An analysis of braking measures

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Abstract

Braking to a full stop at a prescribed target position is a driving manoeuvre regularly used in experiments to investigate driving behaviour or to test vehicle acceleration feedback systems in simulators. Many different performance measures have been reported in the literature for analysing braking. These may or may not be useful to analyse the stopping manoeuvre, because a number of potential problems exist: 1) the scores on a measure may be insufficiently reliable, 2) the measure may be invalid, or 3) the measure may be strongly intercorrelated.

A simulation and empirical study were conducted to analyse various measures. From the simulation study it was concluded that 1) An R^2 measure based on the speed vs time relationship can be used to measure deviations from a constant deceleration, 2) minimum time-to-collision is sensitive to target position offsets, and 3) mean TTC-dot can capture braking behaviour characteristics but the required definition of a begin and end sample-point for its calculation is a disadvantage.

The empirical study calculated a set of measures using data of 60 participants driving a simulation-based session of 10 stops. It is concluded that reliable and valid measures for a braking experiment are provided by the speed and distance to the target position at braking onset, the stopping position with respect to the target and the R^2 measure to measure deviations from a constant deceleration. Recommended additional measures are: The mean speed of the complete braking manoeuvre, stopping position consistency, maximum deceleration and onset jerk.

Introduction

Braking to a full stop is a driving manoeuvre regularly used in experiments to investigate driver behaviour or to test acceleration feedback and support systems. Although the braking manoeuvre seems straightforward to analyse (i.e., participants should decelerate the car from driving speed and stop close to a stopping target), the analysis of braking behaviour is a complex trade. Our aim is to clarify the analysis of the braking manoeuvre by testing a number of measures found in literature. In addition, we provide recommendations about which measures to include in future analyses.

To introduce the braking manoeuvre and the critical time-points, Figure 1 illustrates a representative braking manoeuvre. At Time = t_0 the throttle is fully released, after which the brake is pressed at Time = t_1. The brake pedal is depressed further, until the vehicle reaches its maximum deceleration during the manoeuvre at Time = t_2. Finally, the vehicle comes to a complete stop at Time = t_3.

Many different performance measures for analysing braking are reported in the literature. Boer et al. (2000) compared the braking manoeuvre in a real car to the same manoeuvre performed in a simulator. They concluded that drivers braked later, harder and in a multi-modal manner (multiple separate brake pedal applications) in the simulator rather than with a constant deceleration as was found in a real car. Following this comparison, Boer et al. (2001) introduced a driver model for stopping behaviour which could reproduce the multi-modal braking profiles. Differences between simulated and real driving behaviour were also demonstrated by Jamson and Smith (2003). They fitted a second order polynomial on the speed vs distance data and quantified multi-modal braking using the R^2 measure.

Other braking experiments investigated the influence of motion platforms or low-cost motion cueing solutions on braking behaviour (Siegler et al., 2001; Pinto et al., 2004; Brünger-Koch et al., 2006; De Winter et al., 2007 & 2008). Both papers by De Winter et al. used the same measures as Siegler et al., with the exception of the distance to the target position at Time = t_3. De Winter et al. adapted this measure to exclude inter-participant differences of the desired target position (line or sign) by using the standard deviation of the position error instead of the mean position error as used by Siegler et al. (2001). Brünger-Koch et al. calculated approach speed (t_0), total stopping distance (t_0-t_3) and the maximum deceleration (t_2), but also time-to-collision (TTC) at braking onset (t_1), total stopping time (t_0-t_3), and pedal transition time (t_0-t_1). They used Time = t_0 as the start point for their calculations, where most other researchers have used Time = t_1. Pinto et al. calculated time-to-collision at the onset of braking, maximal deceleration, the instant of maximal deceleration ($t_2/(t_3-t_1)$), and braking smoothness measured by the number of inversions of the deceleration profile, total braking duration and total stopping distance. All these papers report significant differences for the maximum deceleration during braking.

Many studies regarding braking behaviour have been reported outside the Driving Simulator Conference (DSC) community. Particularly the research into the visual perception of speed and distance focused on the braking manoeuvre. Researchers were inspired by the introduction of the tau (or visually obtained time-to-collision; TTC) and tau-dot (or the time rate of change of TTC, TTC-dot) concepts of Lee (1976). This resulted in many experiments focussing on the braking manoeuvre to explore the concept of direct perception and time-based control (e.g., Horst, 1990; Yilmaz and Warren, 1995; Groeger, 2000; Flach et al., 2003).

Measures used to analyse the braking manoeuvre may or may not be useful, because a number of potential problems exist:

- The scores on a measure may be insufficiently reliable;
- A measure may be invalid, thereby not capturing the phenomenon of interest;
- When multiple measures are used, measures may be strongly intercorrelated and therefore not sufficiently diverse. Essentially, this would mean that same construct is paraphrased in different measures.

This paper will evaluate a performance measures, obtained from literature and regards the braking manoeuvre by means of simulation and the analyses of experimental data. Our main goal is to investigate which measures are valuable for analysing braking and offer a better general understanding of the braking manoeuvre itself.

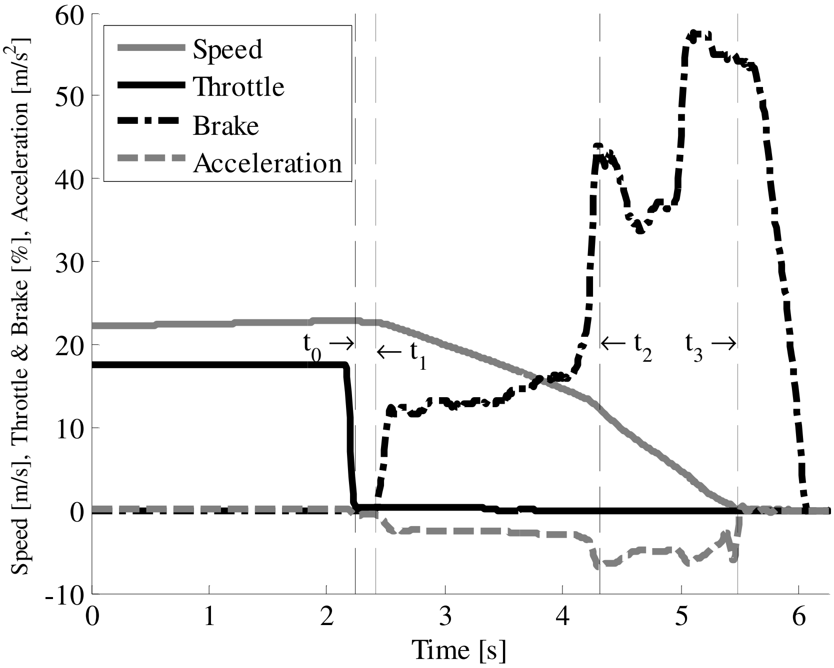

Figure 1: Definition of time-points during a single braking manoeuvre of a subject in a fixed-base driving simulator.

Simulation study

Before the measures were tested using experimental data, some complex measures first required an additional simulation analysis to investigate the mathematical properties without the disturbances introduced by human operators. The (complex) measures evaluated during the simulation study were R^2, TTC_{min} and mean TTC-dot (see Table 3 for further information concerning these measures).

Concerning R^2, Jamson and Smith intended to find a measure to quantify multi-modal braking, as Boer et al. (2000) defined it. They used a procedure to fit a second-order polynomial to the speed vs distance graph, which resulted in what we define as the $R^2_{distance}$ measure. Because the speed vs distance graph is, for a constant deceleration, not a second order function, we propose another way to calculate this measure (R^2_{time}) and compare these two R^2 measures during the simulation study.

Method

The simulation modelled the movement of a car slowing down from a given initial speed with a prescribed deceleration profile. The simulation started at the moment the deceleration began (the brake onset). Eight braking manoeuvres with different deceleration profiles were simulated to get a clear view of the impact of these diverse deceleration profiles on the calculated measures. An overview of the simulated cases is provided in Table 1. Cases 1 to 4 had constant deceleration profiles, from 30 and 80 km/h with different decelerations, whereas cases 5 to 8 had variable decelerations without (5, 6) or with (7, 8) modal braking.

Table 1: Simulated cases

Case	Speed (km/h)	Initial acceleration (m/s^2)	Acceleration rate of change (m/s^3)	Multi-modality (total number of brake releases)
1	30	-4	0	0
2	80	-4	0	0
3	80	-2	0	0
4	80	-8	0	0
5	80	-2	-2	0
6	80	-8	1	0
7	80	-4	0	5
8	80	-4	0	1

Figures 2a and 2b show the speed vs time and the speed vs distance graphs for the cases of Table 1.

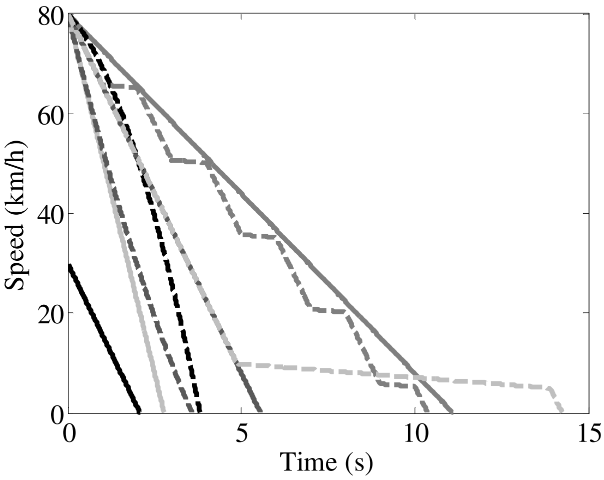

Figure 2a: Speed vs time for the 8 simulated cases

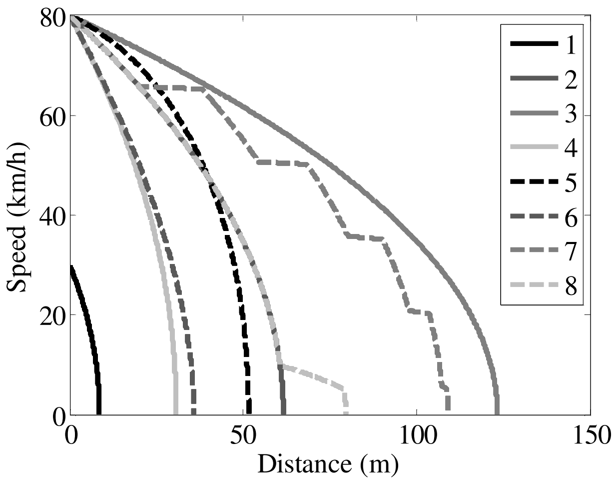

Figure 2b: Speed vs distance for the 8 simulated cases

Results and discussion

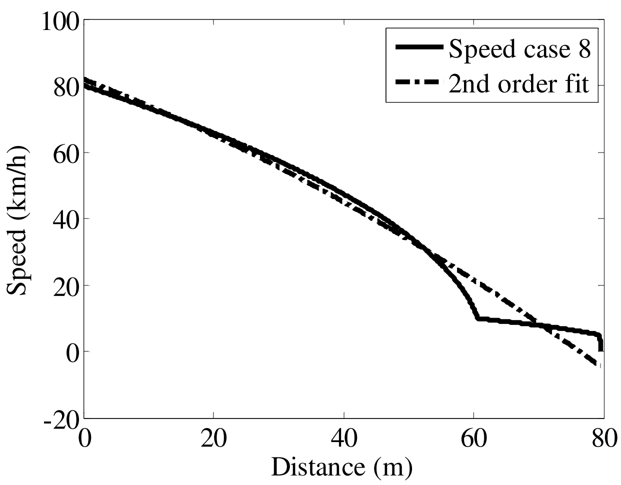

Figure 3a: Speed vs distance profiles for case 2 with the 2nd order polynomial fit ($R^2_{distance}$).

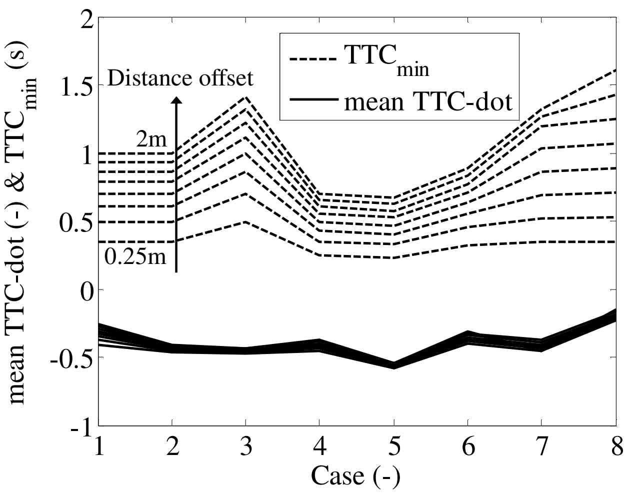

Figure 3b: TTCmin and mean TTC-dot for the 8 cases with varied target distance offset (range:0.25-2 m)

The results of $R^2_{distance}$ and R^2_{time} are presented in Table 2. For cases 1 to 4, R^2_{time} has a value of exactly 1 as expected with a constant deceleration, whereas $R^2_{distance}$ has a value slightly below 1 showing the suboptimal fit. The largest difference between these measures is found for case 8, where the driver is simulated to completely release the brake for a number of seconds before applying the brake again at low speed and close to the stop line. The speed vs distance graph is shown together with a second-order fit in Figure 3a, showing the relatively good fit and thus high $R^2_{distance}$ score (0.981, see Table 2). Table 2 shows that R^2_{time} captures the multi-modal braking better for case 8 (0.683).

The focus now shifts to the TTC_{min} and mean TTC-dot measures. Table 2 shows that the mean TTC-dot measure is able to distinguish between increased and decreased accelerations, as intended by Lee (1976) and also by Yilmaz and Warren (1995). However, the start and endpoint for the calculation of a mean TTC-dot (or the determination of a regression line such as Yilmaz and Warren) is critically important for the measure's value. We used the TTC_{min} sample-point (t_{TTCmin}) as endpoint and brake onset as start-point of the calculation interval. We see that for case 1 (low speed) the nonlinear contribution of TTC-dot at the end of the calculation interval has a larger influence on the measure score than for case 3 (braking from a higher speed). Case 3 results in a mean value of -0.47, which is closest to the theoretical value of -0.5 for a constant deceleration. If the stopping point is taken as endpoint, the mean TTC-dot value is infinite. Figure 3b illustrates the sensitivity of the TTC_{min} measure to a distance offset. It can be seen that the TTC_{min} measure is very sensitive to variations of the target stopping position, thereby reducing reliability and validity. When a participant interprets the stopping target differently (e.g. stop-sign instead of stop-line), or the person's head position instead of the front of the car is used to calculate the distance to the target, it is easy to obtain distance offsets of around 2m.

Table 2: Simulation results for the R^2, TTC_{min} and mean TTC-dot measures

Case	$R^2_{distance}$	R^2_{time}	TTC_{min}	mean TTC-dot
1	0.993	1.000	0.50	-0.38
2	0.992	1.000	0.50	-0.45
3	0.993	1.000	0.70	-0.47
4	0.993	1.000	0.35	-0.44
5	0.992	0.972	0.32	-0.57
6	0.996	0.995	0.45	-0.38
7	0.979	0.992	0.52	-0.44
8	0.981	0.683	0.53	-0.22

Empirical study

A set of braking measures (Table 3) was calculated for experimental data of which the results were partly published at previous DSC conferences (De Winter et al., 2007; De Winter et al., 2008). These experiments compared the effects of various forms of motion cueing against a baseline condition without motion cueing during a brake manoeuvre. Only a participants' first driving session, and only when it was driven in the baseline condition, was included in the present paper. The total number of sessions was 60, and each session comprised of 10 stopping manoeuvres. The discriminant validity of the measures was determined using the driving behaviour differences between experienced and inexperienced drivers. Additionally, an adaptation analysis was performed by analysing the first and last four stopping manoeuvres. Differences between the measures were investigated using the *t* test and Cohen's *d* effect size measure, whereas a correlation matrix of all the measures was used to assess the redundancy of the measures. The split-half reliability of the measures was investigated by correlating the measures with themselves between the five even and five odd stop numbers.

Table 3: Measures used for braking analyses calculated for each participant

Nr. ValidStops[b]	[-]	Number of successful braking manoeuvres per run[a] (De Winter et al., 2007)
Mean V	[m/s]	Mean speed of the braking manoeuvre ($-175m < dis_{t3} < 30m$) (De Winter et al., 2007)
V_{ini}	[m/s]	Speed at braking onset (t_1) (Siegler et al., 2001)
DTT_{ini}	[m]	Distance to target at braking onset (t_1) (Siegler et al., 2001)
DTT_{fin}	[m]	Distance to target at stopping position (t_3) (Siegler et al., 2001)
SD DTT_{fin}[b]	[m]	Standard deviation of distances to target at stopping position (t_3) (De Winter et al., 2007)
Max. dec.	[m/s^2]	Maximum deceleration during the braking manoeuvre (t_1-t_3;=t_2) (Siegler et al., 2001)
Onset jerk	[m/s^3]	Mean jerk during the first part of the braking manoeuvre (t_1-(t_1-t_2)/2) (Siegler et al., 2001)
TTC_{ini}	[s]	Time-to-Collision (line-crossing) at the onset of braking (t_1) (Lee, 1976; Horst, 1990)
TTC_{min}	[s]	Minimum Time-to-Collision (t_1-t_3) (Horst, 1990)
Max. dec. pos.	[%]	Time of maximum deceleration with respect to the braking time (t_1-t_3) (Pinto et al., 2004)
Dec. inversions	[-]	Number of inversions of the deceleration profile (t_1-t_3) (Pinto et al., 2004)
SD dec.	[m/s^2]	Standard deviation of deceleration during braking (t_1-t_3)
TransferTime	[s]	Time it takes from throttle release to brake onset (t_0-t_1) (Brünger-Koch et al., 2006)
BrakeEvents	[-]	Number of brake applications after first braking onset (t_1-t_3)
ThrottleEvents	[-]	Number of throttle applications (t_1-t_3)
Max. Brake	[%]	Maximum brake position during braking (t_1-t_3)
Max. Throttle	[%]	Maximum throttle position during braking (t_1-t_3)
StopTime	[s]	Braking duration (t_1-t_3) (Pinto et al., 2004)
StopDistance	[m]	Stopping distance (t_1-t_3) (Pinto et al., 2004)
R^2_{time}	[-]	Squared correlation coefficient of the speed vs time relationship (t_1-t_3) (adapted from Jamson, 2001)
mean TTC-dot	[-]	Mean TTC-dot until the minimal TTC (t_1-t_{TTImin}) (adapted from Yilmaz, 1995)

[a] A successful stop was defined as a stop where the minimum speed is smaller than 1 km/hour.
[b] Measures without [b] are scored as the mean per subject of successful stops during one driving session.

Table 4: Results of the experience comparison, adaptation analysis and split-half reliability.

	Experience comparison				Adaptation analysis				Split-half correlation
	Inexp.	Exp.	p	d	First4	Last4	p	d	
Nr. ValidStops	8.56	7.77	0.13	0.39	3.23	3.35	0.46	-0.11	0.53
Mean V	10.16	10.12	0.90	0.03	10.19	10.43	0.27	-0.19	**0.70**
V_{ini}	15.77	16.13	0.54	-0.16	16.76	16.44	0.41	0.13	**0.75**
DTT_{ini}	47.84	53.38	0.26	-0.30	59.66	50.45	**0.02**	**0.39**	0.48
DTT_{fin}	6.00	4.35	**0.04**	**0.54**	5.61	5.07	0.19	0.15	**0.69**
SD DTT_{fin}	3.38	2.36	**0.05**	**0.55**	3.07	2.09	**0.01**	**0.41**	0.09
Max. dec.	6.92	6.33	0.17	0.36	6.77	6.66	0.36	0.06	**0.85**
Onset jerk	7.16	5.22	0.08	0.48	6.00	6.27	0.90	-0.05	**0.73**
TTC_{ini}	2.94	3.10	0.53	-0.17	3.44	2.91	**0.01**	**0.42**	0.55
TTC_{min}	1.55	1.54	0.94	0.02	1.57	1.53	0.62	0.07	**0.73**
Max. dec. pos.	47.19	42.14	0.14	0.41	48.11	45.13	0.22	0.18	0.41
Dec. inversions	2.92	3.32	0.09	-0.45	3.45	3.01	**0.01**	**0.35**	0.29
SD dec.	2.09	1.85	0.14	0.39	2.03	2.01	0.65	0.02	**0.77**
TransferTime	1.97	2.24	0.29	-0.28	2.19	2.10	0.86	0.07	0.31
BrakeEvents	1.34	1.57	**0.04**	**-0.56**	1.51	1.41	0.22	0.18	0.61
ThrottleEvents	0.18	0.19	0.81	-0.06	0.25	0.16	0.16	0.25	0.33
Max. Brake	0.65	0.54	**0.03**	**0.58**	0.61	0.60	0.20	0.08	**0.84**
Max. Throttle	0.22	0.19	0.26	0.30	0.23	0.17	**0.01**	**0.49**	0.54
StopTime	5.07	6.14	0.05	-0.52	6.28	5.42	**0.04**	**0.32**	0.63
StopDistance	41.84	49.03	0.13	-0.41	54.05	45.38	**0.02**	**0.37**	0.43
R^2_{time}	0.93	0.93	0.47	0.19	0.91	0.95	**0.02**	**-0.44**	0.40
mean TTC-dot	-0.47	-0.46	0.35	-0.24	-0.47	-0.47	0.97	0.01	0.43

Table 5: Correlation matrix

	Nr. ValidStops	Mean V	V_{ini}	DTT_{ini}	DTT_{fin}	SD DTT_{fin}	Max. dec.	Onset jerk	TTC_{ini}	TTC_{min}	Max. dec. pos.	Dec. inversions	SD dec.	TransferTime	BrakeEvents	ThrottleEvents	Max. Brake	Max. Throttle	StopTime	StopDistance	R^2_{time}	mean TTC-dot
Nr. ValidStops																						
Mean V	-0.40																					
V_{ini}	-0.30	**0.76**																				
DTT_{ini}	-0.33	-0.01	0.36																			
DTT_{fin}	-0.08	0.02	0.20	0.26																		
SD DTT_{fin}	-0.11	0.11	0.24	-0.04	0.33																	
Max. dec.	0.06	0.54	0.34	-0.56	-0.01	0.18																
Onset jerk	0.07	0.36	0.18	-0.58	0.02	0.28	**0.74**															
TTC_{ini}	-0.24	-0.29	0.04	**0.93**	0.24	-0.08	**-0.70**	**-0.67**														
TTC_{min}	-0.01	-0.42	-0.13	0.53	**0.68**	0.10	-0.60	-0.39	0.63													
Max. dec. pos.	-0.12	-0.05	-0.11	0.36	0.01	-0.14	-0.23	-0.55	0.40	-0.06												
Dec. inversions	-0.12	0.03	0.05	0.06	-0.18	-0.17	0.16	-0.12	0.00	-0.22	0.16											
SD dec.	-0.03	**0.67**	0.58	-0.45	0.12	0.33	**0.92**	**0.73**	**-0.66**	-0.50	-0.32	0.03										
TransferTime	-0.01	-0.26	-0.42	-0.13	-0.03	-0.03	-0.16	-0.15	-0.01	0.10	0.04	-0.02	-0.23									
BrakeEvents	-0.17	-0.27	0.01	0.55	0.10	-0.05	-0.33	-0.35	0.59	0.47	-0.11	0.20	-0.36	0.13								
ThrottleEvents	-0.18	0.08	0.23	0.45	-0.14	-0.09	0.04	-0.08	0.45	-0.03	0.06	0.19	0.03	0.00	0.41							
Max. Brake	0.06	0.49	0.27	-0.54	-0.08	0.17	**0.96**	**0.72**	**-0.66**	-0.64	-0.13	0.11	**0.87**	-0.08	-0.35	0.09						
Max. Throttle	-0.18	0.57	0.59	0.06	0.20	0.11	0.50	0.29	-0.13	-0.19	-0.04	0.04	0.61	-0.06	-0.14	0.24	0.57					
StopTime	-0.23	-0.29	0.06	**0.89**	0.05	-0.17	**-0.72**	-0.63	**0.93**	0.59	0.16	0.01	**-0.66**	0.03	**0.71**	0.49	**-0.69**	-0.15				
StopDistance	-0.33	-0.01	0.34	**0.99**	0.09	-0.10	-0.57	-0.60	**0.92**	0.42	0.37	0.10	-0.48	-0.13	0.55	0.49	-0.54	0.02	**0.91**			
R^2_{time}	-0.10	0.22	0.14	-0.10	0.11	0.14	-0.17	-0.05	-0.20	-0.04	0.18	-0.31	0.00	-0.09	-0.51	-0.61	-0.19	-0.13	-0.28	-0.12		
mean TTC-dot	-0.01	-0.24	-0.04	0.29	0.34	-0.19	-0.50	-0.09	0.32	0.63	-0.29	-0.13	-0.36	0.08	0.21	-0.08	-0.55	-0.20	0.38	0.24	0.15	

Results

Table 4 presents the results of the experience comparison, adaptation analysis and split-half reliability, Table 5 presents the correlation matrix. The results can be summarized as follows:

a) The experience comparison resulted in a number of differences between experienced and inexperienced drivers. DTT_{fin} was lower for the experienced drivers, and the stopping consistency was higher (lower SD DTT_{fin}) as could be expected. BrakeEvents was higher for experienced drivers, and Max. Brake was smaller.
b) The adaptation analysis showed that during the driving session, drivers started to brake later with similar speed which was shown by the following measures: smaller DTT_{ini}, lower TTC_{ini}, lower StopTime and StopDistance. Drivers increased their stopping consistency (lower SD DTT_{fin}) and had fewer fluctuations in their deceleration profile which was shown by: lower Dec. Inversions, higher R^2 and lower Max. Throttle.
c) The correlation matrix revealed that the braking manoeuvre is largely determined by the distance to the target at braking onset (DTT_{ini}) and the closely related TTC_{ini} (closely related because of the conditioned speed in this experiment). These correlate with many other measures which are related to the overall characteristics of the braking manoeuvre, such as Max. dec., Onset jerk, Max. Brake, StopTime and StopDistance. The accuracy with which the vehicle is placed near the target can be expressed by two relatively uncorrelated accuracy measures: DTT_{fin} and SD DTT_{fin}.
d) The split-half reliability analysis shows that the scores on the measures Mean V, V_{ini}, DTT_{fin}, Max. dec., Onset jerk, TTC_{min}, SD dec. and Max. Brake have a high reliability (correlation coefficient between odd and even stops > 0.65). The lowest reliability was found for the stopping consistency measure (SD DTT_{fin}). The low reliability can be explained by the fact that this measure is based on a standard deviation amongst stops instead of a mean amongst stops, therefore requiring a larger sample size for high reliability.

Conclusions

The simulations provided insights into the characteristics of three complex braking measures. The R^2_{time} measure was suggested to replace $R^2_{distance}$, because it distinguishes better between constant deceleration and multimodal braking. Furthermore, the simulations showed that the TTC_{min} measure is sensitive to distance offsets. The necessity to determine an (arbitrary) start and end-point for the mean TTC-dot calculations is a weak-point of this measure, although it is successful in measuring an increase or decrease of the deceleration during braking.
The empirical study showed that the distance and time to the target at the onset of braking are the dominating variables determining the global characteristics of the braking manoeuvre.
A valid, reliable and unique accuracy measure was provided by DTT_{fin}. This measure was successful in discriminating between experience levels. The stopping consistency (SD DTT_{fin}) performed likewise, but proved to be unreliable when too little stops are taken into account.
The empirical study used data from earlier experiments, in which speed was regulated by traffic signs. Participants were instructed to obey the traffic signs, and this might have been of influence on differences found for example on the speed at braking onset measure. With other experimental designs, other conclusions could have resulted concerning this and other measures. Furthermore, we only looked at adaptation and experience, not at for example the influence of systems feeding back accelerations. Literature shows that for such systems, the maximum deceleration and brake onset jerk often reveal significant differences. We did show that the maximum deceleration and onset jerk correlate with each other and with the overall brake manoeuvre characteristics determined by the speed and distance at brake onset. We

advise that these measures should be included in an analysis with the notion that they are intercorrelated, because they provide extra information on *how* participants slowed down.
We suggest that the following measures should be included in braking manoeuvre analyses: speed at braking onset (V_{ini}), distance at braking onset (DTT_{ini}), the stopping position (DTT_{fin}) as accuracy measure and the multi-modality of the braking (R^2_{time}). Recommended additional measures are: The mean speed over the complete braking manoeuvre (Mean V), stopping consistency (SD DTT_{fin}), maximum deceleration (Max. dec.) and Onset jerk.

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