DRIVERS' ASSESSMENT OF DRIVING A 32 METER A-DOUBLE WITH AND WITHOUT FULL AUTOMATION IN A MOVING BASE SIMULATOR

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Abstract

In situations where Long Combination Vehicles can be challenging to maneuver, drivers could be supported through automated driving systems. A safe way to assess prototypes of such systems is to take advantage of driving simulators. This study assessed the realism of driving a 32m and 80 ton A-double in an advanced moving-base driving simulator, with and without full automation. The conclusions were that the realism of the road environment, vehicle suspension, vibrations, steering-wheel feeling and the maneuverability/drivability was on adequate levels but would benefit of more tuning. More urgent were adjustments of braking, acceleration, level of engine sound and improved view in the right-hand side mirror. Two tested automated driving systems were appreciated for their lane positioning and driving performance, with a slight preference of the more advanced system for lateral control. Negative comments referred to harsh decelerations before curves. The subjective assessment was much in correlation with the objective data from the same simulator experiment.

Keywords: Higher Capacity Vehicles, High Capacity Transport, Heavy Vehicles, LCV, automation, Optimal Control Problem, Cost Function, Rearward Amplification, RWA, High Speed Offtracking, HSO

1. Introduction

Higher Capacity Vehicles (HCVs) are expected to increase transport and energy efficiency and thereby decrease costs as well as carbon dioxide emissions (OECD 2009). Since about two decades, Sweden and Finland allows a maximum length of 25.25m and a gross vehicle weight of 60 ton within the Europe and Modular System (EMS). In Sweden, an increasing number of different Higher Capacity Vehicle combinations are permitted for transport on designated roads. In June 2014, there were 46 active HCVs (Energieffektiva Transporter 2014). One of those HCVs is an A-double transporting goods between the cities Göteborg and Malmö. The A-double has a maximum allowed gross vehicle weight of 80 ton, is 32m long, consist of a 6x4 tractor unit followed by a three-axle semi-trailer, two-axle dolly and a three-axle semi-trailer unit.

Depending on the configuration of a Long Combination Vehicle (LCV), it can be more difficult to maneuver than conventional heavy vehicles. One way to support the driver of a LCV could be to partially or fully automatize the maneuvering in challenging driving situations (Nilsson et al., 2014). Automated passenger cars are now a boiling subject for research and development. In Sweden for example, Volvo Cars, the Swedish Transport Administration and other stakeholders are collaborating around a public pilot with eventually 100 self-driving cars on selected real roads around Göteborg (VCC 2014). Public pilots with self-driving heavy vehicles, and in particular LCVs, implies much greater challenges due to their more complex vehicle dynamics and size which may lead to severe consequences if something would go wrong.

A safe way to test prototypes of automated driving systems for heavy vehicles is to take advantage of advanced moving-base driving simulators (Jansson et al., 2014). Conducting experiments with heavy vehicles, and in particular LCVs, put great demands on the simulator performance and fidelity regarding the representation of vehicle dynamics. Unlike for the majority of passenger-car drivers, truck driving is a profession. Experienced truck drivers have impressive skills in maneuvering a heavy vehicle. Therefore, one might hypothesize that experienced truck drivers will have very high demands on the realism of driving a truck in a simulator, and the way an automated driving system controls a heavy vehicle. Therefore on might expect that experienced truck drivers will only accept an automated driving system if it drives "at least" as good as themselves.

There were three objectives of this study. Firstly, a general assessment of the realism of an advanced driving simulator, secondly, the assessment of driving a model of a 32m and 80 ton A-double in the simulator, and thirdly, the assessment of two automated driving systems for the A-double.

2. Method

2.1 Driving Simulator

The study was conducted in the advanced moving-base driving simulator Sim IV, located at VTI in Göteborg, Sweden. In Sim IV, the heavy vehicle mock-up is a Volvo FH12, where the left and right hand side mirrors are replaced with LCD screens. The motion system, delivered by Bosch-Rexroth, combines the possibilities of a hexapod motion base with the extended motion envelope in x- and y-direction through a 5x5 m sled-system (Figure 1a). The visual system gives the driver a 210-degree forward field of vision (Figure 1b). Sound simulating the own vehicle and the directional sound of surrounding traffic is given via a 6.1 speaker system integrated in the truck cabin (Jansson et al., 2014).

Figure 1. VTI Sim IVs a) motion platform and b) 210-degree forward field of vision

2.2 Truck Model

A high-fidelity two-track model of an A-double was implemented in the simulator to emulate the vehicle dynamics. The A-double consisted of a 6x4 tractor unit followed by a three-axle semi-trailer, two-axle dolly and a three-axle semi-trailer unit (Figure 2). The total vehicle length was 32m and the total weight was set to 80 ton. To accomplish high realism considering truck vehicle dynamics, extensive subjective testing was carried out prior to the experiment by experienced truck drivers.
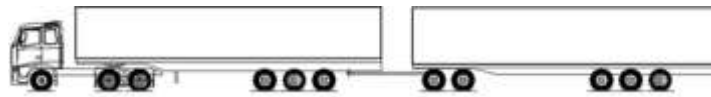

Figure 2. Illustration of the 32 meter and 80 ton A-double used in the study

2.2 Two Automated Driving Systems

Prior to the driving simulator experiment, two automated driving systems (Auto 1 and Auto 2) were implemented in the simulator. The implementation was done using independent control systems for the vehicle's longitudinal velocity and the vehicle's steering input, referred to as the longitudinal and lateral control system respectively. The same longitudinal control system was used for both automated modes. In the case of lateral control, two different closed-loop control systems were used to handle the vehicle steering in the two automated driving modes. Both lateral control systems were defined as linear feedback tracking controllers using a pre-calculated geometric reference path. For Auto 1, the geometric reference path was defined as the lane center from which the requested road wheel angle was calculated. For Auto 2, the reference path was calculated using a path planning algorithm based on a receding horizon optimization approach considering the accelerations and positions of all vehicle units. The prediction horizon for the path planner in Auto 2 was set to 10s. The algorithms for Auto 1 and Auto 2 are described in more detail by Nilsson et al. (2014). The values for the algorithm parameters were determined by subjective evaluation to achieve smooth and comfortable driving. In the simulator experiments the auto modes were limited to a maximum speed of 70 km/h.

2.3 Subjects

The subjects were divided into two groups. Group A consisted of drivers from Volvo Product Development, and Group B consisted of professional truck drivers from a haulage contractor. All participants had driver license for heavy truck and trailer except two, who had driver license for heavy truck only. In Group A, years with truck license ranged between 0-39 years, with an average of 7 years, and the km driven/year ranged between 10-500 km/year with an average of 100 km/year. In Group B, years with truck license ranged between 2-39 years, with an average of 30 years, and the km driven/year ranged between 65 000-130 000 km/year with an average of 110 000 km/year. Three of the professional drivers regularly drive longer vehicle combinations with special permit from the Swedish Transport Administration authority. In total, 18 out of 20 drivers completed the experiment. Two subjects had to interrupt due to motion sickness. Thus, Group A consisted of 11 drivers, and Group B consisted of 7 drivers which completed the experiment.

2.4 Driving Scenario and Experimental Procedure

The driving scenario was set up to reflect a transport mission on a relatively demanding two-lane country road, where each lane was 3.5m wide. The driven road section was 8.3 kilometers and was based on measurements of a real road. Thus, the road implemented in the simulator included profiles of the road curvature, elevation, lateral inclination and the surface roughness. The drivers were instructed to drive in the right lane and were informed that there would be no other traffic and that no critical events would occur.

The experiment followed the setup illustrated in Figure 3. The experiment was divided in four sessions: Training, Manual driving, Automated driving 1 and Automated driving 2. The subjects started with a training session, directly followed by the Manual driving session. All sessions except Training were driven on the same eight kilometer route and took approximately ten minutes each. The two sessions with automated driving differs from each other by the usage of two different lateral control systems, see Section 2.2. The order of the two automated driving sessions was shifted randomly for each subject. After the Manual driving and after each Automated driving session the subjects filled in a questionnaire.

Instructions   Questionnaire A,B   Questionnaire C

| Training | Manual driving | Automated driving 1/2 | Automated driving 2/1 |
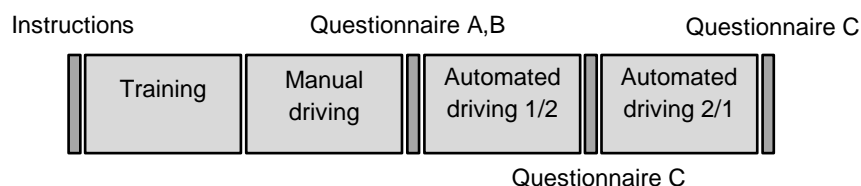
Questionnaire C

Figure 3. Experiment setup. Each session block was 10 min. The two automated driving modes were shifted randomly for each subject

2.5 Questionnaires

The drivers filled in three types of questionnaires:

A. General Assessment of the Realism of Driving in the Simulator
B. Assessment of Driving the A-double Manually in the Simulator
C. Assessment of the Automated Driving Systems

Questionnaires A and B were filled in after the 'Manual driving' session, and a one questionnaire C was filled in after each session of 'Automated driving' (Figure 3).

The majority of questions were in the form of 7 degree rating scales with the possibility to write voluntary comments, see example below.

How realistic was the driving in the simulator in general?

1 2 3 4 5 6 7

Not realistic at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very realistic

Comment:_____

The average rating were calculated for each question and driver group separately, and presented in of staple diagrams
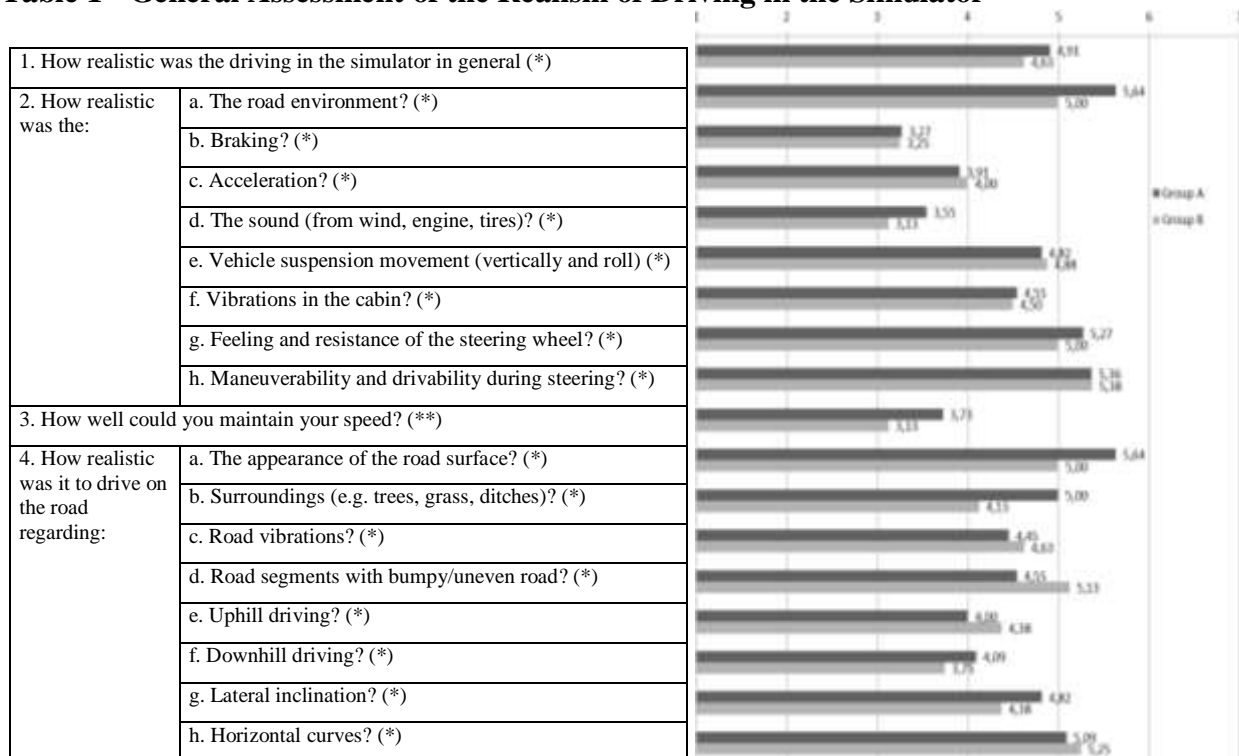
3. Results

3.1 General Assessment of the Realism of Driving in the Simulator (Questionnaire A)

Table 1 shows the average ratings for Questionnaire A for the two driver groups separately.

Both groups of drivers rates the realism of the road environment, vehicle suspension, vibration, steering-wheel feeling and the maneuverability/drivability during steering higher than the realism of braking, acceleration and the sound. The ability to maintain the speed was also rated low. The realism of driving on the road is rated as adequate except for uphill and downhill driving which is rated somewhat lower. Overall, driver group A seems to rate the visual realism of the road environment and surroundings somewhat higher than group B.

The drivers' comments refer mostly to poor acceleration ability and a low engine sound which made it difficult to hear the engine workload.

Table 1 - General Assessment of the Realism of Driving in the Simulator

1. How realistic was the driving in the simulator in general (*)	
2. How realistic was the:	a. The road environment? (*)
	b. Braking? (*)
	c. Acceleration? (*)
	d. The sound (from wind, engine, tires)? (*)
	e. Vehicle suspension movement (vertically and roll) (*)
	f. Vibrations in the cabin? (*)
	g. Feeling and resistance of the steering wheel? (*)
	h. Maneuverability and drivability during steering? (*)
3. How well could you maintain your speed? (**)	
4. How realistic was it to drive on the road regarding:	a. The appearance of the road surface? (*)
	b. Surroundings (e.g. trees, grass, ditches)? (*)
	c. Road vibrations? (*)
	d. Road segments with bumpy/uneven road? (*)
	e. Uphill driving? (*)
	f. Downhill driving? (*)
	g. Lateral inclination? (*)
	h. Horizontal curves? (*)

(*) Not realistic at all - Very realistic, (**) Not good at all - Very good
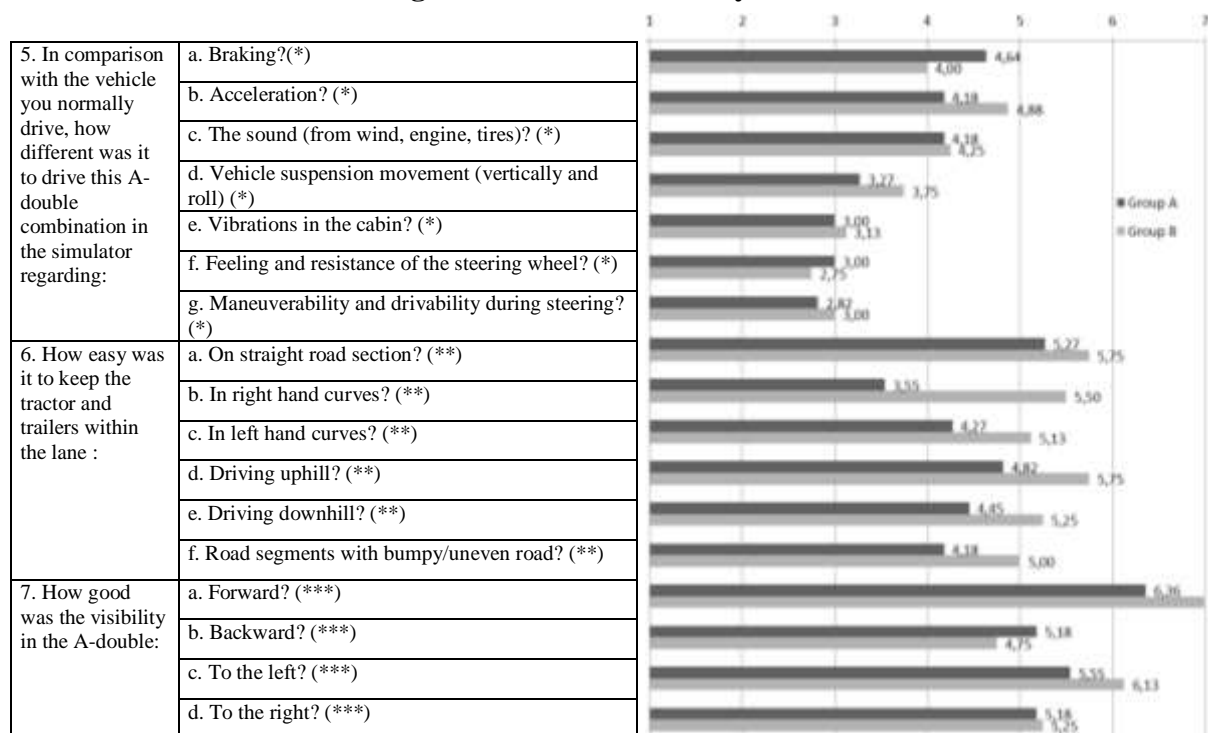
3.1 Assessment of Driving the A-double Manually in the Simulator (Questionnaire B)

Table 2 shows the average ratings for Questionnaire B for the two driver groups separately.

When comparing the driving of the A-double with the vehicle they normally drive, both groups of drivers rates a larger difference in braking, acceleration, and sound than when compared to the suspension, vibrations, steering-wheel feeling and the maneuverability/drivability. Concerning how easy it was to keep the A-double within the lane in different driving situations, the professional drivers in Group B consistently rates that it was less difficult than the drivers in Group B. The visibility is rated as adequate, with somewhat lower rates for the visibility towards the back and to the right.

The drivers' comments refer mostly to the difficulty to see the trailers in the right-hand side mirror, especially in right-hand curves.

Table 2- Assessment of Driving the A-double Manually in the Simulator

5. In comparison with the vehicle you normally drive, how different was it to drive this A-double combination in the simulator regarding:	a. Braking?(*)	Group A 4,64; Group B 4,00
	b. Acceleration? (*)	Group A 4,18; Group B 4,88
	c. The sound (from wind, engine, tires)? (*)	Group A 4,18; Group B 4,25
	d. Vehicle suspension movement (vertically and roll) (*)	Group A 3,27; Group B 3,75
	e. Vibrations in the cabin? (*)	Group A 3,00; Group B 3,13
	f. Feeling and resistance of the steering wheel? (*)	Group A 3,00; Group B 2,75
	g. Maneuverability and drivability during steering? (*)	Group A 2,82; Group B 3,00
6. How easy was it to keep the tractor and trailers within the lane :	a. On straight road section? (**)	Group A 5,22; Group B 5,75
	b. In right hand curves? (**)	Group A 3,55; Group B 5,50
	c. In left hand curves? (**)	Group A 4,22; Group B 5,13
	d. Driving uphill? (**)	Group A 4,82; Group B 5,75
	e. Driving downhill? (**)	Group A 4,45; Group B 5,25
	f. Road segments with bumpy/uneven road? (**)	Group A 4,18; Group B 5,00
7. How good was the visibility in the A-double:	a. Forward? (***)	Group A 6,36
	b. Backward? (***)	Group A 5,18; Group B 4,75
	c. To the left? (***)	Group A 5,55; Group B 6,13
	d. To the right? (***)	Group A 5,18; Group B 5,25

(*) No difference at all – Very large difference, (**) Very difficult – Not difficult at all, (***) Not good at all – Very good

3.3 Assessment of the Automated Driving Systems (Questionnaire C)

Table 3 shows the avarage ratings for Auto 1 and Auto 2 for the two driver groups separately (Questionnaire C).

The driver groups' rates the driving performance of both automated driving systems rather high (Question 10 and 11), although there is a slight tendency to rate Auto 2 higher. The groups' rates are also more equivalent for Auto 2. According to the drivers' comments they were positive to how well the systems performed regarding lane positioning and maintaining speed on straight road sections. In uphill sections however, the acceleration could start sooner and be higher. A reoccurring comment referred to unduly harsh decelerations before curves – mainly with Auto 2. With Auto 1, the driving was a bit wobbly, the rearmost trailers tended to oscillate, and the trailer(s) were close or crossed the centerline in right-hand curves. With Auto 2, the

"planning" of the road positioning was better for the whole vehicle combination and the driving speed was perceived as higher. On the negative side, the driving of Auto 2 was perceived as more "intense" with nervous steering-wheel movements.

Questions 12-15 concern the willingness to use the systems in reality. Here, there is a slight tendency for Auto 1 to get higher rates; especially in Group A. Herein is also the largest difference between the two driver groups, where the experienced drivers would clearly be less willing to use them on country roads and in city traffic. There is also a large difference between the groups regarding whether they would feel safe with the system in reality and in the same driving situation as they drove in the simulator, with or without other vehicles within sight but not in the immediate vicinity. According to the drivers' comments, they do not believe that automated systems can assess a more complex traffic environment with several other "unpredictable" road users (this was especially the opinion from the professional drivers). Requirements on a more developed automated driving system would be good feedback of what the system "is about to do", and the possibility to take over the control if needed.

An additional question was asked about whether the drivers wanted to take control of the vehicle at some occasion when driving with any of the automated systems (however they were instructed not to do this in the experiment). The answers showed that of the 18 drivers in total, 5 wanted to take control at some occasion when driving with Auto 2, and 6 wanted to take control at some occasion when driving with Auto 1. It was mostly before or in curves they wanted to take over the control.

Table 3 - Assessment of the Automated Driving Systems Auto 1 and Auto 2
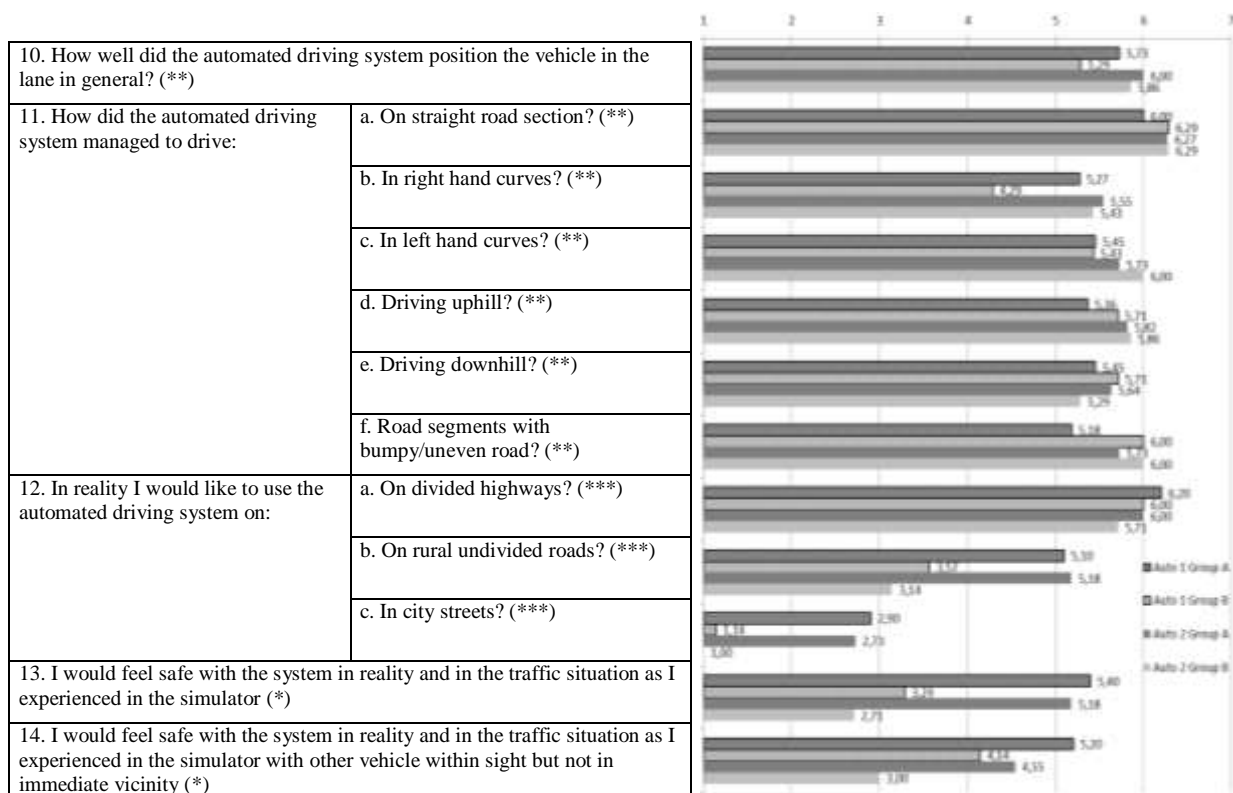
(*) Not safe at all – Very safe, (**) Not good at all – Very good, (***) Not often at all – Very often

4. Discussion

There were three objectives of this study. Firstly, a general assessment of the realism of an advanced driving simulator, secondly, the assessment of driving a model of a 32m and 80 ton A-double in the simulator, and thirdly, the assessment of two automated driving systems for the A-double. Two driver groups participated in the study; Group A consisting of drivers from Volvo Product Development, and Group B consisting of professional truck drivers. The drivers in Group A had less driving hours compared to the professional drivers. However, many of them were used to daily judge new truck features and give subjective feedback

The results from the assessment questionnaires showed that both driver groups rated the realism of the road environment, vehicle suspension, vibration, steering-wheel feeling and the maneuverability/drivability during steering to be adequate as well as higher than the realism of braking, acceleration and the sound. The same difference in ratings were observed when the drivers were asked to compare the simulator driving of the A-double with the vehicle combination they normally drive, which for the majority of drivers was truck and semitrailer. The driver comments revealed poor acceleration ability, and that the engine sound was too low which made it difficult to hear the engine workload. The visibility was rated as adequate, but according to the comments it was difficult to see the trailers in the right-hand side mirror, especially in right-hand curves (the side mirrors are in Sim IV replaced with one LCD screen on each side which lacks a wide-angle effect). Nevertheless, the professional drivers clearly found it easier to keep the A-double within the lane on all types of road sections. This difference was expected but perhaps not to that degree.

The realism of driving on the road was rated as adequate except for uphill and downhill driving which was rated somewhat lower. This may be related to both the poor acceleration ability, and the low rating of the ability to maintain the speed during manual driving. To achieve an accurate speed perception in driving simulators is a general, well-known and complex issue that requires further research (Fischer et al., 2012).

Regarding the two automated driving systems, the driver groups rated both automated driving systems rather high in terms of lane positioning and driving performance. However, based on ratings and comments the drivers seemed to prefer Auto 2 as it kept the vehicle combination better in the lane than Auto 1. Auto 2 however was perceived as more "intense" with nervous steering-wheel movements. A reoccurring comment referred to unduly harsh decelerations before curves – especially with Auto 2.

The ratings and comments about the two automated driving systems are much related to their different lateral control systems. The difference between Auto 1 and Auto 2 was the path planning algorithm in Auto 2 that enabled the calculation of a feedforward road wheel angle considering the accelerations and positions of all vehicle units. The road wheel angle in Auto 1 was merely based on the immediate position of the front axle center relative to the lane center. Nilsson et al (2014) analyzed the logged data from the current simulator study. In order to objectively compare the performance of the manual driving and the automated driving systems Auto 1 and Auto 2, the authors formulated an optimal control problem with a selection of parameters that were expected to reflect the features of traffic safety, ride comfort, transport efficiency, and the general performance of a LCV. The parameters are listed in Table 4, and the result of the calculations over the complete driving route is shown in Figure 4.

Figure 4 shows that the (cost function) components RWA_u (Rearward Amplification) and HSO_u (High Speed Offtracking) were slightly smaller in the manual driving than for Auto 1 and Auto 2. The centerline distance offset components d_1 and d_{11} were significantly smaller for Auto 2 mode than for Auto 1. This can be an effect of the control system gain settings which were

determined through subjective evaluations prior the experiments to accomplish smooth and comfortable driving. In particular, the gain settings for Auto 1 had to be set more "soft". The more exact lane positioning of Auto 2 likely explain the somewhat more consistent and higher ratings of Auto 2 regarding lane positioning and driving performance on straight road segments, in right and left hand curves. Noteworthy is that for the manual driving, the offset components d_1 and d_{11} are between the values for Auto 1 and Auto 2.

The harsh decelerations perceived by the drivers, especially before curves, can also be discerned from Figure 4. The levels of the lateral jerk and the longitudinal deceleration components were as much as 60-70% lower for the manual driving than both automated systems. The latter indicates that the manual driving was performed smoother and thus focused on the feature ride comfort. This is also supported by the negative longitudinal jerk in Figure 4 which also about 60% smaller for the manual driving than both automated systems. Lastly, Figure 4 shows that the vehicle speed component is slightly lower for the manual driving which leads to a higher final driving time. This is despite the fact that the maximum speed during manual driving in several cases was higher than Auto 1 and Auto 2 which had a set speed limitation of 70 km/h (Nilsson et al., 2014).

Table 4. Characteristics Used in the Optimal Control Problem Cost Function (from Nilsson et al. (2014)).

| Characteristics	Symbol	Unit
Utilized Rearward Amplification	RWA_u	[-]
Utilized Offtracking	HSO_u	[m]
Centerline Distance Offset, Axle 1	d_1	[m]
Centerline Distance Offset, Axle 11	d_{11}	[m]
Lateral Acceleration, Unit 1	$a_{y,1}$	[m/s^2]
Lateral Jerk, Unit 1	$\dot{a}_{y,1}$	[m/s^3]
Positive Longitudinal Acceleration, Unit 1	$a_{x(+),1}$	[m/s^2]
Negative Longitudinal Acceleration, Unit 1	$a_{x(-),1}$	[m/s^2]
Positive Longitudinal Jerk, Unit 1	$\dot{a}_{x(+),1}$	[m/s^3]
Negative Longitudinal Jerk, Unit 1	$\dot{a}_{x(-),1}$	[m/s^3]
Road Wheel Angle	δ	[rad]
Yaw Rate, Unit 4	r_4	[rad/s]
Final Driving Time	t_f	[s]
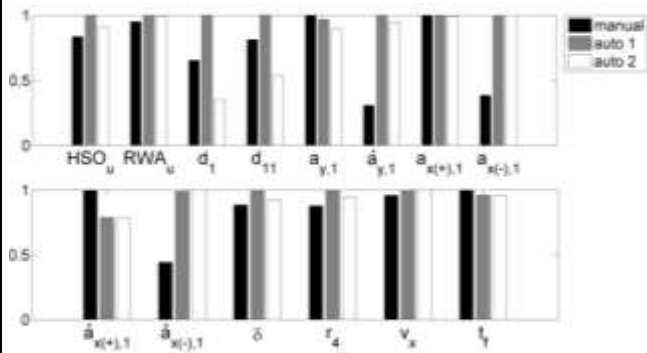
Figure 4. The Calculated Normalized Cost Function Components. Normalized Values on the Y-axes (from Nilsson et al. (2014)).

5. Conclusions

VTIs driving simulator Sim IV is a complex and advanced research tool that continuously is being developed and improved. The driving experience in a simulator depends on the combined performance of visual system, sound, motion system, dynamic vehicle model, powertrain model and, in the present study, the two tested automatic driving systems. The conclusions from the assessment questionnaires is that the realism of the road environment, vehicle suspension, vibration, steering-wheel feeling and the maneuverability/drivability during steering is adequate but would benefit of more tuning. More urgent is adjustments of braking, acceleration, level of engine sound and improved view in the right-hand side mirror.

Based on ratings and comments, both automated driving systems were appreciated for their lane positioning and driving performance, with a slight preference of the more advanced lateral control system. Reoccurring comments referred to harsh decelerations before curves. These subjective statements were in correlation with the objective data from the same simulator experiment. Driver requirements on a more developed automated driving system would be good feedback of what the system "is about to do", and the possibility to take over the control if needed.

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