6
0.2	0.0555	0.322	69.4
0.25	0.0867	0.503	55.6

Table 1.: Description of periodic steering input cases (50 km/h)

The gain value K for minimum path error for a given preview length is shown in figure 6 for different frequencies, and therefore for different paths. Clearly, the variation in path wavelength has a limited effect on the optimal K-L curve. Comparing figure 6 with figure 4 for 50 km/h also shows that the steady state curve (described by (7)) is a very good estimate for the optimal K-L characteristics for oscillatory input. This conclusion was verified for other vehicle speeds as well.

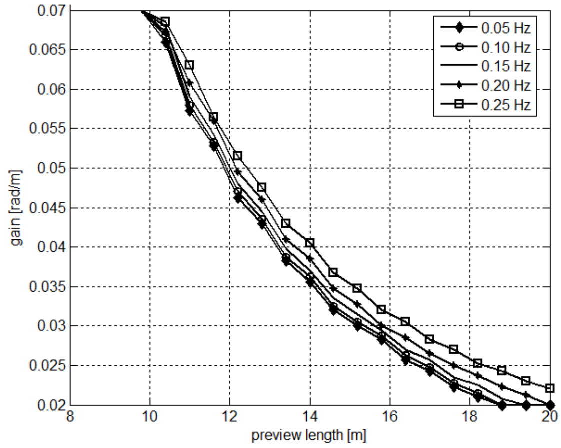

Figure 6.: Optimal preview length vs. driver gain for various path wave lengths, cf. table 1

Remark:
As an alternative to minimum path error, one might also use the minimum steering error, i.e. the difference between (9) and the solution of (1) for ideal path tracking. It turns out that the two approaches lead to optimal gain values (along the optimal K-L curve) with less that 2.5 % difference. Consequently, both approaches lead to similar results.

4. CLOSED LOOP STABILITY.

Varying (K, L) over the curve shown in figure 4 leads to problems for small L and for large L. For large L, the path error increases along this curve, as indicated in figure 2. For small L, the closed loop stability is lost. The closed loop problem is at least a fifth order problem with vehicle states being the yaw rate, body slip angle, yaw angle, steering angle and lateral vehicle position, see for example [3]. We have determined stability areas in terms of K and L, with the resulting areas shown in figure 7 for two different speeds and certain vehicle parameters. For the same parameters and speeds, we have depicted the optimal K-L curves.

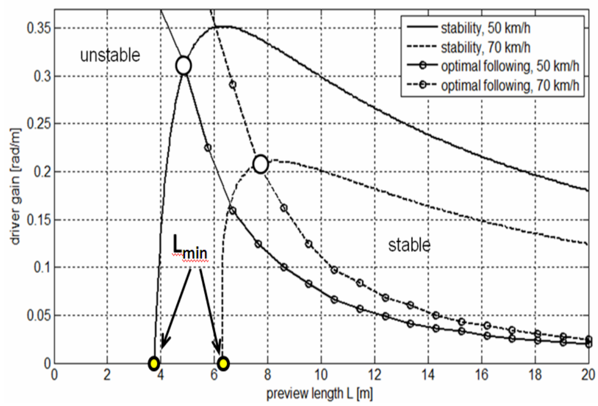

Figure 7.: Stability areas and optimal path following characteristics in terms of driver gain K and preview length L, for different speeds.

Please observe that the stability area is reduced for increased speed, whereas the optimal K-L curve is moving up for increasing speed.

Abe [1] has examined this closed loop stability under the simplifying conditions of equal axle cornering stiffnesses and a centre of gravity with equal distances to both axles. Furthermore, the body slip angle is neglected. This analysis resulted in stability areas in the K-L plane of the typical shape as shown in figure 7. Instability occurs for small preview length as well as for large driver gain, with the maximum driver gain, for stable closed loop behaviour, decreasing with increasing preview length. The boundary of these areas intersects the K-L curve of optimal path following as derived in the preceding section. Moreover, for increasing speed, stability is reduced to smaller gains whereas the optimal K-L curve is shifting to large gains. Hence, there is a conflict between stability and performance (optimal path following), as indicated in figure 7.

For arbitrary vehicle properties and no simplifications, we have found (for a one-track vehicle model) that the preview length L_{min} for zero gain (indicated in figure 7) can be written in terms of vehicle properties and driver delay time t in the following way:

$$L_{\min} = -b + V.\tau.\left[1 - \frac{1}{\tau.\omega_n^2}.\left(\frac{Y_\beta}{m.V} + \frac{N_r}{J}\right)\right] \qquad (10)$$

with the vehicle undamped radial natural frequency ω_n, the so-called derivatives of stability Y_β and N_r, speed V, mass m, yaw inertia J, and distance b from rear axle to CoG.. Based on (10), the stability boundary depends strongly on vehicle properties, speed and driver delay time.

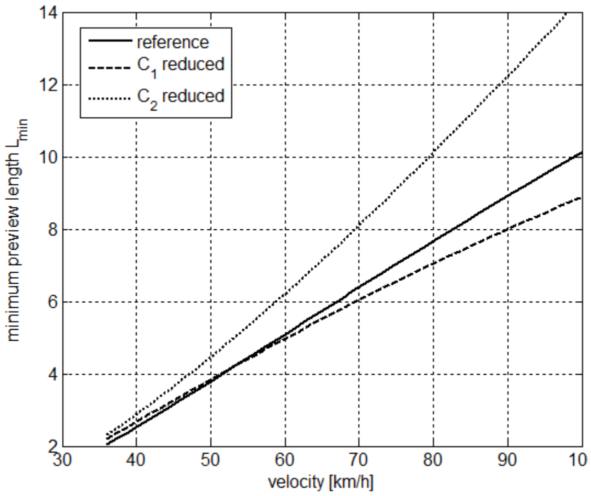

Figure 8: Minimum preview length L_{min} vs. speed V

We have determined the relationship between L_{min} and speed V for fixed t and with one of the axle slip stiffnesses (C_1, C_2 for the front and rear axle, respectively) reduced by 25 %, see figure 8. As expected, the closed loop stability is reduced for smaller rear axle slip stiffness (large L_{min}) with the opposite effect for the front axle slip stiffness for larger speeds (beyond 60 km/h).

We have studied closed loop performance for the oscillatory steering input (9), with preview length now step by step increased, and with the gain again based on minimum path error. These simulations show that the path error in terms of the cost function (2) will start to rise significantly beyond some preview length. Some results are shown in table 2, also giving the minimum preview length value where the stability boundary is reached.

V [km/h]	Freq. [Hz]	Delay [s]	Path derived from	min L [m]	max L [m]
50	0.2	0.2	50 km/h	4.9	15.3
50	0.05	0.2	50 km/h	4.9	> 30
70	0.2	0.2	70 km/h	7.7	21.8
70	0.2	0.1	70 km/h	7.7	18.6
70	0.2	0.2	50 km/h	7.7	16.5

Table 2.: Possible range of acceptable L-values

This shows:

- larger frequency (i.e. different path) and smaller delay time limit the acceptable upper L-boundary but not the lower boundary.
- Speed has a strong effect on the acceptable L-values

5. VARYING DRIVER PARAMETERS

Based on the preceding discussions, it is clear that the driver parameters K and L may vary during one manoeuver, as long as the (K, L) values vary along the optimal K-L curve, within boundaries, based on closed loop stability (lower boundary) and path deviation (upper boundary). Close examination of the available test results confirm that, and it is of interest to examine this behaviour.

A typical test result is shown in figure 9. The dotted lines at the bottom and left indicate the lane change path. Figure 9 shows the preview location (solid line) and preview length vs. the vehicle position in the longitudinal direction. The driver is inexperienced. The preview length varies between 9 and 20 meter. Observe that the preview length is increasing before the preview location (vehicle position + L) reaches the first curvature change in the lane change. Approaching the second lane change (return to original lane) leads to a decrease of L but only for a small period. Again, L is already increasing again when the preview location is still more than 10 m away of the point where the path starts to move back. For an experienced driver, this distance is consistently much smaller than this 10 meter.

This is just one of the many results, and one should be careful to generalize it. On the other hand, this behaviour asks for a driver model, allowing varying control parameters, but with limitations of the acceptable preview length. Similar phenomena have been treated by Salvucci and Gray in [10].

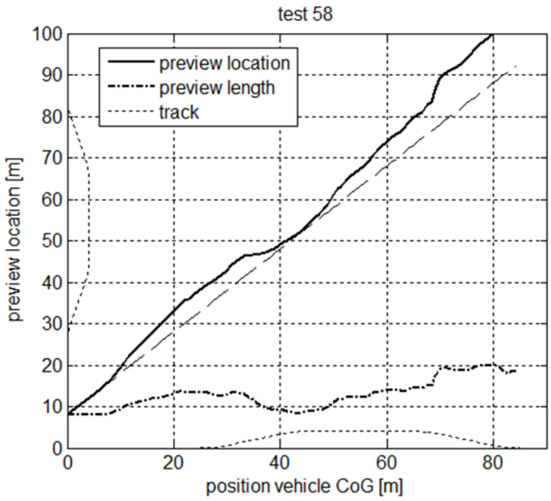

Figure 9.: Vehicle lane change behaviour

How should one interpret this phenomenon? Is the driver responding to the curvature of the road or only to the change in curvature. And is he or she responding by increasing the steering gain (and therefore a smaller preview length) or by decreasing the preview length (and therefore increasing the steering gain)? What is the mechanism?

6. Conclusions

This paper deals with driver state estimation through identification of driver model parameters.The research has resulted in the following conclusions:

1. Driver steering gain and preview length cannot be chosen independently, but they are related in a way which can best be described as hyperbolic.
2. In order to keep the path error low, the range of acceptable preview lengths is bounded. Too small values lead to instability, whereas too large values lead to unacceptable path error.
3. The optimal driver control parameters K (gain) and L (preview length) depend primarily on vehicle properties and speed. The path contributes to the maximum boundary for L, whereas the driver delay time has an effect on both boundaries. Other driver characteristics may play a (minor) role in accepting these upper and lower limits. Consequently, if we assume that driver delay time does not vary much over different drivers, then the driver itself has a limited impact on the gain and the preview length
4. Instead of a fixed set of driver model parameters for a specific closed loop situation, driver model parameters vary in time, which seems to be related to the anticipated future (change of) manoeuvring effort.

The available test results and the approach of accepting varying preview length for pairs of optimal (K, L) values, will be used to derive a driver model. A better understanding of driver performance for different road situations will improve our understanding of closed loop vehicle behaviour, and therefore contribute to more effective driver assistance to avoid conflicting situations.

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