DRIVER HEAD DISPLACEMENT DURING (AUTOMATIC) VEHICLE BRAKING TESTS WITH VARYING LEVELS OF DISTRACTION

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ABSTRACT
Vehicle occupant behavior in emergency driving conditions has a large effect on traffic safety. Distraction is estimated to be the cause of 15-20% of all crashes. Additionally, the posture of the occupants prior to the possibly unavoidable crash is known to have a large effect on the injury reducing performance of the restraint system. In this study it is investigated whether braking settings as well as driver distraction influence the kinematic response of an occupant during braking events, in order to improve the design of crash avoidance or crash and injury mitigation systems.

A mid-size passenger vehicle was instrumented with an automatic brake actuator and a warning light, which could be operated by the test leader, seated on the passenger side. The motion of the driver's head in six degrees of freedom was recorded via an eye-tracking system, as well as relevant vehicle parameters. A single professional test driver was used, which was driving on a large test track, allowing velocities up to 120 km/h and full braking with 50 km/h velocity reduction in both straights and curves. A total of 61 braking events were generated in a varied order in the following four categories: 1) driver-induced while being attentive, 2) automatic while being attentive, 3) driver-induced after a warning was provided while being distracted and 4) automatic while being distracted. Driver distraction was achieved by asking the driver to type a text message while operating the vehicle.

From 61 braking tests with a single professional test driver, entrance speed, braking deceleration and jerk time histories as well as brake pedal force were plotted in combination with head motion. Head forward displacement varied between 37 and 128 mm, while head forward pitch (relative to vehicle) was in between 4 and 23 degrees. In attentive scenarios, head rearward displacement in anticipation of an oncoming braking event was observed up to 110 mm. Automatic braking for a distracted driver induces on average 123 mm of head forward displacement, which is 67 mm larger than for an attentive driver that applies the brakes himself. Automatic braking for an attentive driver induced substantially higher head motion, which indicates that posture control is dependent on anticipation on the braking pulse.

This study is limited by the fact that tests were performed with one single, professional driver that was aware of the tests to be performed. Wider variation is expected with different drivers and no conclusions could be drawn on habituation. Furthermore, no accurate information is available on timing, such that no information regarding reaction time can be provided.

Sensitivity of driver head kinematic response during emergency braking for various parameters was shown in fairly realistic driving conditions. This information is relevant for the design of safety systems that interface with the occupants, such as a motorized belt pre-tensioner and autonomous emergency braking systems. Obviously this data can also be used for the validation of human models that are used to support the design and functioning of these systems.

INTRODUCTION
Vehicle occupant behavior in emergency driving conditions has a large effect on traffic safety. First of all, the state of the driver can affect the ability of the driver to properly control the vehicle. In 2008, the United States National Highway Traffic Safety Administration (NHTSA) published the results of a crash causation survey in which the cause of over 5,000 crashes was analyzed [NHTSA, 2008]. Driver distraction was a large cause of error, as 18% of the drivers involved in crashes were involved in at least one non-driving activity, the majority of them using cell-phones. In addition, fatigued drivers were twice as likely to make performance errors that ultimately resulted in a crash. A different study based on around 48,000 crashes in the US concluded that 16.5% of all fatal crashes were caused by driver drowsiness, even though officially reported numbers are 4 times lower [Tefft, 2011]. In the Netherlands, it is estimated that annually around 8 to 12% of all traffic fatalities are (partially) caused by drowsiness [SWOV, 2010].

Additionally, the posture of the occupants prior to the possibly unavoidable crash is known to have a large effect on the injury reducing performance of the restraint system. Ejima et al. [2009] performed a series of tests with volunteers seated on rigid seats, restrained by a three-point belt system and subjected to a 600 ms 0.8 G constant deceleration, representative of emergency braking. For a tensed volunteer, kinematic figures indicate that head forward displacement was in the order of 100 mm at 200 ms after impact, while T1 forward displacement was in the order of 25 mm and hip forward displacement around 10 mm. For a relaxed occupant restrained by a lap belt only, the head displacement was in the order of 600 mm at 600 ms after impact with T1 displacement around 400 mm. Bose et al. [2008] used a numerical human model [de Lange et al., 2005 & Cappon et al., 1999] to study the effect of pre-impact posture, as well as levels of muscle bracing in the lower extremities and body mass and stature, on the injury risk in the event a crash was unavoidable. Pre-impact posture was shown to be the parameter affecting the injury risk the most. In an optimization routine it was found that with a seat belt system with adaptive force limiting settings and variable pretensioner firing time, a reduction of injury risk of up to 35% could be achieved.

In this study, the objective is to investigate whether braking settings as well as driver distraction influence the kinematic response of an occupant during braking events, in order to improve the design of crash avoidance or crash and injury mitigation systems.

METHODS

A test series was developed in which an instrumented research vehicle was used. The research vehicle was a mid-size passenger vehicle with the following additional instrumentation:

- An automatic brake actuator was implemented to apply controlled brake pressure on the additional brake pedal at the passenger side. This actuator was controlled by a laptop in the hands of the test leader, which was seated in the vehicle.
- An LED was added as a warning device to the driver. This LED was controlled from the laptop as well.
- A SmartEye Pro [Smart Eye, 2013] eye tracking system was used to track the head motion in six degrees of freedom.
- A video camera monitoring the driver.
- Force sensors on both the driver brake pedal as well as on the actuated brake pedal.
- Vehicle accelerometers recording vehicle acceleration in six degrees of freedom.
- A Trimble RTK-GPS system [Trimble, 2013] tracking vehicle position.

An oval test track [ATP, 2013] with 4 km long straight and 2 km long curves was used to allow highway driving conditions and induce surprise braking events. Test track requirements were that a professional test driver had to drive the vehicle. Therefore, this study is limited to a single professional test driver.

The test driver was asked to drive at a constant velocity of 120 km/h in both straights and curves after which four types of braking events were induced:

1. Attentive – Driver: The driver was attentive and was asked to induce emergency braking himself.
2. Attentive – Automatic: The driver was attentive and the automatic brake actuator was operated while the driver was informed.
3. Distracted – Warning – Driver: The driver was distracted and was instructed to induce emergency braking after the warning light was turned on.
4. Distracted – Automatic: The driver was distracted and the automatic brake actuator was operated at a for the driver unknown moment.

In driver-induced braking events, the driver was asked to make an emergency braking maneuver with a speed reduction of approximately 50 km/h. The automatic brake actuator could apply varying levels of braking force and various rates of force build-up. Driver distraction was achieved by asking the driver to type a text message on a button-operated cell phone while operating the vehicle.

In total, 61 tests were performed with test parameters as shown in Table 1. Test variations were offered in a fairly random order.

Table 1: Overview of tests and test parameters.

Parameter	Option	Nr. of tests
All tests	-	61 *(100%)*
Driver state	Attentive	24 *(39%)*
	Distracted	37 *(61%)*
Braking type	Driver	6 *(10%)*
	Warning – Driver	13 *(21%)*
	Automatic	42 *(69%)*
Track	Straight	40 *(65%)*
	Curve	20 *(33%)*
	Unknown	1 *(2%)*
Braking force setting (automatic braking only)	360 N	21 *(34%)*
	500 N	21 *(34%)*
Braking rate setting (automatic braking only)	300 N/s	21 *(34%)*
	600 N/s	21 *(34%)*

RESULTS

Occupant kinematics

First of all, the kinematics of the driver are shown from two tests from two braking scenarios.

Figure 1. Occupant kinematics in Attentive-Driver braking scenario, before braking (top) and at time of highest head excursion (bottom).

Figure 2. Occupant kinematics in Distracted-Automatic braking scenario, before braking (top) and at time of highest head excursion (bottom).

In Figure 1, for an attentive driver that induces emergency braking himself, the initial posture just before braking is shown, as well as the posture during braking, at the time of maximum head forward excursion. It can be observed that the head moves forward and that the driver maintains his eyes on the road during the event.

In Figure 2, for a distracted driver with automatically induced braking, the initial posture just before braking is shown, as well as the posture during braking, at the time of maximum head forward excursion. It can be observed that the driver was distracted by typing a text message just before the braking occurred. During the braking, the head moves forward to a large extent and the driver maintains his eyes on the road. Also, the driver is only holding the steering wheel with one hand, since the other hand holds the cell phone.

The driver posture in the other two braking scenarios was comparable to that in the scenarios discussed above, however at different magnitudes. The shown test results are examples of the scenarios. In other tests within the same scenario, the kinematics were slightly different, but in terms of typical characteristics it was the same.

In appendix 1, for the four different braking scenarios time-history plots are shown of four tests, as examples of the four scenarios. In a time-frame of 16 seconds the velocity of the vehicle, the head forward displacement and head pitch angle as well as the braking force is indicated. It is shown that prior to braking head forward displacement and head pitch are fairly constant, except for the distracted scenarios where irregular periods of around 2-3 seconds are shown in which the test driver changes focus between downward looking at the cell phone and looking at the road. It is shown that during braking, typically head forward displacement occurs as well as head pitch. Also, when the braking force is removed, the head typically goes into a rebound, i.e. backward displacement of the head relative to the initial position.

Statistical analysis on head motion

A statistical analysis was performed on head position parameters that were recorded from the Smart Eye system. In Appendix 2 a correlation matrix is shown for all parameters. In Table 2, the results from a one-way ANOVA and a Tukey post-hoc test are shown for peak head forward displacement.

Head forward displacement varied between 37 and 128 mm, while head forward pitch (relative to vehicle) was in between 4 and 23 degrees. In attentive scenarios, head rearward displacement in anticipation of an oncoming braking event was observed up to 110 mm.

It is shown that in all 5 Attentive-Driver tests the mean peak head forward displacement was 57 mm with a standard deviation of 18 mm. In 17 Attentive-Automatic tests, the mean peak head forward displacement was equal to 95 mm with a standard deviation of 21 mm. The Tukey post-hoc test showed that the mean difference of -38 mm was statistically significant (p=0.00). This indicates that automatic braking for an attentive driver induces on average 38 mm more peak head forward displacement than when an attentive driver brakes himself (p=0.00).

It is shown that in all 18 Distracted-Automatic tests the mean peak head forward displacement was 123 mm with a standard deviation of 14 mm. In 12 Distracted-Warning-Driver tests, the mean peak head forward displacement was equal to 54 mm with a standard deviation of 24 mm. The Tukey post-hoc test showed that the mean difference of -70 mm was statistically significant (p=0.00). This indicates that automatic braking for a distracted driver induces on average 70 mm more peak head forward displacement than when a distracted driver brakes himself after a warning was provided (p=0.00).

Additionally, it is shown that no statistical significant difference exists in peak head forward motion between an attentive driver that induces the brakes himself and a distracted driver that induces the brakes himself after a warning (p=0.99).

In Table 3, the results from a one-way ANOVA and a Tukey post-hoc test are shown for peak head forward displacement in anticipation and in rebound. Head forward displacement in anticipation is defined as the difference between the peak head forward displacement in the second prior to the braking and the average head forward displacement in the ten seconds prior to braking. Head forward displacement in rebound is defined as the difference between the peak head forward displacement in the two seconds after braking and the average head forward displacement in the ten seconds prior to braking.

Table 2: One-way ANOVA and Tukey post-hoc test results for peak head forward displacement (95% confidence interval).

Braking event	Braking event	Mean difference	p
Peak head forward displacement [mm]			
Attentive – Driver (μ=57, σ=18, n=5)	Attentive – Automatic (μ=95, σ=21, n=17)	-38	0.00
	Distracted – Warning – Driver (μ=54, σ=24, n=12)	3	0.99
	Distracted - Automatic (μ=123, σ=14, n=18)	-67	0.00
Attentive – Automatic (μ=95, σ=21, n=17)	Distracted – Warning – Driver (μ=54, σ=24, n=12)	40	0.00
	Distracted - Automatic (μ=123, σ=14, n=18)	-30	0.00
Distracted – Warning – Driver (μ=54, σ=24, n=12)	Distracted - Automatic (μ=123, σ=14, n=18)	-70	0.00

A statistically significant difference peak head forward displacement in anticipation is observed between Attentive-Automatic and both Distracted-Warning-Driver and Distracted-Automatic. The difference is 5 mm, which indicates that an attentive driver in automatic braking puts his head 5 mm more backward than distracted drivers do. For an attentive driver that applies the brakes himself, the difference is 3 mm, however not statistically significant.

The analysis on rebound indicates that an attentive driver that applies the brakes himself shows 52 mm less head backward rebound than an attentive driver undergoing automatic braking, as well as a distracted driver undergoing automatic braking. Both comparisons are statistically significant (p=0.00). The same comparison holds for a distracted driver that applies the brakes after a warning, however a lower difference of 37 mm is shown for both cases (p=0.01).

Statistical analysis on braking parameters
Furthermore, a statistical analysis is performed on braking parameters. Braking force in Distracted-Warning-Driver scenarios (μ = 1020 N, σ = 99, n = 13) is significantly lower than in all other events: 265 N, 284 N and 265 N lower respectively (all p=0.00). Braking mean acceleration in Attentive-Driver scenarios (μ = 7.16 m/s^2, σ = 0.51, n = 6) is larger than in all other events: 1.18 m/s^2, 1.11 m/s^2, 1.43 m/s^2 larger (all p=0.00).

Table 3: One-way ANOVA and Tukey post-hoc test results for peak head forward displacement in anticipation and in rebound (95% confidence interval).

Braking event	Braking event	Mean difference	p
Peak head forward displacement - anticipation [mm]			
Attentive – Driver (μ=-3, σ=7, n=4)	Attentive – Automatic (μ=-5, σ=4, n=16)	-2	0.79
	Distracted – Warning – Driver (μ=0, σ=3, n=12)	3	0.52
	Distracted - Automatic (μ=0, σ=3, n=17)	3	0.42
Attentive – Automatic (μ=-5, σ=4, n=16)	Distracted – Warning – Driver (μ=0, σ=3, n=12)	5	0.00
	Distracted - Automatic (μ=0, σ=3, n=17)	5	0.00
Distracted – Warning – Driver (μ=0, σ=3, n=12)	Distracted - Automatic (μ=0, σ=3, n=17)	0	1.00
Peak head forward displacement - rebound [mm]			
Attentive – Driver (μ=-10, σ=10, n=5)	Attentive – Automatic (μ=-62, σ=31, n=15)	52	0.00
	Distracted – Warning – Driver (μ=-25, σ=17, n=6)	15	0.72
	Distracted - Automatic (μ=-61, σ=21, n=16)	52	0.00
Attentive – Automatic (μ=-62, σ=31, n=15)	Distracted – Warning – Driver (μ=-25, σ=17, n=6)	-37	0.01
	Distracted - Automatic (μ=-61, σ=21, n=16)	0	1.00
Distracted – Warning – Driver (μ=-25, σ=17, n=6)	Distracted - Automatic (μ=-61, σ=21, n=16)	37	0.01

Brake force build-up rate in Attentive-Driver scenarios (μ = 3898 N/s, σ = 996, n = 6) is larger than in both Attentive-Automatic and Distracted-Automatic braking events: 1455 N/s and 1474 N/s larger respectively (all p=0.00). Similarly, brake force build-up rate in Distracted-Warning-Driver (μ = 3530 N/s, σ = 512, n =

13) is larger than in both automatic braking events: 1087 N/s and 1106 N/s larger respectively (all p=0.00).

Furthermore, the initial rise of the vehicle deceleration as a result of braking was computed, and here called braking jerk. The braking jerk in Attentive-Driver scenarios ($\mu = 21.8$ m/s^3, $\sigma = 5.6$, n = 6) is larger than in both Attentive-Automatic and Distracted-Automatic braking events: 10.5 m/s^3 and 11.0 m/s^3 larger respectively (all p=0.00). Similarly, braking jerk in Distracted-Warning-Driver scenarios ($\mu = 20.9$ m/s^3, $\sigma = 2.7$, n = 13) is larger than in both Attentive-Automatic and Distracted-Automatic braking events: 9.6 m/s^3 and 10.0 m/s^3 larger respectively (all p=0.00).

DISCUSSION

This test series was performed in conditions that are different from everyday traffic. First of all, a professional test driver was the driver of the car, who most likely has better vehicle handling skills than an average consumer driver. Test tracking testing, compared to real-world traffic, has some implications as well. There was no other traffic, which could have reduced attentiveness. On the other hand, test track driving involves high responsibilities, which probably elevated the awareness level of the driver. Even though the driver was distracted from his driving task through cell phone message typing, he was aware that somewhere along the 4 km straight an emergency braking event would occur. Therefore, realistic distraction is probably more serious, i.e. causes even slower or later reactions.

In order to make a good comparison between self-induced and automatic braking events, a design emergency braking pulse was used in the brake actuator. In spite of this, the self-induced braking effort was typically higher than the automatic braking effort. Brake force build-up rate was over 30% larger for self-induced scenarios than for automatic scenarios. Closely related, the estimated braking jerk was nearly 50% larger in self-induced scenarios. In Attentive-Driver scenarios, the mean acceleration was above 7 m/s^2 while in other scenarios it was below 6 m/s^2. An additional factor influencing the braking performance were wet road conditions and a vehicle with large additional mass due to equipment. As such, if the driver would have induced lower levels of braking, lower levels of head motion would have been observed as well.

Time synchronization of all measured data was unfortunately not possible. Therefore, no statements could be made on reaction time. The figures in Appendix 1 are derived by overlaying the initial rise of head motion with the build-up of braking force.

The eye tracking system used for computing head motion is sensitive to rapid variations in light conditions, as is shown in the noisy signal in for example Figure 3 just after 470 s. Tests in which this noise occurred during the braking event were excluded from the dataset.

This study has shown that if a driver is attentive and aware of automatic braking about to occur, his head forward motion is 38 mm larger than when he applied the brakes himself. This indicates that a driver is better able to control his body posture if he fully controls the braking action himself.

It is also shown that providing a warning to a distracted driver does not hamper his ability to control his posture, compared to a fully attentive driver, since there was no statistical difference. Possibly, the reaction time of a distracted and warned driver is reduced, but this could not be quantified.

This study quantified a significant difference in anticipation, i.e. the driver moved his head rearward in anticipation of braking, however this was only 5 mm and as such does not have consequences for safety. The rebound of the head once the braking is removed is over 60 mm for automatic braking scenarios, while it is on average 10-25 mm for self-induced braking.

The largest difference in head forward displacement was found between attentive, self-induced braking and distracted, automatic braking. The distracted driver with automatic braking underwent on average 123 mm head forward displacement, compared to 57 mm. Head pitch was observed in this study, but no significant differences between braking scenarios was observed.

CONCLUSIONS

Based on 61 braking tests with a professional driver in four different braking scenarios, the following conclusions regarding head posture can be drawn:

- Automatic braking for a distracted driver induces on average 123 mm of head forward displacement, which is 67 mm larger than for an attentive driver that applies the brakes himself.
- Automatic braking for an attentive driver induced substantially higher head motion, which indicates that posture control is dependent on anticipation on the braking pulse.
- Head rebound after braking was substantial, but head motion as a result of anticipation was not. Head pitch was statistically insignificant.

Recommendations for further study include performing tests with multiple volunteers, extending vehicles motion to lane change emergency maneuvers and by using a vehicle environment that can easily be modeled in a simulation environment, to allow for the validation of human models.

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APPENDIX 1: Time-history plots

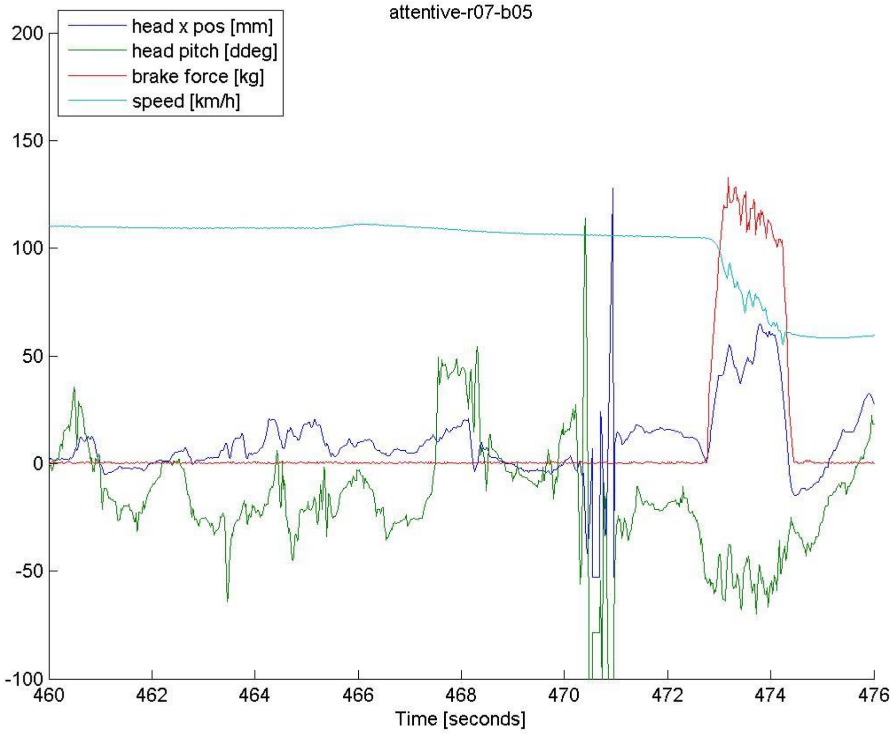

Figure 3. Head forward position, head pitch angle, brake force and vehicle speed in one example test for an Attentive-Driver braking scenario.

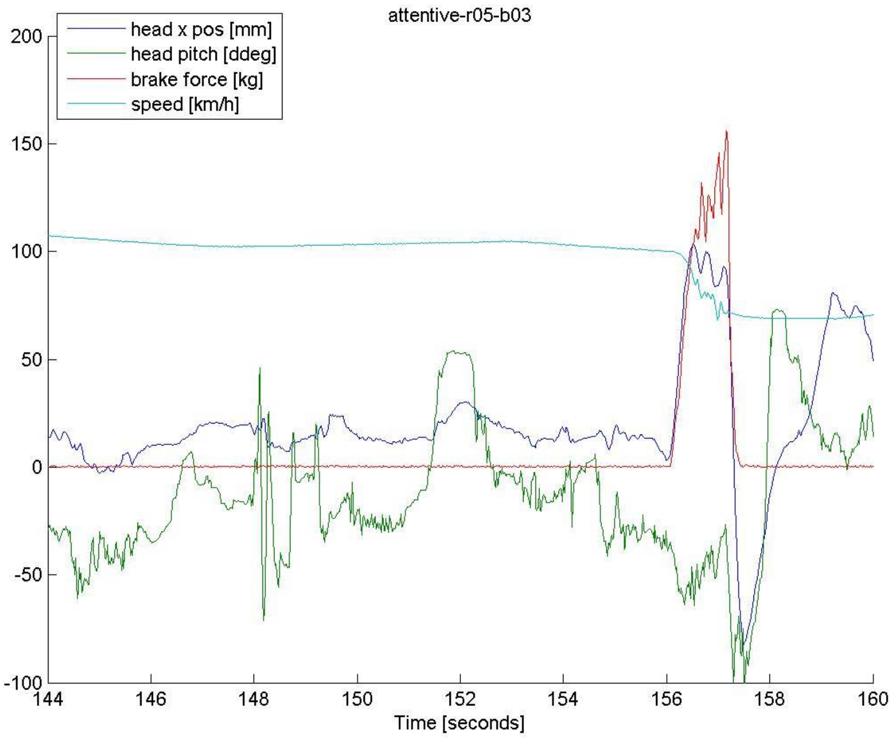

Figure 4. Head forward position, head pitch angle, brake force and vehicle speed in one example test for an Attentive-Automatic braking scenario.

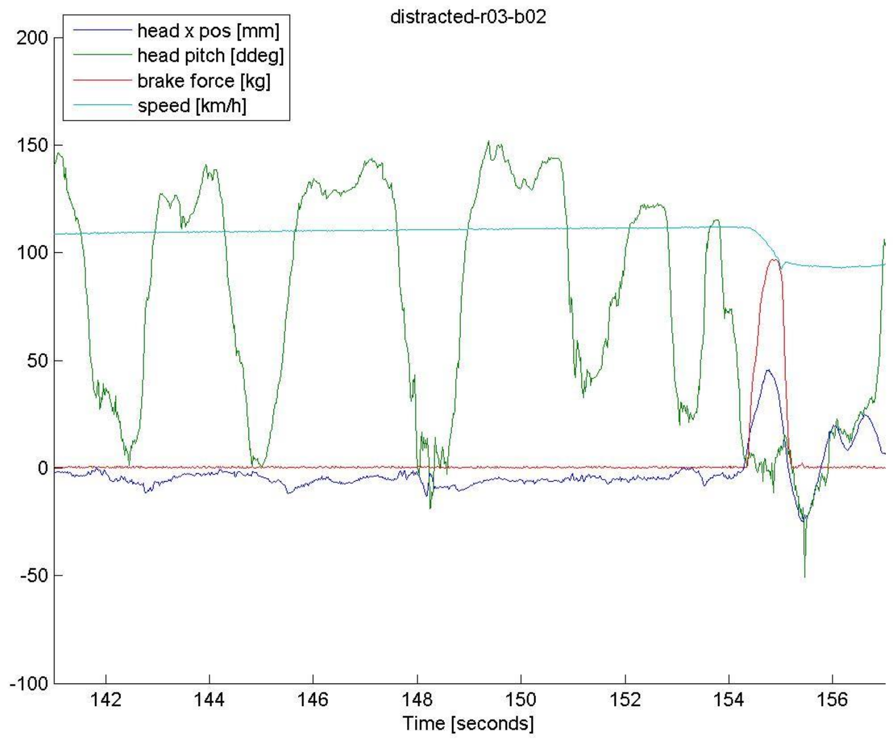

Figure 5. Head forward position, head pitch angle, brake force and vehicle speed in one example test for a Distracted-Warning-Driver braking scenario.

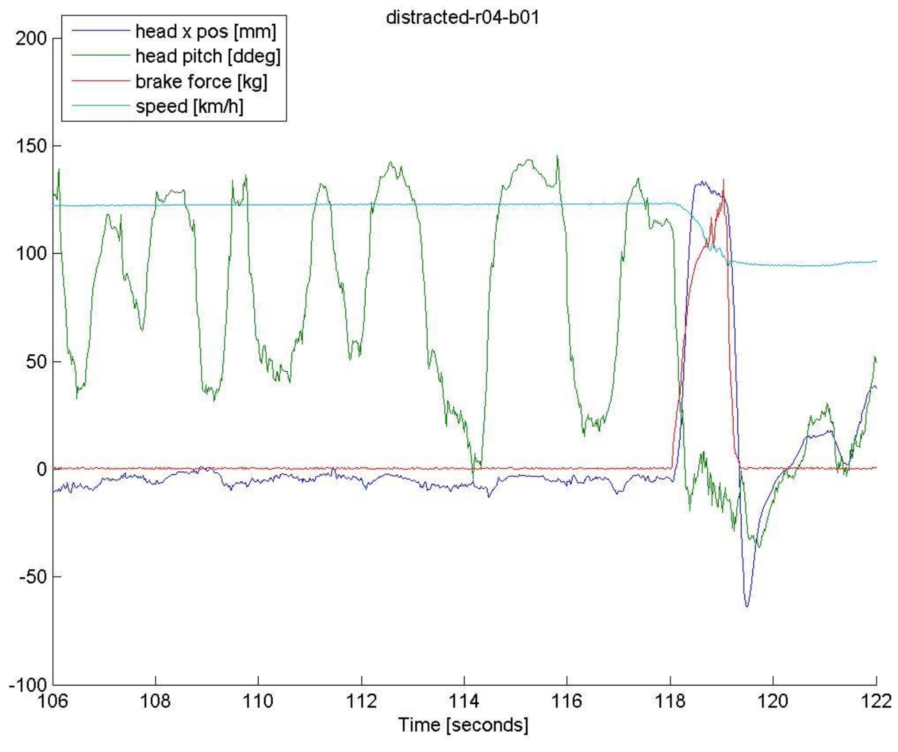

Figure 6. Head forward position, head pitch angle, brake force and vehicle speed in one example test for a Distracted-Automatic braking scenario.

APPENDIX 2: Correlation Matrix

		Peak head forward displacement [mm]	Peak head pitch [deg]	Estimated jerk [m/s^3]	Braking force [N]	Braking jerk [N/s]	Mean acceleration [m/s^2]	deltaV [km/h]	Entrance speed [km/h]	Braking force setting [N]	Braking rate setting [N/s]
Peak head forward displacement [mm]	Pearson Correlation	1	.095	-,644**	.256	-,635**	-.197	.253	,311*	,658**	,512**
	Sig. (2-tailed)		.586	.000	.067	.000	.163	.070	.025	.000	.000
	N	52	35	52	52	52	52	52	52	52	52
Peak head pitch [deg]	Pearson Correlation	.095	1	.113	-.233	.113	-.085	-,375*	.319	-.052	-.041
	Sig. (2-tailed)	.586		.518	.179	.518	.626	.026	.061	.766	.817
	N	35	35	35	35	35	35	35	35	35	35
Estimated jerk [m/s^3]	Pearson Correlation	-,644**	.113	1	-,345**	,926**	,587**	-.097	-.043	-,776**	-,475**
	Sig. (2-tailed)	.000	.518		.006	.000	.000	.455	.745	.000	.000
	N	52	35	61	61	61	61	61	61	61	61
Braking force [N]	Pearson Correlation	.256	-.233	-,345**	1	-.069	.162	,433**	.192	,611**	,581**
	Sig. (2-tailed)	.067	.179	.006		.599	.212	.000	.137	.000	.000
	N	52	35	61	61	61	61	61	61	61	61
Braking jerk [N/s]	Pearson Correlation	-,635**	.113	,926**	-.069	1	,479**	-.168	-.045	-,583**	-.225
	Sig. (2-tailed)	.000	.518	.000	.599		.000	.195	.730	.000	.081
	N	52	35	61	61	61	61	61	61	61	61
Mean acceleration [m/s^2]	Pearson Correlation	-.197	-.085	,587**	.162	,479**	1	,661**	.191	-,371**	-.244
	Sig. (2-tailed)	.163	.626	.000	.212	.000		.000	.140	.003	.058
	N	52	35	61	61	61	61	61	61	61	61
deltaV [km/h]	Pearson Correlation	.253	-,375*	-.097	,433**	-.168	,661**	1	.212	.073	.006
	Sig. (2-tailed)	.070	.026	.455	.000	.195	.000		.100	.577	.965
	N	52	35	61	61	61	61	61	61	61	61
Entrance speed [km/h]	Pearson Correlation	,311*	.319	-.043	.192	-.045	.191	.212	1	.200	.168
	Sig. (2-tailed)	.025	.061	.745	.137	.730	.140	.100		.122	.195
	N	52	35	61	61	61	61	61	61	61	61
Braking force setting [N]	Pearson Correlation	,658**	-.052	-,776**	,611**	-,583**	-,371**	.073	.200	1	,845**
	Sig. (2-tailed)	.000	.766	.000	.000	.000	.003	.577	.122		.000
	N	52	35	61	61	61	61	61	61	61	61
Braking rate setting [N/s]	Pearson Correlation	,512**	-.041	-,475**	,581**	-.225	-.244	.006	.168	,845**	1
	Sig. (2-tailed)	.000	.817	.000	.000	.081	.058	.965	.195	.000	
	N	52	35	61	61	61	61	61	61	61	61

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).