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A STEERING WHEEL REVERSAL RATE METRIC FOR ASSESSING EFFECTS OF VISUAL AND COGNITIVE SECONDARY TASK LOAD

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Abstract

This paper presents a steering wheel reversal rate metric intended for assessment of the effects of secondary tasks, such as interacting with in-vehicle information systems, on vehicle lateral control performance. The metric was compared to a number of other common steering wheel metrics with respect to the sensitivity to visual and cognitive secondary task load. It was shown that the proposed reversal rate metric, together with the existing steering entropy metric, was the most sensitive across experimental conditions. Different parameter settings for the metric were systematically investigated and suitable values for capturing the effects of visual and cognitive secondary task load recommended.

Introduction

Performing secondary tasks such as talking to a passenger or operating in-vehicle functions while driving potentially affects driving performance in different ways, e.g. in terms of reduced vehicle control, reduced event detection ability and generally reduced situation awareness (see [15] for a general review of known effects of different types of systems and functions). It is clear that many of these effects may be detrimental to road safety and there is today a growing interest in the development of methods and metrics for quantifying them, with the ultimate goal of a generic methodology for safety evaluation of ITS applications, in particular in-vehicle information systems (IVIS) (e.g. [6] and [16]). A wide variety of methods and metrics can be found in the literature, including the measurement of longitudinal and lateral control performance, reaction time to external events, visual allocation and general situation awareness (see [9] for a review).

Lateral control performance metrics is one of the most common types of metrics used in IVIS evaluation studies [9, 15]. Lateral control performance can be quantified directly based on measurement of the lane position (e.g. in terms of the lane position standard deviation, mean time-to-line-crossing or the number of lane exceedences), or indirectly based on the control input, i.e. the steering wheel movements. While lane position metrics have strong face validity as driving performance indicators, they are somewhat difficult to measure in field and require relatively expensive equipment (e.g. video-based lane tracking systems). Moreover, the lane position data may include voluntary lane changes (i.e. resulting from overtaking and cutting curves) which have to be removed before computing the performance metrics (due to discontinuities in the data). Thus, steering wheel metrics are interesting as a complement/alternative to lane position metrics for quantifying lateral control performance. Steering wheel metrics have the main advantage that the steering wheel angle signal is easy to measure, both in the field and in simulators using low-cost sensors. The main disadvantage is that steering patterns are somewhat more difficult to interpret than lane position metrics and, as further described below, increased steering activity may be indicative of both increased and reduced lane position variance [5]. Thus, a key requirement on steering wheel metrics to be used for IVIS evaluation is that they have a straightforward interpretation in terms of driving performance improvement/decrement.

A wide variety of steering wheel metrics have been proposed in the literature for assessing effects of secondary task on driving, from standard deviation of steering wheel angle [7, 10], to more advanced metrics such as reversal rate [11, 16], high frequency component of steering wheel angle [16] and steering entropy (e.g.[1, 2, 12]). These metrics all represent different aspects of increased steering activity, e.g. magnitude, increased frequency and/or reduced predictability, but are often commonly interpreted as an index of driving performance and/or secondary task workload. However, increased steering wheel activity does not necessarily lead to a degraded lateral control performance. Several studies have found that purely cognitive secondary tasks (i.e. tasks requiring no visual interaction, such as mobile phone conversation) lead to *increased* lateral control, in terms of reduced lateral position variation [3, 5, 8, 16]. In particular, the results from a large number of parallel studies in the HASTE EU-funded project [5, 8, 16] indicate a pattern of increased steering wheel activity and reduced lane position variance for cognitive tasks, while visual tasks generally led to increased steering wheel activity and increased lane position variation. Thus, increased steering wheel activity may be associated with both increased- (cognitive load) and reduced (visual load) lateral control performance. (It should, however, be stressed that cognitive secondary tasks have a number of other safety-degrading effects, in particular related to reduced detection and situation assessment ability – see [15] for numerous examples). Thus, care needs to be taken when interpreting steering wheel metrics. In the context of IVIS safety assessment it would be desirable to have metrics able to distinguish between the different effects of visual and cognitive load. (It could be noted that in other contexts, such as when using vehicle control metrics online in a vehicle for real-time detection of degraded driving performance as a part of an advanced driver assistance system, a differentiated sensitivity may not be needed, since the exact cause of an observed performance degradation may not be relevant.)

The present paper focuses specifically on the development of a steering wheel reversal rate (SRR) metric for quantifying effects of secondary task activity on driving, with the focus on its application to IVIS evaluation. While SRR metrics are not new (see e.g. [11]), precise definitions are generally lacking in the literature. The objective of the present paper is to provide a detailed specification of a reversal rate metric, and to compare it to existing steering wheel metrics with respect to the sensitivity to visual and cognitive secondary task load, and the ability to differentiate between different types of effects. The work reported here was performed as part of the development towards a generic HMI evaluation methodology within Sub-project 2 of the AIDE (Adaptive Integrated Driver-vehicle InterfacE) project, and based on re-analysis of data collected in the HASTE project. For a more detailed description of the present work and other related AIDE work on driving performance metrics, see [17]. For an overview of the general AIDE project, see [6].

The paper is structured as follows: The next section briefly describes the data used for the present analysis, followed by a brief qualitative analysis of steering wheel patterns resulting from secondary task load. Next, the proposed steering wheel reversal rate metric is defined and a quantitative comparison to existing steering wheel metrics is presented. Different parameter combinations for the reversal rate metric are then analysed and, finally, some general conclusions are given.

Data

The data used in the present analysis were originally collected in the HASTE EU-funded project [16]. The work in HASTE (Work Package 2) comprised 10 parallel experiments conducted at 8 different sites across Europe and Canada during 2003-2004. The main purpose of these experiments was to investigate systematically the effects of visual and cognitive secondary task load on driver behaviour and performance. All experiments had the same general design and differed mainly in terms of the test setting, which included desktop simulators, medium-to-high fidelity simulators as well as field trials. Visual and cognitive secondary task load was varied systematically by means of two so-called surrogate (S-) IVIS, one visual and one auditory/cognitive. The visual S-IVIS, known as the Arrows Task, required the driver to judge the presence or non-presence of an arrow with upward direction in a displayed matrix of arrows. If the arrow was present, the subject was instructed to press yes on a touch display and no otherwise. The difficulty of the task was varied by changing the orientation and number of the non-target arrows. Each task consisted of 6 arrows displays, presented every 5s. The cognitive task, called the Auditory Continuous Memory Task (aCMT), involved the presentation of fifteen sounds at a rate of 2 seconds. The task was to keep track of certain target sounds identified before the trial. The difficulty was varied by changing the number of target sounds. The task lasted about 30-40 seconds. For both the Arrows Task and the aCMT task there were three difficulty levels. See [16] for more detailed descriptions of the S-IVIS tasks.

The data used for the present analyses were collected in three settings: (1) the Volvo Technology fixed-base simulator, (2) the VTI moving-base simulator and (3) a field study using an instrumented Volvo S80. In the simulators, data from two road types, motorway and rural road, were used. The simulated roads were identical for the two simulators. The simulated motorway had two lanes in each direction with a separating rail between them. The lane width was 3.75 m and the speed limit was 110 km/h. The simulated rural road had one lane in each direction, a lane width of 3.65 meters and a speed limit of 90 km/h. For the simulated rural road, straight and curved sections were included. The latter were gentle s-shaped curves, which required some negotiation by the driver. Finally, the field study was conducted on a motorway outside Linköping, Sweden. The road was similar, but not identical, to the simulated motorway. A wide range of behavioural data was collected, including driving performance data, eye-movements, physiological data and subjective ratings. The steering wheel angle was measured with an angular accuracy of 0.1 degrees.

48 subjects participated in each of the two simulator studies. Half of these subjects performed the visual- surrogate IVIS (S-IVIS) task and the other half did the cognitive task. In the simulators, each subject drove both the motorway and the rural road. In the field study, 24 subjects participated, all performing both the visual and the cognitive task. The subject groups were selected to represent "normal" driver populations (age 25-50 years, driving experience 10000 – 1 000 000 km, both males and females represented). The groups were thus roughly comparable, although not exactly matched.

The different test settings and road types in this data set combine into the following six environment conditions that were compared in the present analysis:

1. Fixed-base simulator, motorway
2. Fixed-base simulator, rural road straight
3. Fixed-base simulator, rural road, curve
4. Moving base simulator, rural road, straight
5. Moving base simulator, rural road, curve
6. Field, motorway

Before defining and analysing the steering wheel reversal metric, a qualitative analysis of the effects on steering wheel activity of secondary task loads is presented in the next section.

Qualitative analysis of steering wheel activity under visual and cognitive loads

Figure 1 and Figure 2 show representative sequences of eye glance behaviour and steering wheel activity from rural road driving in the fixed base simulator for baseline and secondary task conditions. The quantity "radial gaze" in these figures is the Euclidean distance from the mode (peak) of the cluster of glances towards the forward roadway. Thus, high values represent glances away from the road.

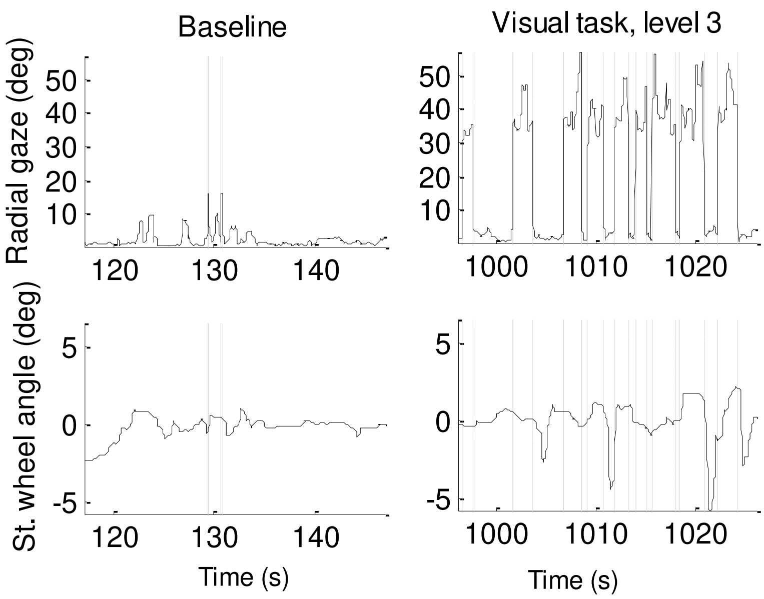


Figure 1. Eye glance behaviour and steering wheel activity in baseline and visual task conditions.

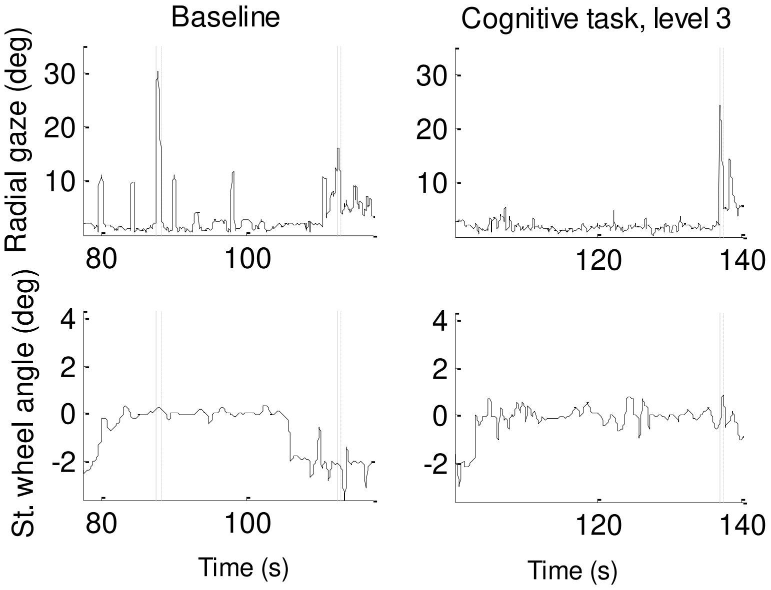


Figure 2. Eye glance behaviour and steering wheel activity in baseline and cognitive task conditions.

These figures suggest that visual and cognitive loads induce markedly different behavioural patterns. Based on these and from these and similar plots included in [17], some general observations that can be made:

- Visual load induces abrupt steering wheel corrections, generally occurring immediately after the driver has shifted his visual attention back to the road. Most of these corrections are in the range of 2-6 degrees. (Figure 1.)
- Cognitive load induces an increased amount of micro steering corrections, most of which are smaller than 2 degrees. (Figure 2.)
- Curves have a strong effect on the steering wheel data, which are often larger in magnitude than the effects of secondary task load [17]
- For visual load, the magnitude of the steering corrections increases somewhat in curves [17]
- Field data looks generally similar to the simulator data, but seems to contain more variance from sources other than the secondary task [17]

Definition of steering wheel reversal rate

The *steering wheel reversal rate* is generally defined as the number, per minute, of *steering wheel reversals* larger than a certain minimum angular value, referred to here as the *gap size* [11]. Thus, the metric could be used to capture the types of steering corrections illustrated in Figure 1 and 2. However, even though the idea of steering wheel reversals may be intuitively simple to grasp, a rigorous explicit definition is not entirely straightforward. Here we will provide an algorithm for calculating metric values, in practice letting this algorithm operationally define what is considered as a steering wheel reversal.

Roughly, given a steering wheel angle signal $\theta(t)$, a steering wheel reversal is taken to be a portion $[t_1; t_2]$ of the signal such that θ is stationary at both t_1 and t_2 (i.e. $d\theta(t_1)/dt = 0$ and $d\theta(t_2)/dt = 0$), and such that $|\theta(t_1) - \theta(t_2)| \geq \theta_{min}$, where θ_{min} is the gap size. Reversals can not be overlapping. Note that a stationary point can be a local minimum, a local maximum, a saddle point, or a point on a constant segment of the steering wheel angle signal. Figure 3a shows an example of a steering wheel angle signal, with calculated reversals for a gap size (θ_{min}) of 1°. Below, the different steps of the proposed algorithm for reversal rate calculation are described in detail.

1. *Low pass filtering.* A low pass second order (higher orders also acceptable) Butterworth filter with cut-off frequency f_{LP} is applied. The filter reduces high-frequency noise in the steering wheel angle signal, and makes it possible to find stationary points using the method described below.

2. *Finding stationary points.* Let θ_i be the value of the low pass filtered steering wheel angle signal at time step i, with $i \in \{1, 2, 3, \ldots, T\}$, where T is the total number of samples in a measurement. We calculate the following quantity:

$$\theta'_i = \begin{cases} 0 & i = 1 \\ \theta_i - \theta_{i-1} & i > 1 \end{cases}$$

Note that θ'_i is a scaled version of $\theta'_i / \Delta t$, an approximation to the first order derivative of the steering wheel signal at time step i. Here, Δt is the difference between two time steps, but we don't need to include it in our calculations in order to find the stationary points. We use θ'_i directly, and find all i such that either:

$$\theta'_i = 0 \qquad 2 \le i \le T \qquad \textbf{(1)}$$

or:

$$\left| sign(\theta'_i) - sign(\theta'_{i+1}) \right| = 2 \qquad 1 \le i \le T-1 \qquad \textbf{(2)}$$

where we have defined:

$$sign(x) = \begin{cases} -1 & x < 0 \\ 0 & x = 0 \\ 1 & x > 0 \end{cases}$$

Any i satisfying equation 1 or 2 is thus a position in the steering wheel angle signal where the approximate first-order derivative of the steering wheel angle is either zero (equation 1), or just about to pass zero (equation 2). We thus take any such point to be a stationary point. This procedure is illustrated in Figure 3b.

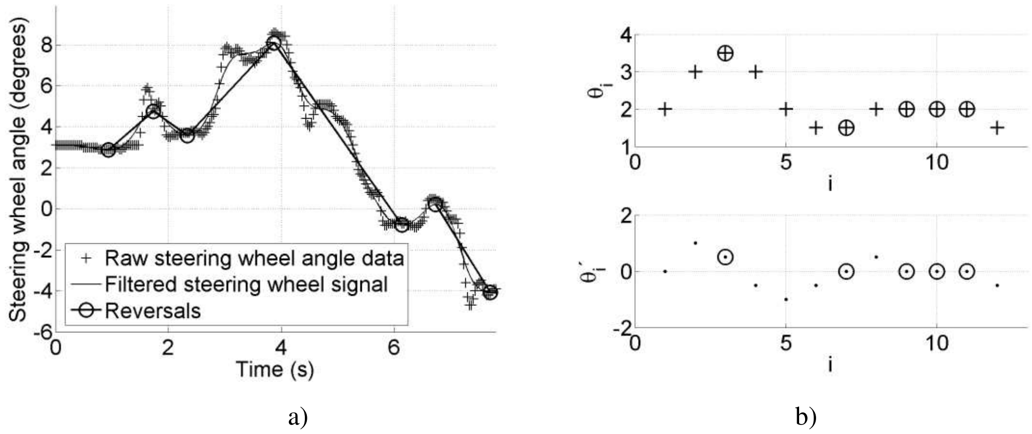


Figure 3. a) Example of steering wheel reversals. Reversals are marked as lines extending between their respective starting and ending stationary points, marked with circles. b) An illustration of the method for finding stationary points of the steering wheel angle signal. An example signal θ_i is plotted in the top graph, and corresponding values of θ'_i are plotted in the bottom graph. i = 3 satisfies equation 2, and i $\in$ {7, 9, 10, 11} satisfies equation 1, so all i $\in$ {3, 7, 9, 10, 11} are stationary points of the steering wheel angle signal.

3. *Finding reversals.* Let $e(k)$ be the kth value of i such that i is a stationary point, sorted in time order so that $e(k) > e(l)$ if $k > l$. (For the example of Figure 3b, we thus have $e(1) = 3$, $e(2) = 7$, $e(3) = 9$, $e(4) = 10$, and $e(5) = 11$.) Let N be the total number of stationary points. Then the following algorithm counts all "upwards" reversals (from a stationary point of lower angle value to one of higher angle value, e.g. from a local minimum to a local maximum) in the steering wheel angle signal that are bigger than the gap size threshold θ_{min}.

1. $k \leftarrow 1$
2. $N_r \leftarrow 0$
3. For each l in [2, 3, 4, …, N]
   a. If $\theta_{e(l)} - \theta_{e(k)} \geq \theta_{min}$:
      i. $N_r \leftarrow N_r + 1$
      ii. $R(N_r) \leftarrow [e(k), e(l)]$
      iii. $k \leftarrow l$
   b. Else if $\theta_{e(l)} < \theta_{e(k)}$:
      i. $k \leftarrow l$

This algorithm positions k at the first stationary point (k = 1), and then iterates l through the subsequent stationary points until either a stationary point l is found that is more than θ_{min} larger in angle value than the stationary point at k, or a stationary point l is found that is smaller in angle value than the stationary point at k. In the first case an "upwards" reversal has been found. In either case, k is set to l and the iteration is continued through higher values of l. Setting k to l in the latter case, when l is a stationary point with smaller angle value than k, ensures that an "upwards" reversal will be found as soon as possible, since this will require a lower angle value in subsequent stationary points for a reversal to be counted.

When the algorithm above has terminated, N_r is the number of "upwards" reversals, and $R(m)$ is a vector with two elements where the first is the time step where the mth reversal begins, and the second element is the time step where it ends. $R(m)$ is useful for visualizing the results of the algorithm, as in Figure 3a, but if this is not needed step 3.a.ii of the algorithm can be omitted.

To count also the "downwards" reversals, the same algorithm is then applied on the negative of the steering wheel angle, i.e. on $-\theta_i$, instead of on θ_i, and the total number of reversals in the steering wheel angle signal is obtained as the sum of "upwards" and "downwards" reversals.

4. Calculating the reversal rate. The steering wheel reversal rate is finally calculated as the total number of reversals detected in the steering wheel angle signal, divided by this signal's total length in minutes.

Secondary task load sensitivity

The reversal rate metric defined in the previous section was compared to a number of existing steering wheel metrics with respect to the sensitivity to visual and cognitive secondary task load. The sensitivity was measured in terms of the standardised effect size d [4] with respect to the difference between baseline and the secondary task condition (in the present analysis, all three S-IVIS difficulty levels were lumped together into a single secondary task condition). The effect sizes were calculated as:

$$d = \frac{\mu_{task} - \mu_{baseline}}{\sqrt{\dfrac{(n_{task} - 1)\sigma^2_{task} + (n_{baseline} - 1)\sigma^2_{baseline}}{n_{task} + n_{baseline} - 2}}}$$

Where μ denotes mean values, σ^2 variances, and n sample sizes. As a rule-of-thumb for interpreting d, Cohen [4] suggests that effect sizes in the region of 0.2 could be considered as small, those around 0.5 as medium and those around 0.8 as large.

The following steering wheel metrics were included in the comparison:

- *Standard deviation of steering wheel angle,* used in numerous studies (e.g. [10]).
- *The steering wheel reversal rate metric used in the HASTE project* [16]. The main difference between this metric and the one proposed here is that the HASTE metric does not as easily lend itself to use of gap sizes below 1 degree in size. The free parameters of this metric were low pass filter cut-off frequency (f_{LP}) and gap size. This is henceforth referred to as ReversalRate1.
- *The steering wheel reversal rate metric defined in the previous chapter*, henceforth referred to as ReversalRate2. As described above, the free parameters were f_{LP} and gap size. In addition to these, low pass filter order and an initial re-sampling to a higher sample rate were also included in the parameter variations, but these had only minor effects on metric sensitivity.

- Three *high frequency steering* metrics, also used in HASTE [16]. These metrics represent the steering "power" of delimited portions of the frequency spectrum of the steering wheel angle signal. The first metric (HFSteering1) is based on band pass filtering, the second and third (HFSteering2 and HFSteering3) on numerical integration under a frequency spectrum curve. The two latter differed with respect to the methods for computing the frequency spectrum (see [17] for details). The free parameters were: frequency interval start and end points, Butterworth filter order (HFSteering1), and different methods of scaling the spectrum curve before or after integration (HFSteering2 and HFSteering3).
- Two versions of the *steering entropy* metric, defined in [1] and [2] respectively (referred to here as SteeringEntropy1 and SteeringEntropy2). Re-sampling frequency was a free parameter in both versions, and in the second version the parameter α was also varied, as well as the method used for adapting the predictive model to data. (The Burg method proposed in [2] was used, as well as a simpler least-squares parameter fit.)

For each metric, a range of parameter settings were tested, where the selection of parameter values was based on the respective literature sources. For each experimental setting the highest effect size values for each metric, i.e. those obtained for the optimal parameter settings, were picked. Figure 4 and Figure 5 show these maximum standardised effect sizes for the visual and the cognitive task, respectively, in the different driving environment conditions.

From Figure 4 it can be observed that, for the visual task, the effects were generally quite large for most metrics. However, the effects for the standard deviation metric were smaller, especially for the rural curved road condition in the moving base simulator and the field condition. This was probably due to the fact that the standard deviation metric mainly captures steering magnitude and thus did not discriminate between the variation induced by the secondary task and the variance induced by other factors such as curvature and traffic events. It can also be observed that the effects were generally smaller in the field than in the simulators. The largest effects were obtained in the fixed base simulator, rural curved road condition (except for the standard deviation metric). The main conclusion from these results was that all metrics investigated except standard deviation seem to be strongly sensitive to visual load in all experimental conditions, and the differences in sensitivity between the metrics were small.

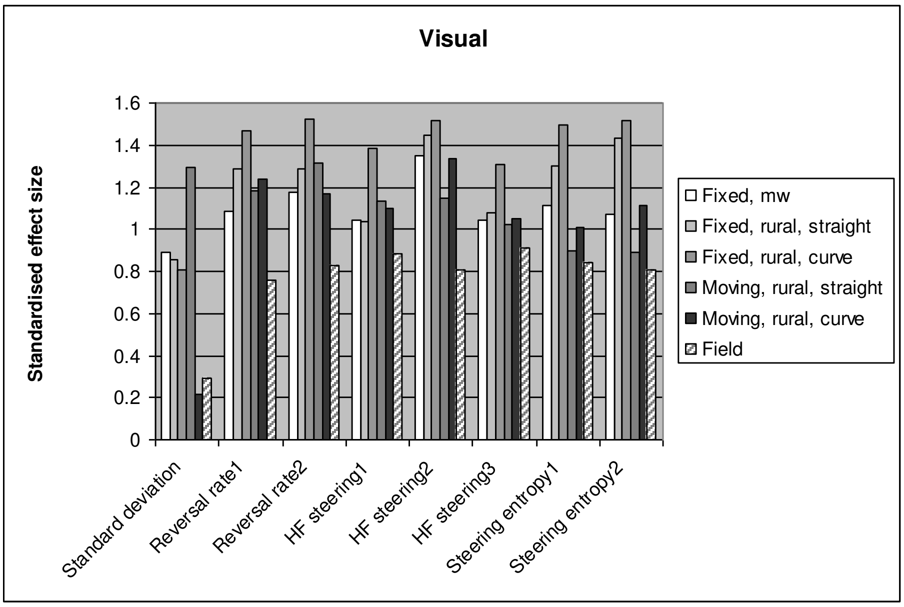


Figure 4. Maximum standardised effect sizes (i.e. those obtained for the optimal parameter setting) for the different steering wheel metrics for the visual task in the different experimental settings.

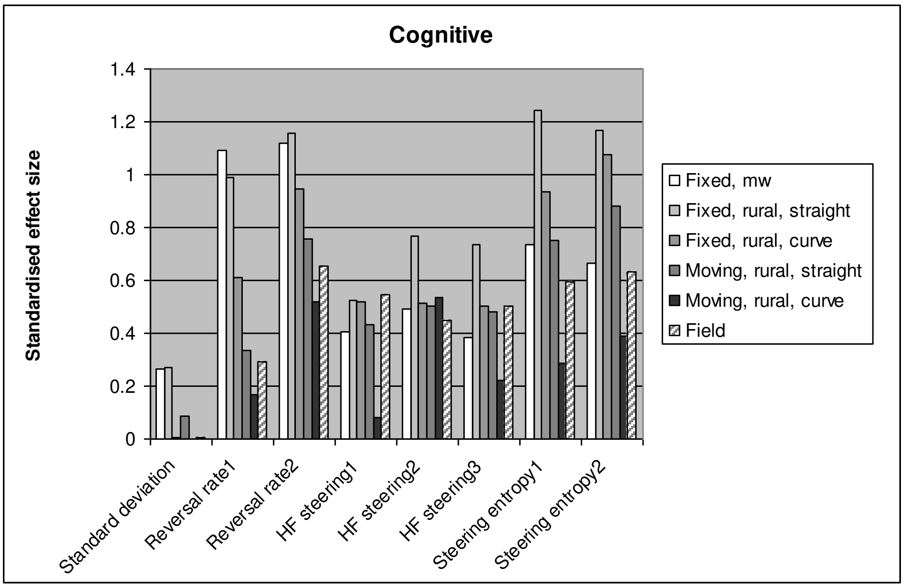


Figure 5. Maximum standardised effect sizes (i.e. those obtained for the optimal parameter setting) for the different steering wheel metrics for the cognitive task in the different experimental settings.

For cognitive load, the picture was different. From Figure 5 it can be observed that the standard deviation metric hardly captured *any* effects of cognitive load, while all other metrics were sensitive in most conditions The reversal rate and steering entropy metrics yielded markedly stronger effects than the high frequency steering metrics. It can also be observed that the new reversal rate metric (ReversalRate2) did improve performance compared to ReversalRate1, especially in the moving base simulator and field conditions. The two steering entropy metrics yielded fairly similar results. Finally, by contrast to the visual task (where the strongest effects were found in curves), the effects of the cognitive task were strongest in the straight-driving conditions.

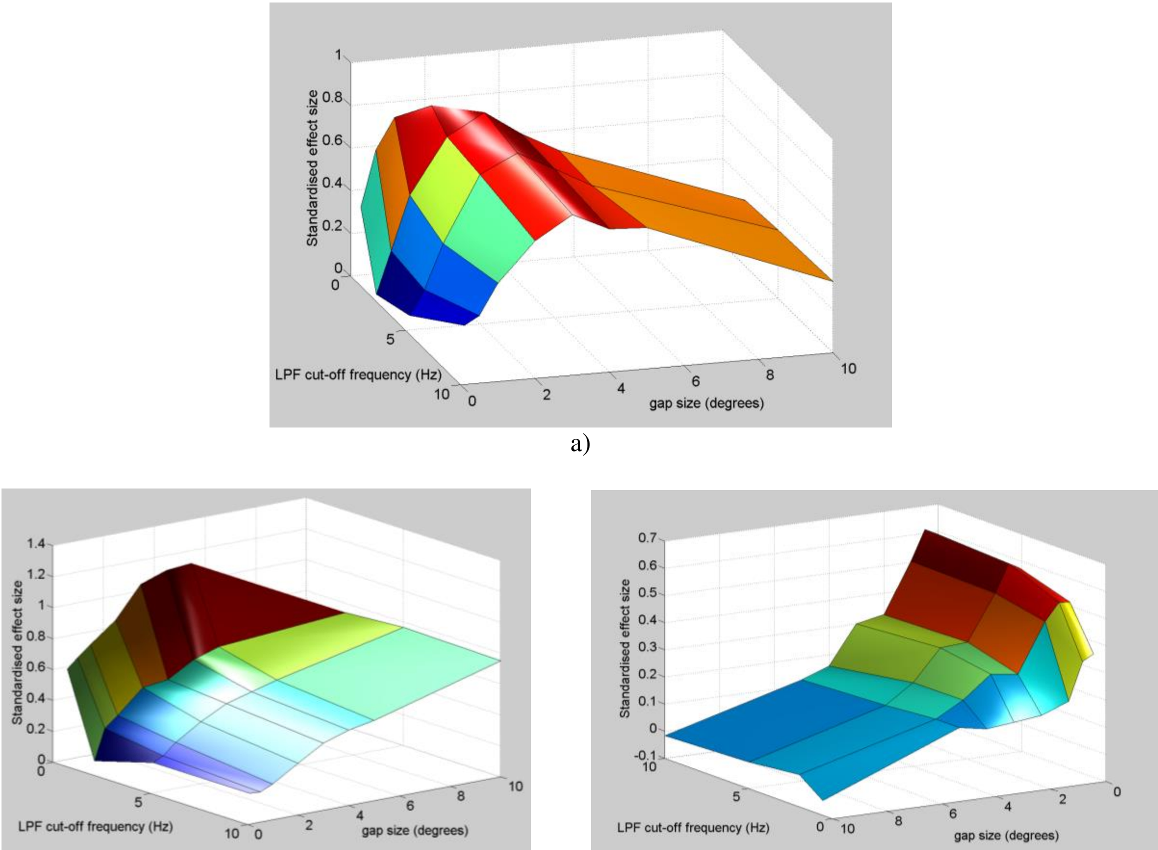
Parameter setting for the proposed steering wheel reversal rate metric

In the next step, the effects of different parameter settings for the proposed steering wheel reversal rate metric (i.e. ReversalRate2) were investigated in more detail. The two free parameters of the metric having major effects on metric sensitivity, gap size and low pass filter cut-off frequency, were varied through all combinations of:

- Gap-size (degrees): {0.1, 0.5, 1, 2, 3, 4, 5, 10}
- Low pass filter (LPF) cut-off frequency f_{LP} (Hz): {0.6, 2, 5, 10}

The analysis was mainly done by means of visual inspection of surface plots where effect size was plotted as a function of gap size and LPF cut-off frequency (see Figure 6). The following were the main findings from this analysis:

- For the visual task in straight driving conditions, the optimal gap size could be found in the range of 2-4 degrees and the LPF cut-off frequency did not have a major influence. A representative example, from the field data, is given in Figure 6a.
- For the visual task in curves, the LPF frequency cut-off had a strong influence, where the highest sensitivity was achieved for the lowest cut-off value tested (0.6 Hz). Moreover, the optimum for the gap-size was increased to 5 degrees or even higher, depending on the LPF cut-off setting. An example is given in Figure 6b, showing data from the moving-base simulator.
- For the cognitive task, the optimal gap size is much smaller than for the visual task. In fact, the sensitivity was largest for the smallest of the gap sizes investigated (0.1 and 0.5 degrees). It should be noted that smaller gap sizes could not be detected since the angular resolution of the steering wheel angle sensor was limited to 0.1 degrees. The cut-off frequency parameter had some influence, mainly in the moving base and field conditions, where the effect was reduced somewhat for the lowest value (0.6 Hz). This could be expected since much of the variance related to the cognitive secondary task lies in the higher frequencies. An example, from the field data, is given in Figure 6c.



a)

b)

c)

Figure 6. Effect size as a function of gap size and LPF cut-off frequency for (a) visual task in field motorway experiment, (b) visual task on rural curved road in moving base simulator experiment, and (c) cognitive task in field motorway experiment.

Figure 7 plots effect size as a function of gap size for both the visual and the cognitive tasks in all conditions. In this plot, the cut-off frequency was held constant at 2 Hz. The Figure clearly shows that the largest sensitivity for cognitive load was obtained for the smallest or second smallest gap size in all conditions. By contrast, for the visual task, the optimum gap size varied between 2 and 10 degrees, with the largest optimal gap sizes in curves. The gap size optima were also generally larger in the moving base simulator than in the fixed base simulator and the field. These consistent differences in optimal gap sizes clearly indicate the very different effects of visual and cognitive load on steering and the need for different parameter settings in order to obtain optimal sensitivity of the steering wheel reversal rate metric to visual and purely cognitively demanding tasks respectively.

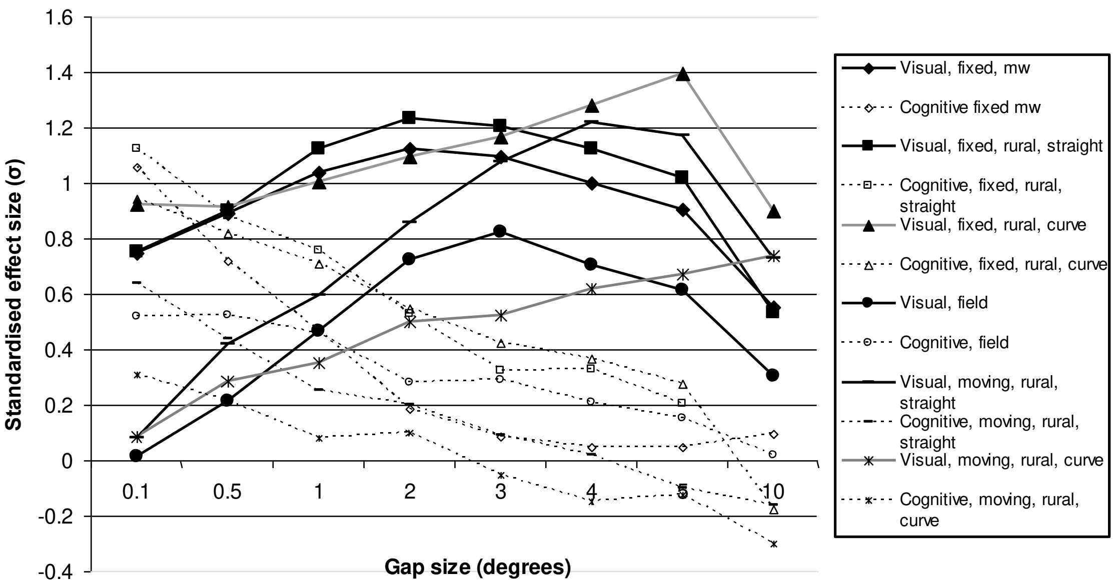


Figure 7. Effect size as a function of gap size for visual and cognitive secondary tasks. The cut-off frequency was held constant at 2Hz.

Discussion and conclusions

The paper presented a detailed specification for a steering wheel reversal rate metric suitable to assess the effect of secondary task load on driving. This metric could be considered as a complement/alternative to lane position metrics for quantifying lateral control performance, with the main advantage of being easier and cheaper to measure in the field. The proposed metric was also compared to other existing steering wheel metrics with respect to its sensitivity to visual and cognitive secondary task load. From this analysis, it could be concluded that it is fairly straightforward to create a metric that captures the effects of visually loading the driver (most metrics were sensitive), but more difficult for cognitive load, where only the steering entropy metric and the proposed steering wheel reversal rate metric showed reasonable sensitivity in all experimental conditions.

Different parameter settings of the proposed steering wheel reversal rate metric were investigated. From this analysis, it was clear that, while both the visual and cognitive secondary tasks increased reversal rate, the effects were quite different. The cognitive task mainly induced very small reversals (less than 1 degree) while most of the reversals in the visual task condition were in the range of 2-6 degrees. Thus, the value of the gap size parameter is of critical importance for optimising sensitivity to different secondary task types.

As mentioned in the introduction, visual and cognitive load have been shown to induce qualitatively different effects on driving, in particular with respect to lane keeping performance which is reduced by visual load but appears to increase as a result of cognitive load ([3, 16]. The present results show that these differences are present also in steering wheel movements, in terms of the different average size of the induced steering wheel reversals.

A key advantage of the present reversal rate metric, when compared e.g. to steering entropy, is that it is possible to tune its sensitivity to different types of secondary task load. The clear semantics of the gap size parameter also facilitates the understanding and interpretation of steering patterns (e.g. in terms of micro corrections or large corrective manoeuvres). For steering entropy, the key parameters (α and re-sampling frequency) are less semantically interpretable and it is more difficult to grasp how they are related to actual steering patterns.

Given the results obtained in the present study, the best choice of parameters for measuring the visual load component using the proposed steering wheel reversal rate metric seems to be f_{LP} = 0.6 Hz and a gap size of 3 degrees. It should however be noted that the optimal gap size may vary between 2-5 degrees depending on the experimental conditions (in particular the steering dynamics of the experimental vehicle/simulator). Thus, it could be useful to calculate a range of gap sizes and only use the most sensitive one. When choosing the gap size for measuring visual load, it should be considered that larger reversals occur more rarely than smaller ones, which means that choosing too large gap sizes may be problematic when evaluating tasks that are short in duration. The best parameterisation for measuring the cognitive load component seems to be f_{LP} = 2 Hz and a gap size of 0.1 degrees.

As an alternative to using one “visual component” parameterisation and one “cognitive component” parameterisation, a general approach of always measuring a full range of gap sizes, from the smallest possible to about ten degrees could also prove useful, at least as a tool for qualitative analysis. Regarding the f_{LP} parameter, it would clearly be preferable to find a single value somewhere between 0.6 and 2 Hz that is acceptable for both visual and cognitive load. This is an issue for further investigation.

In order for steering wheel metrics to really be useful as a safety evaluation tools, the actual mechanisms causing the observed effects on steering wheel activity during secondary task loads need to be further clarified, especially for cognitive load. Some initial attempts to explain these effects can be found in [5] and [14]. Furthermore, a better understanding is needed of the relation between the observed steering activity effects and actual road safety and accident risk. Studying the correlations of steering wheel metrics with other metrics with higher face value (e.g. reaction time metrics) may be one path, analysis of steering wheel data from large scale naturalistic driving studies [13] may be another.

To conclude, the present analysis showed that visual and cognitive loads induce markedly different steering behaviours, of which the effect of cognitive load is the more difficult to measure. We have shown, however, that our proposed steering wheel reversal rate metric can be made sensitive to both effects by means of tuning the gap size parameter. It was argued that using vehicle control metrics that have differentiated sensitivity to the visual and cognitive components of secondary tasks (such as the proposed reversal rate metric) may be preferable in the context of safety evaluation of in-vehicle tasks. A key issue for further research is how the observed changes in steering wheel activity relate to actual accident risk.

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