High speed control of long combination heavy commercial vehicles within safe corridors

Authors

Peter Nilsson, Volvo GTT
Leo Laine, Volvo GTT
Jesper Sandin, VTI

www.vipsimulation.se
High Speed Control of Long Combination Heavy Commercial Vehicles within Safe Corridors

Authors
Peter Nilsson, Volvo GTT
Leo Laine, Volvo GTT
Jesper Sandin, VTI

www.vipsimulation.se
Preface

*High Speed Control of Long Combination Heavy Commercial Vehicles within Safe Corridors* is a collaborative project between Volvo Group Truck Technology (VGTT) and Swedish National Road and Transport Research Institute (VTI) within the competence centre *ViP Driving Simulation Centre* (www.vipsimulation.se).

The main scope of the project was to initiate a technical framework for studying manual and automated high-speed driving of long vehicle combinations (LVCs) in a driving simulator environment.

The project started in 2012 and ended in 2014. The main findings have been published in Nilsson, Laine & Jacobson (2014), and Sandin & Nilsson (2014).

The project has been financially supported by the competence centre ViP, i.e. by ViP partners and the Swedish Governmental Agency for Innovation Systems (VINNOVA).

Participants from VGTT were Peter Nilsson (project manager), Peter Sundström, Leo Laine, Peter Lindroth, Martijn Disse (MSc candidate) and Niklas Fröjd.

Participants from VTI were Bruno Augusto and Jesper Sandin.

Gothenburg, June 2015

*Peter Nilsson*
Quality review

Peer review was performed on 21 July 2015 by Sogol Kharrazi, VTI and on 31 August 2015 by Jolle Ijkema, Scania. Peter Nilsson has made alterations to the final manuscript of the report. The ViP Director Lena Nilsson examined and approved the report for publication on 6 October 2016.
# Table of contents

**Executive summary** .................................................................................................................................................. 11

1. **Introduction** ......................................................................................................................................................... 13
   1.1. Background .................................................................................................................................................. 13
   1.2. Problem formulation .................................................................................................................................. 14
   1.3. Objectives ................................................................................................................................................ 14

2. **Vehicle lateral dynamics of LVCs** ......................................................................................................................... 15
   2.1. Vehicle modelling ........................................................................................................................................ 15
       2.1.1. Kinematic one-track model ........................................................................................................... 15
       2.1.2. One-track model with linear tire slip ............................................................................................. 15
       2.1.3. High-fidelity two-track model ...................................................................................................... 15
   2.2. Performance based characteristics ........................................................................................................... 15

3. **Automated driving control design** ....................................................................................................................... 20
   3.1. Longitudinal control design .................................................................................................................... 20
   3.2. Lateral control design .............................................................................................................................. 21
       3.2.1. Automated driving 1 ....................................................................................................................... 22
       3.2.2. Automated driving 2 ...................................................................................................................... 22

4. **Vehicle dynamics and motion cueing** ................................................................................................................ 24

5. **Simulator study** .................................................................................................................................................... 25
   5.1. Driving simulator ........................................................................................................................................ 25
   5.2. Participants .................................................................................................................................................. 25
   5.3. Driving scenario ........................................................................................................................................ 26
   5.4. Experimental setup .................................................................................................................................... 26
   5.5. Questionnaires ......................................................................................................................................... 27

6. **Results** .................................................................................................................................................................. 28
   6.1. General assessment of the realism of driving in the simulator ................................................................. 28
   6.2. Assessment of driving the A-double manually in the simulator ............................................................... 28
   6.3. Assessment of the automated driving systems Auto 1 and Auto 2 ......................................................... 29
   6.4. Performance characteristics ..................................................................................................................... 30
       6.4.1. Complete route ............................................................................................................................... 31
       6.4.2. Cornering ........................................................................................................................................ 34

7. **Conclusions** ......................................................................................................................................................... 41

References .................................................................................................................................................................... 43

**Appendix I: Vehicle models** ........................................................................................................................................ 45

**Appendix II: Questionnaires (in Swedish)** .............................................................................................................. 47

**Appendix III: Information about the study (in Swedish)** ............................................................................................ 59
Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADAS</td>
<td>Advanced driver assistance system</td>
</tr>
<tr>
<td>ESC</td>
<td>Electronic stability control</td>
</tr>
<tr>
<td>HSO&lt;sub&gt;u&lt;/sub&gt;</td>
<td>Utilized high-speed off-tracking</td>
</tr>
<tr>
<td>HSSO</td>
<td>High-speed steady-state off-tracking</td>
</tr>
<tr>
<td>HSTO</td>
<td>High-speed transient off-tracking</td>
</tr>
<tr>
<td>IPOPT</td>
<td>Interior Point OPTimizer</td>
</tr>
<tr>
<td>LVC</td>
<td>Long vehicle combination</td>
</tr>
<tr>
<td>NLP</td>
<td>Nonlinear Programming</td>
</tr>
<tr>
<td>RWA</td>
<td>Rearward amplification</td>
</tr>
<tr>
<td>RWA&lt;sub&gt;u&lt;/sub&gt;</td>
<td>Utilized rearward amplification</td>
</tr>
<tr>
<td>Sim IV</td>
<td>VTI Simulator IV</td>
</tr>
<tr>
<td>VGTT</td>
<td>Volvo Group Truck Technology</td>
</tr>
<tr>
<td>ViP</td>
<td>ViP Driving Simulation Centre (for Virtual prototyping and assessment by simulation)</td>
</tr>
<tr>
<td>VTI</td>
<td>Swedish National Road and Transport Research Institute</td>
</tr>
<tr>
<td>YDC</td>
<td>Yaw damping coefficient</td>
</tr>
</tbody>
</table>
List of figures

Figure 1. A-double LVC consisting of a tractor unit, semi-trailer, converter dolly and a second semi-trailer.......................................................... 13

Figure 2. Illustration of high-speed steady-state off-tracking (HSSO). Picture from Kati (Kati, 2013).................................................................................................................. 16

Figure 3. Illustration of high-speed transient off-tracking (HSTO). Picture from Kati (Kati, 2013).................................................. 16

Figure 4. Illustration of the yaw damping coefficient (YDC). Picture from Kati (Kati, 2013).............. 17

Figure 5. Illustration of the speed dependency of rearward amplification (RWA) for three different vehicle models of an A-double LVC. The kinematic model is represented by blue filled circles, the one-track model with linear tire slip by black filled squares, and the high-fidelity model by red hollow diamonds. .................................................................................................................. 18

Figure 6. Illustration of the speed dependency of high-speed transient off-tracking (HSTO) for three different vehicle models of an A-double LVC. The kinematic model is represented by blue filled circles, the one-track model with linear tire slip by black filled squares, and the high-fidelity model by red hollow diamonds. .................................................................................................................. 18

Figure 7. Illustration of the speed dependency of the yaw damping coefficient (YDC) for three different vehicle models of an A-double LVC. The kinematic model is represented by blue filled circles, the one-track model with linear tire slip by black filled squares, and the high-fidelity model by red hollow diamonds. .................................................................................................................. 18

Figure 8. Illustration of the speed dependency of high-speed steady-state off-tracking (HSSO) for three different vehicle models of an A-double LVC. The lateral acceleration of the tractor unit has been set to 3 m/s². The kinematic model is represented by blue filled circles, the one-track model with linear tire slip by black filled squares, and the high-fidelity model by red hollow diamonds...... 19

Figure 9. Illustration of the speed dependency of high-speed steady-state off-tracking (HSSO) for three different vehicle models of an A-double LVC. The lateral acceleration of the tractor unit has been set to 1.5 m/s². The kinematic model is represented by blue filled circles, the one-track model with linear tire slip by black filled squares, and the high-fidelity model by red hollow diamonds...... 19

Figure 10. Illustration of the speed dependency of high-speed steady-state off-tracking (HSSO) for three different vehicle models of an A-double LVC. The lateral acceleration of the tractor unit has been set to 0.5 m/s². The kinematic model is represented by blue filled circles, the one-track model with linear tire slip by black filled squares, and the high-fidelity model by red hollow diamonds...... 19

Figure 11. Illustration of the reference velocity profile that was used in the automated driving. The velocity profile is modified in three steps: Firstly, modification is made based on maximum absolute curvature (blue solid line). Secondly, modification is made based on an assumption of constant initial cornering velocity (black dashed line). Finally, the final reference velocity profile is adjusted to reduce the longitudinal jerk level (red dashed dotted line). ................................................................. 21
Figure 12. Exemplification of the geometric reference paths that were used in the automated driving modes. In the first automated driving mode (Auto 1) the reference path is the lane centre line (green dashed line). In the second automated driving mode (Auto 2) the reference path is calculated using an optimal control problem formulation (blue solid line).

Figure 13. VTI Sim IV motion platform.

Figure 14. Road 180 between Borås and Alingsås (blue solid line), with the start (S) and end (E) of the road section used in the simulator study marked.

Figure 15. Experimental setup. Each session was 10 min. The order of the two automated driving modes was shifted randomly for each participant.

Figure 16. Utilized RWA versus vehicle speed. The manual driving (top), Auto 1 (middle) and Auto 2 (bottom) have been compared to vehicle performance RWA (solid line).

Figure 17. Utilized high-speed off-tracking (HSOu) versus vehicle speed for manual driving (top), Auto 1 (middle) and Auto 2 (bottom). A positive value means that the last unit is tracking inward of the first unit.

Figure 18. Normalized cost function components calculated using (15) and (16).

Figure 19. First left curve driving characteristics. Top panel shows curvature (black solid line) and elevation (black dashed line). Other panels from top to bottom: first axle lateral distance offset, last axle lateral distance offset, first axle lateral acceleration, vehicle speed, and first axle longitudinal acceleration. Mean values for manual driving (black solid line), Auto 1 (red dashed line), and Auto 2 (black dashed line). The grey shaded area represents one standard deviation for manual driving.

Figure 20. Second left curve driving characteristics. Top panel shows curvature (black solid line) and elevation (black dashed line). Other panels from top to bottom: first axle lateral distance offset, last axle lateral distance offset, first axle lateral acceleration, vehicle speed, and first axle longitudinal acceleration. Mean values for manual driving (black solid line), Auto 1 (red dashed line), and Auto 2 (black dashed line). The grey shaded area represents one standard deviation for manual driving.

Figure 21. First right curve driving characteristics. Top panel shows curvature (black solid line) and elevation (black dashed line). Other panels from top to bottom: first axle lateral distance offset, last axle lateral distance offset, first axle lateral acceleration, vehicle speed, and first axle longitudinal acceleration. Mean values for manual driving (black solid line), Auto 1 (red dashed line), and Auto 2 (black dashed line). The grey shaded area represents one standard deviation for manual driving.

Figure 22. Second right curve driving characteristics. Top panel shows curvature (black solid line) and elevation (black dashed line). Other panels from top to bottom: first axle lateral distance offset, last axle lateral distance offset, first axle lateral acceleration, vehicle speed, and first axle longitudinal acceleration. Mean values for manual driving (black solid line), Auto 1 (red dashed line), and Auto 2 (black dashed line). The grey shaded area represents one standard deviation for manual driving.

Figure 23. Acceleration diagrams for the four selected curves. First left curve (top left quadrant), second left curve (top right quadrant), first right curve (bottom left quadrant), and second right curve (bottom right quadrant). For each quadrant, the top left picture represents all drivers, the top right picture represents professional drivers, the bottom left picture represents Auto 1, and the bottom right picture represents Auto 2.
Figure 24. Acceleration diagrams for the first left curve. Manual driving (top left), Auto 1 (top middle), Auto 2 (top right), opt 1 (bottom left), opt 2 (bottom middle), and opt 3 (bottom right).
List of tables

Table 1. Characteristics of the route used in the simulator.......................................................... 26
Table 2. General assessment of the realism of driving in the simulator.......................................... 28
Table 3. Assessment of driving the A-double manually in the simulator......................................... 29
Table 4. Assessment of the automated driving systems Auto 1 and Auto 2. ............................... 30
Table 5. Characteristics used in the optimal control problem cost function..................................... 33
High Speed Control of Long Combination Heavy Commercial Vehicles within Safe Corridors

by Peter Nilsson¹, Leo Laine¹ and Jesper Sandin²

¹ Volvo Group Truck Technology (VGTT)
² Swedish National Road and Transport Research Institute (VTI)

Executive summary

The main scope of the project was to initiate a technical framework for studying manual and automated high-speed driving of long vehicle combinations (LVCs) in a driving simulator environment.

The project included implementation and evaluation of vehicle models representing a rigid truck solo (reference vehicle) and an A-double LVC in VTI driving simulator IV (Sim IV). The A-double combination consisted of a 6x4 tractor unit followed by a three-axle semi-trailer, two-axle converter dolly and a second three-axle semi-trailer unit. The total vehicle length of the A-double was 32 metres and the total weight was set to 80 tonnes. The implementation of the vehicle models was evaluated by drivers from Volvo product development. The evaluation was carried out during normal driving conditions, with speeds ranging from 0 to 90 km/h.

Besides the implementation and evaluation of vehicle models, the project also included a driving simulator study in which manual and automated driving of the A-double have been studied. The participants in the study were 12 professional truck drivers from a haulage contractor and 8 drivers from Volvo product development. The driving scenario consisted of a relatively curvy and hilly single-lane Swedish county road (Road 180), without additional road users and safety critical events. Two automated driving strategies for steering, propulsion and braking were formulated, whereof one of the steering strategies included results from an optimal control based receding horizon approach. The drivers’ manual lane keeping and speed profiles were recorded for post-analysis. In addition, the drivers’ subjective acceptance of automated driving trajectories was also collected.

The main conclusion from the assessment questionnaires was that the realism of the road environment, vehicle suspension, steering wheel feeling and the manoeuvrability/drivability during steering was adequate but would benefit from more tuning. More urgent are adjustments of braking, acceleration, level of engine sound and improved view in the right-hand side mirror.

Based on driver ratings and comments, both automated driving systems were appreciated for their lane positioning and driving performance, with a slight preference for the more advanced lateral control system.

When analysing manual driving trajectories from cornering, it was observed that the utilized planar accelerations, i.e. accelerations in longitudinal and lateral direction, had a round shape. This suggests that professional LVC drivers minimize acceleration changes by combined braking/propulsion and steering.
1. Introduction

1.1. Background

To achieve future environmental goals on transported goods set by the European Parliament (EU, 2009), studies on the usage of longer vehicle combinations than those agreed upon in the EU directive 96/53 have been conducted (see e.g. Mellin & Ståhle, 2010; Hjort & Sandin, 2012). The most promising long vehicle combinations (LVCs), such as the A-double illustrated in Figure 1, are based on a modular concept and typically range from 25 to 35 m in length (Aurell & Wadman, 2007). The productivity of these combinations is seen to improve by approximately 20 percent (Löfroth & Svenson, 2010). However, important aspects in a general introduction of the LVCs are road infrastructure and how these vehicle combinations should be managed safely in traffic.

During the last decades, the use of vehicle dynamic control systems has increased for single unit vehicles, especially passenger cars, and to some extent tractor semi-trailer combinations. The utilization of these so-called classic active safety systems, e.g. anti-lock braking systems and electronic stability control (ESC), have contributed to a reduction of injuries and fatalities in traffic accidents (Ferguson, 2007). The benefits of the usage of these systems have resulted in that, starting from 2014, ESC will be mandatory for all new heavy vehicles in Europe (EU, 2011). With the target to further increase the traffic safety, vehicles are beginning to be equipped with a newer type of active safety systems referred to as advanced driver assistance systems (ADASs), e.g. adaptive cruise control, lane departure warning and emergency brake assist. In production, the market penetration for these types of systems is still low but their potential safety benefits are considerable. Future ADASs are predicted to have even more extended automated driving capabilities where propulsion/braking and steering actions are combined.

In the design of automated driving functionalities for LVCs, consideration must be taken to the length of the vehicle combinations as well as a more amplified longitudinal and lateral vehicle dynamics compared to single unit vehicles. Important performance characteristics connected to high-speed manoeuvring of LVCs are: rearward amplification (RWA), high-speed steady-state off-tracking (HSSO), high-speed transient off-tracking (HSTO) and the yaw damping coefficient (YDC). A description of both longitudinal and lateral performance characteristics of LVCs are given in (Kati, 2013) and the lateral performance measures of a number of prospective LVCs have been studied in (Kharrazi, 2012). In a conducted pilot project about LVC utilization in Sweden (Andersson, Fors & Sandin, 2011), the drivers orally state that the increased vehicle length and weight need to be compensated for by the driver using extended planning including increased planning horizon. Typical statements are: "earlier braking due to increased weight", "avoid stopping in uphill in winter conditions” and "important to maximize the radius during low speed cornering”.

Figure 1. A-double LVC consisting of a tractor unit, semi-trailer, converter dolly and a second semi-trailer.
1.2. Problem formulation

The methodology of using driving simulators to gain experience of driving behaviour and driving automation includes both advantages and disadvantages when compared to physical testing. There are several main advantages in the considered situation. Firstly, the studied vehicle combinations are not in general traffic usage. Physical testing would therefore require test-track areas or special traffic permissions. Secondly, vehicle environment sensors and vehicle state estimation are currently not commercially available for the considered vehicle combinations. When using driving simulators focus can be placed directly on the functionality of the motion control. Thirdly, driving simulators offer high controllability, reproducibility, and the possibility of encountering dangerous driving conditions without being physically at risk. On the other hand, the disadvantages with driving simulators are limited physical, perceptual, and behavioural fidelity. To accomplish satisfactory realism regarding truck vehicle dynamics, road environment and driver perception, development of the simulator framework is needed. For example, validity of the vehicle dynamics behaviour is believed to be of high importance in order to judge the driver preferences regarding the extended vehicle dynamics of LVCs. Another example is the driver’s perception of rearward amplification by looking in the rear-view mirrors.

1.3. Objectives

The main objective of this project was to initiate and set up a technical framework that allows evaluation of manual and automated high-speed driving of LVCs in a driving simulator environment. The included parts are:

- Implementation and validation of a rigid truck solo 6x2 (reference vehicle) and an A-double LVC model, which together with the motion queuing system emulates the vehicle dynamics to the driver. This in order to accomplish satisfactory realism in regards to truck vehicle dynamics.
- Evaluation of the road environment developed in the ViP project Known Roads (Nábo, Andhill et al., 2015). The road description includes profiles of the road curvature, elevation, lateral inclination, and the surface roughness. Detailed vertical road input per wheel was accounted for as input to the vehicle dynamic models. This in order to accomplish satisfactory realism in regards to road environment.
- Evaluation and comparison of manual and automated driving of an LVC using a driving simulator study including professional truck drivers.
2. Vehicle lateral dynamics of LVCs

This chapter emphasizes the important subjects in lateral vehicle dynamics of LVCs.

2.1. Vehicle modelling

In this section three different mathematical vehicle models are presented. The vehicle models have been used in different contexts to describe the dynamics of the studied A-double combination. In common, all three vehicle models have been used for the lateral dynamics in high speed. First, a kinematic one-track model is described. This model has been used in the predictive control design of the automated driving. Secondly, a one-track model with linear tire slip is presented. The model has been used in the post-analysis for generating optimal driving trajectories for selected curves which were compared with the results from the simulator study. Finally, a high-fidelity two-track model is described. This model was used as a vehicle plant in the simulator experiment. The lateral performance measures connected to high-speed manoeuvring, are explained, evaluated, and compared for all models.

2.1.1. Kinematic one-track model

The main model assumption of the kinematic one-track model is that all wheels follow Ackerman steering geometry and they are ideally tracking their own direction (zero side slip). The model parameters and the differential equations describing the vehicle motion in the road plane are given in Appendix I, and in Nilsson, Laine & Jacobson (2014).

2.1.2. One-track model with linear tire slip

The one-track model was derived using Lagrangian formulation of the vehicle's motion (Nilsson & Tagesson, 2013). The main benefit with this starting point is that the coupling forces between the vehicle units are inherently represented and the number of equations is correspondingly fewer. The model parameters are illustrated in Appendix I. The model has been used for generating optimal driving trajectories in cornering situations. The model has been linearized regarding kinematics, steering and tire slip using an assumption of small angles. The linear cornering stiffness values have been tuned using results from the high-fidelity two-track model. The differential equations describing the vehicle motion in the road plane are given in Appendix I.

2.1.3. High-fidelity two-track model

A Volvo in-house developed high-fidelity two-track model library was used in the simulator experiments to emulate the detailed vehicle dynamics while driving the A-double combination on uneven road. The high-fidelity model is valid in the frequency range 0 to 5 Hz. The model includes detailed sub-models of the vehicle chassis, cab suspensions, steering system, powertrain, and brakes. The frame torsion flexibility of the tractor has been considered by using multiple frame bodies connected through springs. A similar chassis setup was used for the dolly and the semi-trailers. The units were connected by articulation joints. The Magic Formula tire model (Pacejka, 2006) with combined slip, dynamic relaxation, and rolling resistance, was used for all tires.

2.2. Performance based characteristics

Important lateral performance characteristics of LVCs (Kati, 2013) used in this study are rearward amplification (RWA), high-speed steady-state off-tracking (HSSO), high-speed transient off-tracking (HSTO) and the yaw damping coefficient (YDC).

Rearward amplification is the relationship between the maximum movement of the first and the last vehicle unit during a specified steering manoeuvre and vehicle speed (ISO, 2002). It is usually given in the metrics lateral acceleration gain, or as here, in yaw velocity gain. It expresses the increased risk
for a last unit rollover or swing-out which can occur if a sudden steering manoeuvre is performed. The RWA has been calculated for the three vehicle models described in Sections 2.1.1, 2.1.2 and 2.1.3., using a pseudo-random steering input (ISO, 2002) and constant vehicle speed in the range 50-90 km/h. In Figure 5, the one-track model with linear tire slip and the high-fidelity two-track model show similar results with increasing RWA for increasing vehicle speed. This should be compared to the kinematic model that cannot correctly capture the dynamics of RWA which is dependent on the generation of lateral tire forces.

Figure 2. Illustration of high-speed steady-state off-tracking (HSSO). Picture from Kati (Kati, 2013).

Figure 3. Illustration of high-speed transient off-tracking (HSTO). Picture from Kati (Kati, 2013).

The off-tracking characteristics, HSSO and HSTO, both describe the lateral deviation between the path of the front axle and the path of the most severely off-tracking axle of the last unit (see Figure 2 and Figure 3). These measures express the additional space needed for the last unit in a specific steering manoeuvre and vehicle speed. A positive value of the HSSO and HSTO means that the last unit is tracking inward of the first unit. Figure 6 shows the HSTO values, calculated for constant vehicle speeds in the range 50-90 km/h and using a single sinewave lateral acceleration (ISO, 2002) with the frequency 0.4 Hz and the lateral acceleration 2 m/s². The absolute values of the HSTO for the one-track model with linear tire slip and the high-fidelity two-track model increase with increasing vehicle speed. This effect is not captured by the kinematic model for which the HSTO is instead constant for all vehicle speeds. HSSO values for constant vehicle speeds in the range 50-90 km/h have been calculated for three levels of constant lateral acceleration: 3 m/s², 1.5 m/s² and 0.5 m/s². The results (Figure 8, Figure 9 and Figure 10) show that the HSSO values are similar for the one-track model with linear tire slip and the high-fidelity two-track model. For a constant lateral acceleration, the values decrease with increasing vehicle speed meaning that for low vehicle speed the last unit is tracking inward of the first unit. For high vehicle speed the last unit is instead tracking outward of the first unit.
The HSSO values of the kinematic model are always positive. The model is relatively correct for low vehicle speed but cannot describe HSSO at higher vehicle speeds.

The yaw damping coefficient (YDC) is the damping ratio of the least damped articulation joint's angle during free yaw oscillations of the vehicle combination after a specific steering manoeuvre and vehicle speed (see Figure 4). A longer decay time might result in higher driver workload and increased safety risk for other road users. In Figure 7, the YDC values have been calculated using a single sinusoidal steering input with the frequency 0.4 Hz for constant vehicle speeds in the range 50-90 km/h. The YDC for the one-track model with linear tire slip and the high-fidelity two-track model both decrease with increasing vehicle speed. The kinematic model cannot represent the dynamics of YDC correctly which is in accordance with the results of the RWA and HSTO.

![Figure 4](image-url). Illustration of the yaw damping coefficient (YDC). Picture from Kati (Kati, 2013).

Finally, step response analysis has been carried out for the vehicle speed 70 km/h to compare the dynamic response times of the vehicle models. When applying a steering step input, the first unit of the kinematic one-track model has an instantaneous response and the last vehicle unit responds after approximately 1.7 s. For the one-track model with linear tire slip the first unit responds after approximately 0.1 s and the last vehicle unit responds 2.4 s later. The results for the high-fidelity two-track model are similar to those for the one-track model with linear tire slip. The difference in response times influences the performance of the kinematic one-track model when used as prediction model for path planning (see Section 3.2).

The specific values of the different characteristics reflect the actual vehicle configuration, such as number of units, equivalent wheel base, towing bar length and position, and tire characteristics, during a dynamic manoeuvre. However, while driving a realistic transport mission it is possible and sometimes necessary for the driver to consider the vehicle characteristics and compensate for these to ensure safe manoeuvring. Typical examples are: maximize cornering radius while negotiating a curve, lowering the vehicle speed, and/or avoid sudden steering. The evaluation of the performance characteristics during a specific driving route is here defined as utilized performance characteristics and aims to reflect the combination of vehicle performance, road characteristics and driver preference.
Figure 5. Illustration of the speed dependency of rearward amplification (RWA) for three different vehicle models of an A-double LVC. The kinematic model is represented by blue filled circles, the one-track model with linear tire slip by black filled squares, and the high-fidelity model by red hollow diamonds.

Figure 6. Illustration of the speed dependency of high-speed transient off-tracking (HSTO) for three different vehicle models of an A-double LVC. The kinematic model is represented by blue filled circles, the one-track model with linear tire slip by black filled squares, and the high-fidelity model by red hollow diamonds.

Figure 7. Illustration of the speed dependency of the yaw damping coefficient (YDC) for three different vehicle models of an A-double LVC. The kinematic model is represented by blue filled circles, the one-track model with linear tire slip by black filled squares, and the high-fidelity model by red hollow diamonds.
Figure 8. Illustration of the speed dependency of high-speed steady-state off-tracking (HSSO) for three different vehicle models of an A-double LVC. The lateral acceleration of the tractor unit has been set to 3 m/s². The kinematic model is represented by blue filled circles, the one-track model with linear tire slip by black filled squares, and the high-fidelity model by red hollow diamonds.

Figure 9. Illustration of the speed dependency of high-speed steady-state off-tracking (HSSO) for three different vehicle models of an A-double LVC. The lateral acceleration of the tractor unit has been set to 1.5 m/s². The kinematic model is represented by blue filled circles, the one-track model with linear tire slip by black filled squares, and the high-fidelity model by red hollow diamonds.

Figure 10. Illustration of the speed dependency of high-speed steady-state off-tracking (HSSO) for three different vehicle models of an A-double LVC. The lateral acceleration of the tractor unit has been set to 0.5 m/s². The kinematic model is represented by blue filled circles, the one-track model with linear tire slip by black filled squares, and the high-fidelity model by red hollow diamonds.
3. Automated driving control design

This section describes the control design of the automated driving conducted in the simulator study. The implementation was done using independent control systems for the vehicle’s longitudinal velocity, referred to as longitudinal control system, and the vehicle’s steering input, referred to as lateral control system. In the case of lateral control, two different linear feedback tracking controllers with different geometric reference paths were used. In the driving simulator study the same longitudinal control system was used for both automated modes.

3.1. Longitudinal control design

The longitudinal motion control of the vehicle was performed by a velocity interface for coordinating engine propulsion and braking of each wheel in the combination. The coordination of these actuators was performed by control allocation formulation according to Laine (2007) and Tagesson et al. (2009). The closed-loop control of the longitudinal velocity was defined as a linear feedback proportional tracking controller using a pre-calculated reference velocity profile $v_{ref}(s)$ along the distance $s$.

The total longitudinal force for the vehicle combination was calculated as

$$F_x = K_F_x \cdot \left( \frac{v_{ref}(s) - v_x}{\Delta t} \right) \cdot m_{tot} \quad (1)$$

where $F_x$ is the input for the control allocation, $K_F_x$ is a varying proportional gain factor, $m_{tot}$ is the total vehicle mass, $v_x$ is the actual longitudinal velocity, and $\Delta t$ is a tuning variable set to 0.5 s. The reference velocity was calculated using several pre-processing steps.

Firstly, the reference velocity is calculated according to

$$v_{ref}(s) = \min_{s \in [0, s_{end}]} \left( v^{max}, \sqrt{a_y^{max} / c(s)} \right) \quad (2)$$

where $v^{max}$ denotes the speed limit, $c(s)$ denotes the road curvature and $a_y^{max}$ denotes the maximum allowed lateral acceleration which was set to 3 m/s$^2$. The reference velocity profile calculated using (2), is illustrated in Figure 11 (blue solid line).

Secondly, constant velocity is assumed during the initial cornering. The reference velocity is therefore reduced to the minimum cornering velocity, illustrated in Figure 11 (black dashed line).

Finally, in order to avoid too high longitudinal jerk levels, the starting distance for braking, $\Delta s$, is adjusted according to

$$\Delta s = \frac{\Delta v^2}{a_x^{max}} \quad (3)$$

where $\Delta v$ is the velocity difference and $a_x^{max}$ is the maximum allowed longitudinal acceleration, which was set to 2 m/s$^2$. The final reference velocity profile is illustrated in Figure 11 (red dashed dotted line).
Figure 11. Illustration of the reference velocity profile that was used in the automated driving. The velocity profile is modified in three steps: Firstly, modification is made based on maximum absolute curvature (blue solid line). Secondly, modification is made based on an assumption of constant initial cornering velocity (black dashed line). Finally, the final reference velocity profile is adjusted to reduce the longitudinal jerk level (red dashed dotted line).

3.2. Lateral control design

This section describes the two different closed-loop control systems used to handle the vehicle steering in the automated driving modes. Both control systems were defined as linear feedback tracking controllers using a pre-calculated geometric reference path (Figure 12).

Figure 12. Exemplification of the geometric reference paths that were used in the automated driving modes. In the first automated driving mode (Auto 1) the reference path is the lane centre line (green dashed line). In the second automated driving mode (Auto 2) the reference path is calculated using an optimal control problem formulation (blue solid line).
3.2.1. Automated driving 1

In the first case (Auto 1), the reference path was defined as the lane centre and the requested road wheel angle $\delta(t)$ was calculated according to

$$\delta(t) = K_e \cdot (d(t) + \dot{d}(t) \cdot t_p)$$  \hspace{1cm} (4)

where $K_e$ is a gain factor, $t_p$ is a tuning variable, $d(t)$ and $\dot{d}(t)$ are the perpendicular distance offset to the centre line and its time derivative. The used values of the gain factor $K_e$ (0.3 rad/m) and the tuning variable $t_p$ (1 s) were determined by subjective evaluation to accomplish smooth and comfortable driving.

3.2.2. Automated driving 2

In the second case (Auto 2), the geometric reference path was calculated using a path planning algorithm based on a receding horizon optimization approach which was formulated as a Nonlinear Programming (NLP) problem with the open source Interior Point OPTimizer (IPOPT) as a solver in Matlab/Simulink (Disse, 2012). The prediction horizon for the path planner was set to 10 s.

The locally optimized reference path was calculated using the following cost function and constraints

$$\min_{\hat{C}_\theta} \sum_{i=1}^N \left[ K_j \cdot \hat{j}_i^2 + K_{d1} \cdot \hat{d}_{1,i}^2 + K_{d11} \cdot \hat{d}_{11,i}^2 \right]$$ \hspace{1cm} (5)

$$-\hat{a}_{d,l} \leq \hat{a}_i \leq \hat{a}_{d,l}$$  \hspace{1cm} (6)

$$-\hat{j}_{d,l} \leq \hat{j}_i \leq \hat{j}_{d,l}$$

$$-\hat{d}_{d,l} \leq \hat{d}_i \leq \hat{d}_{d,l}$$

$$-\hat{d}_{d,l} \leq \hat{d}_{11} \leq \hat{d}_{u,l}$$

$$\begin{bmatrix} \hat{\theta}_1 \\
\hat{\theta}_1 \end{bmatrix} = T_{eq} \cdot M_{eq} \begin{bmatrix} C_{\theta,1} \\
C_{\theta,2} \\
C_{\theta,3} \end{bmatrix}$$ \hspace{1cm} (7)

where the optimization variable $C_{\theta,i}$ is the B-spline control points and $j = l, ..., N$ are the number of collocation points. Further, $K_j$, $K_{d1}$ and $K_{d11}$ are gain factors whose values were set to 50, 100 and 25, respectively. The lateral acceleration $\hat{a}_i$ and the lateral jerk $\hat{j}_i$ for vehicle unit $i = 1, ..., 4$ were constrained by lower and upper limits which were set to $\hat{a}_{d,l} = 1.6 \text{ m/s}^2$ and $\hat{j}_{d,l} = 3 \text{ m/s}^3$. The perpendicular distance offset of the first and last vehicle axle with respect to the preferred path, $\hat{d}_{1,i}$ and $\hat{d}_{11,i}$, were constrained by the lower and upper limits set to $\hat{d}_{d,l} = 0.7 \text{ m}$ and $\hat{d}_{u,l} = 4.2 \text{ m}$. The equality constraints (7) are needed for the initial state at the start of the prediction. At the start of the trajectory, i.e. at $s = 0$, the angle $\hat{\theta}_1$ is set to zero, $\hat{\theta}_1$ is constrained to avoid steps in the steering wheel angle and $\hat{\theta}_1$ is constrained to avoid steps in the steering wheel angle rate and hence discontinuities in jerk.
The matrices $T_{eq}$ and $M_{eq}$ are defined as

$$T_{eq} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & t_p/N_{int} & 0 \\ 0 & 0 & (t_p/N_{int})^2 \end{bmatrix}$$

(8)

$$M_{eq} = \frac{1}{6} \begin{bmatrix} 1 & 4 & 1 \\ -3 & 0 & 3 \\ 6 & -12 & 6 \end{bmatrix}$$

(9)

where $N_{int}$ is the number of B-spline intervals and $t_p$ is the prediction horizon length. To achieve real-time performance of the receding horizon optimization approach, the kinematic vehicle model (see Section 2.1.1) was used as a prediction model for path planning. One benefit with the kinematic model is that part of the model exploits differential flatness which enables real-time performance. The trajectory planner had poor closed-loop performance when used together with the vehicle motion control and the high-fidelity plant model. The main cause for this is the lack of transient dynamics in the kinematic model, e.g. response time (see Section 2.2). Instead the optimized reference path and feed-forward road wheel angle used in the simulator experiments were pre-calculated with the kinematic model also as a vehicle plant.

The requested road wheel angle $\delta(t)$ was calculated according to

$$\delta(t) = K_e \cdot (d(t) + \dot{d}(t) \cdot t_p) + K_{ff} \cdot \delta_{ff}$$

(10)

where $K_e$ and $K_{ff}$ are gain factors, $t_p$ is a tuning variable, $d(t)$ and $\dot{d}(t)$ are the perpendicular distance offset to the lane centre line and its time derivative, and $\delta_{ff}$ refers to a feed-forward road wheel angle calculated in the path planning algorithm. The used values for the gain factors $K_e$ (0.2 rad/m) and $K_{ff}$ (0.1), and the tuning variable $t_p$ (1 s) were determined by subjective evaluation to accomplish smooth and comfortable driving.
4. Vehicle dynamics and motion cueing

The following issues related to the truck driving in Sim IV were identified prior to the simulator study:

- motion and visual mismatching
- steering wheel oscillations
- steering wheel vibrations
- rear-view mirror view
- engine sound.

To accomplish satisfactory realism, troubleshooting actions and extensive testing were carried out. The main part of the time was put on the problem with Motion and visual mismatching. At the start of the simulator study all issues were improved and rated as acceptable by drivers from VGTT.
5. **Simulator study**

The description of the driving simulator study has been divided into five subsections: Driving simulator, Participants, Driving scenario, Experimental setup and Questionnaires.

5.1. **Driving simulator**

The study was conducted in VTI’s driving simulator Sim IV (Jansson, Sandin et al., 2014) in Gothenburg, Sweden. Sim IV (see Figure 13) is equipped with a motion system that allows for large movements in both longitudinal and lateral direction. The heavy vehicle mock-up used in the simulator study was a Volvo FH, where LCD screens replace the left-hand and right-hand side mirrors. The high-fidelity two-track model described in Section 2.1.3 was used to emulate the vehicle dynamics in the simulator. To accomplish high realism considering truck vehicle dynamics, extensive subjective testing was carried out prior to the study by experienced truck drivers. The final performance was judged to be good regarding the lateral dynamics and acceptable considering the longitudinal dynamics.

![Figure 13. VTI Sim IV motion platform.](image)

5.2. **Participants**

Twenty drivers participated in the study. They 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 a driver’s license for heavy truck and trailer except two, who had a driver’s license for heavy truck only. In Group A, years with a truck driver’s license ranged from 0 to 39 years with an average of 7 years, and the distance driven per year ranged from 10 to 500 km with an average of 100 km/year. In Group B, years with a truck driver’s license ranged from 2 to 39 years with an average of 30 years, and the distance driven per year ranged from 65 000 to 130 000 km with an average of 110 000 km/year. Thus, the drivers in Group A had less driving hours compared to Group B. However, many of the Group A drivers were used to daily judge new features and give subjective feedback. Three of the professional drivers regularly drive longer vehicle combinations with special permit from the Swedish Transport Agency. In total, 18 out of the 20 participants completed the experiment. Two of the participants, one from each group, had to interrupt due to motion sickness. Thus, 11 drivers from Group A and 7 drivers from Group B completed the experiment.
5.3. Driving scenario

The driving scenario was set up to reflect a normal transport mission on a relatively curvy and hilly single-lane county road, where the lane width was 3.5 m. The driven road section was 8.3 kilometres and was based on measurements of Road 180 between Borås and Alingsås (see Figure 14). The road description implemented in the simulator included profiles of the road curvature, elevation, lateral inclination and the surface roughness in Table 1. 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 (see Appendix III: Information about the study”). The allowed speed limit was set to 70 km/h at the major part of the road. One consequence of the chosen simulator setup was that it was not possible for the tractor unit to exceed 1.5 m/s² steady state lateral acceleration without reaching the physical endpoints of the motion platform. This implied that the speed limit was reduced in one section of the route including low radius cornering.

Table 1. Characteristics of the route used in the simulator study.

<table>
<thead>
<tr>
<th>Data</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curvature [10⁻³] [1/m]</td>
<td>-6.7 6.8</td>
<td>1</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Elevation [m]</td>
<td>147 231</td>
<td>190</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>Lateral inclination [rad]</td>
<td>-0.09 0.07</td>
<td>0.03</td>
<td>0.02</td>
<td></td>
</tr>
</tbody>
</table>

Figure 14. Road 180 between Borås and Alingsås (blue solid line), with the start (S) and end (E) of the road section used in the simulator study marked.

5.4. Experimental setup

The study followed the experimental setup illustrated in Figure 15. The experiment was divided into four sessions: training, manual driving, automated driving 1 and automated driving 2. The participants started with the training session, directly followed by the manual driving session. The two sessions with automated driving differed from each other by the usage of two different setups of the lateral control (see Section 3.2). All sessions, except the training, were driven on the same eight kilometres long route and took approximately ten minutes each. The order of the two automated driving sessions was shifted randomly for each participant. After the manual driving and after each automated driving session the participants filled in a questionnaire.
5.5. Questionnaires

The drivers filled in three types of questionnaires (see Appendix II: “Questionnaires”) about

- General Assessment of the Realism of Driving in the Simulator (Questionnaire A)
- Assessment of Driving the A-double Manually in the Simulator (Questionnaire B)
- Assessment of the Automated Driving Systems (Questionnaires C and D).

Questionnaires A and B were filled in after the ‘manual driving’ session, and C and D (same questionnaire) were filled in after each of ‘automated driving’ sessions.

Most 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?

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

Comment: _______________________________________

Average ratings were calculated for each question and driver group separately, and presented in bar diagrams.
6. Results

6.1. General assessment of the realism of driving in the simulator

Table 2 shows the average ratings of the realism of driving the simulator (Questionnaire A) for the two driver groups separately. Both groups of drivers rate the realism of the road environment, vehicle suspension, vibration, steering wheel feeling and the manoeuvrability/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 2. General assessment of the realism of driving in the simulator.

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

(*) Not realistic at all (1) - Very realistic (7); (***) Not good at all (1) - Very good (7).

6.2. Assessment of driving the A-double manually in the simulator

Table 3 shows the average ratings of the manual driving of the A-double in the simulator (Questionnaire B) for the two driver groups separately. When comparing driving the A-double in the simulator and the vehicle they normally drive, both groups of drivers rate a larger difference in braking, acceleration, and sound than in the suspension, vibrations, steering wheel feeling and the manoeuvrability/drivability. Concerning how difficult it was to keep the A-double within the lane in different driving situations, the professional drivers in Group B consistently rate that it was less difficult than the drivers in Group A. The visibility is rated as good, 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 3. Assessment of driving the A-double manually in the simulator.

<table>
<thead>
<tr>
<th>5. In comparison with the vehicle you normally drive, how different was it to drive this A-double combination in the simulator regarding:</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Braking? (*)</td>
</tr>
<tr>
<td>b. Acceleration? (*)</td>
</tr>
<tr>
<td>c. Sound (from wind, engine, tires)? (*)</td>
</tr>
<tr>
<td>d. Vehicle suspension movement (vertically and roll) (*)</td>
</tr>
<tr>
<td>e. Vibrations in the cabin? (*)</td>
</tr>
<tr>
<td>f. Feeling and resistance of the steering wheel? (*)</td>
</tr>
<tr>
<td>g. Manoeuvrability and drivability during steering? (*)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6. How easy was it to keep the tractor and trailers within the lane:</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. On straight road section? (***)</td>
</tr>
<tr>
<td>b. In right-hand curves? (***)</td>
</tr>
<tr>
<td>c. In left-hand curves? (***)</td>
</tr>
<tr>
<td>d. Driving uphill? (***)</td>
</tr>
<tr>
<td>e. Driving downhill? (***)</td>
</tr>
<tr>
<td>f. Road segments with bumpy/uneven road? (***)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7. How good was the visibility in the A-double:</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Forward? (***)</td>
</tr>
<tr>
<td>b. Backward? (***)</td>
</tr>
<tr>
<td>c. To the left? (***)</td>
</tr>
<tr>
<td>d. To the right? (***)</td>
</tr>
</tbody>
</table>

(*) No difference at all (1) – Very large difference (7). (**) Very difficult (1) – Not difficult at all (7). (***) Not good at all (1) – Very good (7).

6.3. Assessment of the automated driving systems Auto 1 and Auto 2

Table 4 shows the average ratings of Auto 1 and Auto 2 (Questionnaire C/D) for the two driver groups separately. The two driver groups rate the driving performance of both automated driving systems rather high (positively) (questions 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 to or crossed the centre line 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 13 to 15 concern the willingness to use the automated driving 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 systems 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. Again, the experienced professional drivers rated lower.
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 of the professional drivers). Requirements on a more developed automated driving system would be better feedback of what the system “is about to do”, and the possibility to take over the control if needed.

An additional question (question 12) was asked about whether the drivers wanted to take control of the vehicle at some occasion when driving with any of the automated systems (they were, however, 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 4. Assessment of the automated driving systems Auto 1 and Auto 2.

<table>
<thead>
<tr>
<th></th>
<th>10. How well did the automated driving system position the vehicle in the lane in general? (***)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11. How did the automated driving system manage to drive:</td>
<td>a. On straight road section? (**)</td>
</tr>
<tr>
<td></td>
<td>b. In right-hand curves? (**)</td>
</tr>
<tr>
<td></td>
<td>c. In left-hand curves? (**)</td>
</tr>
<tr>
<td></td>
<td>d. Driving uphill? (**)</td>
</tr>
<tr>
<td></td>
<td>e. Driving downhill? (**)</td>
</tr>
<tr>
<td></td>
<td>f. Road segments with bumpy/uneven road? (**)</td>
</tr>
<tr>
<td>13. In reality I would like to use the automated driving system:</td>
<td>a. On divided highways? (***)</td>
</tr>
<tr>
<td></td>
<td>b. On rural undivided roads? (***)</td>
</tr>
<tr>
<td></td>
<td>c. In city streets? (***)</td>
</tr>
</tbody>
</table>

14. I would feel safe with the system in reality, and in the traffic situation I experienced in the simulator (*)

15. I would feel safe with the system in reality, and in the traffic situation I experienced in the simulator with other vehicles within sight but not in immediate vicinity (*)

(*) Not safe at all (1) – Very safe (7), (**) Not good at all (1) – Very good (7), (***) Not often at all (1) – Very often (7).

6.4. Performance characteristics

In this section, post-analyses of data from the driving simulator experiment are presented. The analyses were divided into two groups; the complete route and selected curve scenarios. In the analysis of the complete route, the manual driving was compared with the two automated driving modes from the simulator experiments. Utilized performance characteristics are defined and shown. Accumulated performance characteristics for the complete route were also analysed.

The analysis of the selected curve scenario allows detailed studies of utilized vehicle characteristics. To evaluate the manual driving behaviour a new optimal control problem has been formulated with different objective functions. The optimal control problem simulations included the one-track vehicle model with linear tire slip described in Section 2.1.2.
6.4.1. Complete route

Important vehicle performance characteristics for LVC high-speed manoeuvring has been introduced in Section 2.2. The utilized performance characteristics are defined by vehicle performance, road characteristics, and specific driver/auto preference. One of these is the utilized rearward amplification ($RWA_u$) which is defined as

$$RWA_u = \frac{r_{i4}}{r_{L1}} \quad i = 1, ..., N$$

$$|r_{i4}^e| \geq r_{\min} \quad j = 1, 4$$

where $i = 1, ..., N$ are the synchronized extreme values of the yaw rate of the first unit $r_{i1}^e$ and the yaw rate of the last unit $r_{i4}^e$. The threshold value $r_{\min}$ has been used to remove small extreme values not connected to lateral manoeuvring of the vehicle.

In Figure 16 the utilized $RWA_u$ is shown for the manual, Auto 1 and Auto 2 modes together with the vehicle performance $RWA$. The vehicle performance $RWA$ calculated using pseudo-random input is the maximum $RWA$ in the studied frequency range. However, the $RWA_u$ depends on the driver steering input.

![Figure 16](image1)

**Figure 16. Utilized RWA versus vehicle speed. The manual driving (top), Auto 1 (middle) and Auto 2 (bottom) have been compared to vehicle performance RWA (solid line).**

Figure 16 shows that utilized $RWA_u$ in the manual driving up to 70 km/h can be higher than vehicle performance $RWA$. One reason for this is that road input such as lateral inclination and the surface
roughness influence the utilized RWA. For speeds higher than 70 km/h the manual driving has lower utilized $RWA_u$ than vehicle performance $RWA$. For Auto 1 and Auto 2 modes the utilized $RWA_u$ around 70 km/h is quite close to the vehicle performance $RWA$. The automated driving modes were limited to a maximum speed of 70 km/h.

Utilized high-speed off-tracking ($HSO_u$) has been defined as

$$HSO_u = (d_{i,11} - d_{i,1}) \cdot sgn\left(\frac{\theta_{i,1}(s)}{\partial s}\right)$$  \hspace{1cm} (13)

$$|HSO_{u,i}| \geq HSO_{\text{min}}$$  \hspace{1cm} (14)

where $i = 1, ..., N$ are the synchronized extreme values of $d_{i,1}$ and $d_{i,11}$, which are the perpendicular centre line distance offset for the first and last vehicle axle. $\theta_{i,1}(s)$ is the heading of the first unit. To account for left or right curve the sign of $\frac{\theta_{i,1}(s)}{\partial s}$ has been used. The threshold value $HSO_{\text{min}}$ has been used to remove small extreme values not connected to lateral manoeuvring of the vehicle. The $HSO_u$ aims to capture effects from both HSSO and HSTO. In addition, the $HSO_u$ is also influenced by road input such as lateral inclination and the surface roughness.

Figure 17 shows the utilized $HSO_u$ for the different driving modes; manual driving, Auto 1 and Auto 2. For low speeds the $HSO_u$ shows inward off-tracking and for higher speeds the inward off-tracking is reduced.

![Figure 17](image)

*Figure 17. Utilized high-speed off-tracking ($HSO_u$) versus vehicle speed for manual driving (top), Auto 1 (middle) and Auto 2 (bottom). A positive value means that the last unit is tracking inward of the first unit.*
The utilized performance characteristics have been considered together with other driving characteristics as cost function components in an optimal control problem.

The chosen characteristics aim to reflect the features traffic safety, ride comfort, transport efficiency, and general LVC traffic behaviour. All different characteristics, apart from the final driving time $t_f$, were squared and summed up over the complete route and normalized using the maximum value of the three compared driving modes. This was done to compare the manual driving cost function components with the automated driving modes.

The cost function components were defined as

$$ C_{jk} = \frac{\sum_i^{N_j} (\cdot)^2_{i,j,k}}{\max_k \sum_i^{N_j} (\cdot)^2_{i,j,k}}, \quad j = 1, \ldots, 12 $$

$$ C_{jk} = t_{f,k}, \quad j = 13 $$

$i = 1, \ldots, N_{j,k}$ are the number of samples

$j = 1, \ldots, 13$ are the components

$k = 1, \ldots, 3$ are the driving modes

where $(\cdot)$ represents the characteristics defined in Table 5, and $k$ represents the driving modes manual, Auto 1 and Auto 2.

**Table 5. Characteristics used in the optimal control problem cost function.**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilized high-speed off-tracking</td>
<td>$HSO_u$</td>
<td>m</td>
</tr>
<tr>
<td>Utilized rearward amplification</td>
<td>$RWA_u$</td>
<td>-</td>
</tr>
<tr>
<td>Centre line distance offset, axle 1</td>
<td>$d_{1}$</td>
<td>m</td>
</tr>
<tr>
<td>Centre line distance offset, axle 11</td>
<td>$d_{11}$</td>
<td>m</td>
</tr>
<tr>
<td>Lateral acceleration, unit 1</td>
<td>$a_{y,1}$</td>
<td>m/s^2</td>
</tr>
<tr>
<td>Lateral jerk, unit 1</td>
<td>$\dot{a}_{y,1}$</td>
<td>m/s^3</td>
</tr>
<tr>
<td>Positive longitudinal acceleration, unit 1</td>
<td>$a_{x(+),1}$</td>
<td>m/s^2</td>
</tr>
<tr>
<td>Negative longitudinal acceleration, unit 1</td>
<td>$a_{x(-),1}$</td>
<td>m/s^2</td>
</tr>
<tr>
<td>Positive longitudinal jerk, unit 1</td>
<td>$\dot{a}_{x(+),1}$</td>
<td>m/s^3</td>
</tr>
<tr>
<td>Negative longitudinal jerk, unit 1</td>
<td>$\dot{a}_{x(-),1}$</td>
<td>m/s^3</td>
</tr>
<tr>
<td>Road wheel angle</td>
<td>$\delta$</td>
<td>rad</td>
</tr>
<tr>
<td>Yaw rate, unit 4</td>
<td>$r_4$</td>
<td>rad/s</td>
</tr>
<tr>
<td>Vehicle speed</td>
<td>$v_s$</td>
<td>m/s</td>
</tr>
<tr>
<td>Final driving time</td>
<td>$t_f$</td>
<td>s</td>
</tr>
</tbody>
</table>

Figure 18 shows that the cost function components $RWA_u$ and $HSO_u$ were slightly smaller in the manual driving than in Auto 1 and Auto 2 mode. The centre line distance offset components $d_1$ and $d_{11}$ were much smaller for the Auto 2 mode than the Auto 1 mode. This can be due to the control
system gain settings. The offset components for the manual driving mode were performing in between Auto 1 and Auto 2. Considering the lateral jerk and the longitudinal deceleration components, the levels were much lower, about 60-70 %, for the manual driving than both automated modes. This indicates that the manual driving was performed smoother and thus focused on the feature ride comfort. This is also supported by the longitudinal jerk in Figure 18 which was much smaller, about 60 %, for the manual driving than both automated modes. Figure 18 also shows that the vehicle speed component is slightly lower for the manual driving which results in higher final driving time. However, as noted above, the maximum vehicle speed for several cases of manual driving was higher than for the modes Auto 1 and Auto 2.

6.4.2. Cornering

To further analyse the utilized characteristics, four curves (two leftwards and two rightwards) have been studied in detail. The curvature and elevation profiles of the selected curves are shown in the top panels of Figure 19 to Figure 22.

The second top panels in Figure 19 to Figure 22 show the centre line distance offset for the front axle. The mean values of the manual driving were compared with the two automated modes. For the first left curve, just before the peak in curvature, at distance 265 m, the main difference between manual and Auto 1 and Auto 2 is seen. The manual driving has a positive offset of approximately 0.25 m on average, while the auto modes have a negative offset of approximately 0.25 m (see Figure 19). Also, for both right curves (see Figures 21 and 22) there is a significant difference between the offset of the manual and automated driving. The Auto 2 offset is in general closer to the manual driving than Auto 2.

The third top panels in Figure 19 to Figure 22 show the centre line distance offset for the last axle. The results for the last axle are similar to those for the front axle, but with a time delay.

The second lowest panels in Figure 19 to Figure 22 show the vehicle longitudinal velocity for the front axle. The manual driving is in general smoother than both automated driving modes.

The bottom panels in Figure 19 to Figure 22 show the vehicle longitudinal acceleration for the front axle. Comparing the manual driving with the automated modes it can be noted that both the absolute level of the deceleration and the longitudinal jerk is higher for the automated modes.

Figure 18. Normalized cost function components calculated using (15) and (16).
Figure 19. First left curve driving characteristics. Top panel shows curvature (black solid line) and elevation (black dashed line). Other panels from top to bottom: first axle lateral distance offset, last axle lateral distance offset, first axle lateral acceleration, vehicle speed, and first axle longitudinal acceleration. Mean values for manual driving (black solid line), Auto 1 (red dashed line), and Auto 2 (black dashed line). The grey shaded area represents one standard deviation for manual driving.
Figure 20. Second left curve driving characteristics. Top panel shows curvature (black solid line) and elevation (black dashed line). Other panels from top to bottom: first axle lateral distance offset, last axle lateral distance offset, first axle lateral acceleration, vehicle speed, and first axle longitudinal acceleration. Mean values for manual driving (black solid line), Auto 1 (red dashed line), and Auto 2 (black dashed line). The grey shaded area represents one standard deviation for manual driving.
Figure 21. First right curve driving characteristics. Top panel shows curvature (black solid line) and elevation (black dashed line). Other panels from top to bottom: first axle lateral distance offset, last axle lateral distance offset, first axle lateral acceleration, vehicle speed, and first axle longitudinal acceleration. Mean values for manual driving (black solid line), Auto 1 (red dashed line), and Auto 2 (black dashed line). The grey shaded area represents one standard deviation for manual driving.
Figure 22. Second right curve driving characteristics. Top panel shows curvature (black solid line) and elevation (black dashed line). Other panels from top to bottom: first axle lateral distance offset, last axle lateral distance offset, first axle lateral acceleration, vehicle speed and first axle longitudinal acceleration. Mean values for manual driving (black solid line), Auto 1 (red dashed line), and Auto 2 (black dashed line). The grey shaded area represents one standard deviation for manual driving.
In Yamakado et al. (2009), the coordination of the longitudinal and lateral acceleration for smooth and safe driving was investigated by using acceleration diagrams, relating lateral jerk to longitudinal acceleration. Here, a similar approach for studying acceleration diagrams was conducted for the first vehicle unit (see Figure 23). Again, the mean value of the manual driving was compared with the two automated modes. When analysing manual driving trajectories from cornering, it is observed that the utilized accelerations in both left curves and the second right curve have a round shape. This round shape is not seen in the automated driving modes.

Figure 23. Acceleration diagrams for the four selected curves. First left curve (top left quadrant), second left curve (top right quadrant), first right curve (bottom left quadrant), and second right curve (bottom right quadrant). For each quadrant, the top left picture represents all drivers, the top right picture represents professional drivers, the bottom left picture represents Auto1, and the bottom right picture represents Auto 2.

Additional desktop simulations, including an optimal control problem formulation, have been conducted in order to extend the analysis of the results from the simulator study. The simulations include the one-track vehicle model with linear tire slip described in Section 2.1.2.

The optimal control problem formulated as an NLP with the three different objective functions, was defined as

\[
\begin{align*}
\min_{s \in S} t_f & \quad \text{(opt 1)} \\
\min_{s \in S} \sum_{i=1}^{N} \sqrt{(a_{x,1,f,i}^2 + a_{y,1,f,i}^2)} & \quad \text{(opt 2)} \\
\min_{s \in S} \sum_{i=1}^{N} \sqrt{(\dot{a}_{x,1,f,i}^2 + \dot{a}_{y,1,f,i}^2)} & \quad \text{(opt 3)}
\end{align*}
\]
Subject to

\[ a_y \leq a_y,1 \leq \bar{a}_y \]  \hspace{1cm} (20)
\[ a_y \leq a_y,4 \leq \bar{a}_y \]  \hspace{1cm} (21)
\[ v_x \leq v_{x,1} \leq \bar{v}_x \]  \hspace{1cm} (22)
\[ d \leq d_1 \leq \bar{d} \]  \hspace{1cm} (23)
\[ d \leq d_{11} \leq \bar{d} \]  \hspace{1cm} (24)
\[ \delta \leq \delta \leq \bar{\delta} \]  \hspace{1cm} (25)
\[ F_x \leq F_x \leq \bar{F}_x \]  \hspace{1cm} (26)
\[ v_{x,1,N} \leq \bar{v}_{x,N} \]  \hspace{1cm} (27)
\[ x(0) = x_0 \]  \hspace{1cm} (28)

where \( t_f \) is the final driving time, \( a_{x,f} \) and \( a_{y,f} \) are the longitudinal and lateral acceleration of the first unit front axle, and \( \dot{a}_{x,1,f} \) and \( \dot{a}_{y,1,f} \) are the corresponding longitudinal and lateral jerk. The front axle position of the first unit corresponds well to the longitudinal position of the driver. The inequality constraint components represent the lateral acceleration of unit 1 (20) and 4 (21) which were constrained by an upper and lower limit of 1.5 m/s², and the longitudinal velocity of unit 1 (22) which was constrained in the interval 30-70 km/h. The perpendicular centre line distance offset of axle 1 (23) and 11 (24) was constrained by an upper and lower limit of 0.5 m. Also, the final longitudinal velocity was constrained by a lower limit of 60 km/h (27). The model input \( u \), representing the front wheel steering angle \( \delta \) and the longitudinal force \( F_x \), was lower and upper bounded by the limits \( \delta \in [-20,20] \) deg (25) and \( F_x \in [-3 m_{tot},1 m_{tot}] \) N (26). The total mass \( m_{tot} \) was set to 80 t. The problem was solved using Matlab.

For the first left curve, the mean value of the manual driving was compared with the two automated modes and the results from the new optimal control simulations (see Figure 24). A similar round shaped acceleration diagram was seen for the opt 3 solution when compared with the average of the manual driving mode for the curve scenario.

![Acceleration diagrams](image)

*Figure 24. Acceleration diagrams for the first left curve. Manual driving (top left), Auto 1 (top middle), Auto 2 (top right), opt 1 (bottom left), opt 2 (bottom middle), and opt 3 (bottom right).*
7. Conclusions

VTI’s driving simulator Sim IV is a complex 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 main conclusion from the assessment questionnaires was that the realism of the road environment, vehicle suspension, vibration feeling, steering wheel feeling and the manoeuvrability/drivability during steering were adequate but would benefit from more tuning. More urgent is adjustments of braking, acceleration, level of engine sound and improved view in the right-hand side mirror.

Based on driver ratings and comments, both automated driving systems were appreciated for their lane positioning and driving performance, with a slight preference for the more advanced lateral control system (Auto 2). Reoccurring comments referred to harsh decelerations before curves. These subjective statements were in correlation with the objective data from the simulator study. Driver requirements on a more developed automated driving system would be better feedback of what the system “is about to do”, and the possibility to take over the control if needed.

A main hypothesis in this project has been that driver acceptance is important when introducing automated driving and safety functionality to long vehicle combinations. As a tool for studying manual/automated driving or designing automated driving functionalities, utilized characteristics have been introduced. Typical performance characteristics are utilized rearward amplification, utilized high-speed off-tracking, and utilized accelerations. These characteristics can then either be found in an objective function and/or as constraints when defining an optimal control problem formulation.

When analysing manual driving trajectories from cornering, it was observed that the utilized planar accelerations had a round shape. A similar shape was found when using an objective function which included minimizing the resultant jerk. This suggests that professional LVC drivers minimize acceleration changes by combined braking/propulsion and steering. Thus, this is believed to be important for the driver acceptance of automated driving of LVCs.
References


Appendix I: Vehicle models

Kinematic vehicle model

\[
\begin{align*}
\dot{x}_1 &= v_1 \cdot \cos(\theta_1) \\
\dot{y}_1 &= v_1 \cdot \sin(\theta_1) \\
\dot{\theta}_1 &= 0.27 \cdot v_1 \cdot \tan(\delta) \\
\phi_1 &= -\dot{\theta}_1 - 0.13 \cdot v_1 \cdot \sin(\phi_1) + 0.04 \cdot \dot{\theta}_1 \cdot \cos(\phi_1) \\
\phi_2 &= -0.22 \cdot (4.55 \cdot (\dot{\theta}_1 + \phi_1) + 10.4 \cdot (\dot{\theta}_1 + \phi_1) \cdot \cos(\phi_2) - 0.23 \cdot \dot{\theta}_1 \cdot \cos(\phi_1 + \phi_2 + \phi_3)) \\
\phi_3 &= -0.13 \cdot (7.7 \cdot (\dot{\theta}_1 + \phi_1 + \phi_2) + 4.55 \cdot (\dot{\theta}_1 + \phi_1 + \phi_2) \cdot \cos(\phi_3) + 10.4 \cdot (\dot{\theta}_1 + \phi_1) \cdot \cos(\phi_1 + \phi_2 + \phi_3)) \\
\end{align*}
\]

Figure 25. Parameters of the kinematic one-track model.

One-track model with linear tire slip

\[
\begin{align*}
\dot{z}_1 &= 47.0 \cdot \delta - z_{10} \cdot z_3 + 1.9 \cdot z_4 + 0.9 \cdot z_6 - 0.002 \cdot z_8 + (-70.7 \cdot z_1 + 9.7 \cdot z_3 + 21.7 \cdot z_5 + 4.5 \cdot z_7 - 0.02 \cdot z_9)/z_{10} \\
\dot{z}_2 &= z_3 - R_{1,1} \cdot (z_{10} \cdot \cos(z_2) - (z_1 + z_3 \cdot 1.5) \cdot \sin(z_2)) \\
\dot{z}_3 &= 25.0 \cdot \delta - 1.9 \cdot z_4 - 0.8 \cdot z_6 + 0.002 \cdot z_8 + (27.6 \cdot z_1 - 174.2 \cdot z_3 - 20.8 \cdot z_5 - 4.3 \cdot z_7 + 0.02 \cdot z_9)/z_{10} \\
\dot{z}_4 &= z_5 \\
\dot{z}_5 &= -25.5 \cdot \delta - 4.0 \cdot z_4 + 2.5 \cdot z_6 - 0.007 \cdot z_8 + (-36.5 \cdot z_1 + 165.4 \cdot z_3 - 10.9 \cdot z_5 + 13.0 \cdot z_7 - 0.05 \cdot z_9)/z_{10} \\
\dot{z}_6 &= z_7 \\
\dot{z}_7 &= 0.6 \cdot \delta + 2.3 \cdot z_5 - 22.9 \cdot z_6 - 0.9 \cdot z_8 + (19.9 \cdot z_1 - 216.8 \cdot z_3 - 169.7 \cdot z_5 - 125.8 \cdot z_7 - 7.2 \cdot z_9)/z_{10} \\
\dot{z}_8 &= z_{10} \\
\dot{z}_9 &= -0.19 \cdot \delta + 5.1 \cdot z_4 + 22.7 \cdot z_6 - 7.1 \cdot z_8 + (-12.5 \cdot z_1 + 195.8 \cdot z_3 + 168.6 \cdot z_5 + 68.2 \cdot z_7 - 54.7 \cdot z_9)/z_{10} \\
\dot{z}_{10} &= a_{x\text{vi}} \\
\dot{z}_{11} &= (\alpha_{x\text{vi},d\text{es}} - a_{x\text{vi}})/\tau \\
\dot{z}_{12} &= 1/(1 - \kappa_{R,1} \cdot z_{13}) \cdot (z_{10} \cdot \cos(z_2) - (z_1 + z_3 \cdot 1.5) \cdot \sin(z_2)) \\
\dot{z}_{13} &= z_{10} \cdot \sin(z_2) + (z_1 + z_3 \cdot 1.5) \cdot \cos(z_2) \\
\dot{z}_{14} &= 1/(1 - \kappa_{R,1} \cdot z_{15}) \\
&\quad \cdot \left( -24.6 \cdot z_3 - 22.7 \cdot z_5 - 12.3 \cdot z_7 - 7.7 \cdot z_9 - z_{10} - z_6 \cdot z_{10} - z_8 \cdot z_{10} + z_1 \right) \\
&\quad \cdot \sin(z_2 + z_4 + z_6 + z_8 - \theta_{R,4} + \theta_{R,1}) + z_{10} \cdot \cos(z_2 + z_4 + z_6 + z_8 - \theta_{R,4} + \theta_{R,1}) \\
\dot{z}_{15} &= \left( -24.6 \cdot z_3 - 22.7 \cdot z_5 - 12.3 \cdot z_7 - 7.7 \cdot z_9 - z_{10} - z_6 \cdot z_{10} - z_8 \cdot z_{10} + z_1 \right) \\
&\quad \cdot \cos(z_2 + z_4 + z_6 + z_8 - \theta_{R,4} + \theta_{R,1}) + z_{10} \cdot \sin(z_2 + z_4 + z_6 + z_8 - \theta_{R,4} + \theta_{R,1}) \\
\dot{z}_{16} &= \delta \\
z &= [\alpha_{x\text{vi},f\text{es}}, \psi, \Delta\psi_1 , \Delta\psi_2, \Delta\psi_3, \Delta\psi_4, \Delta\psi_5, \Delta\psi_6, v_{x\text{vi},f}, a_{x\text{vi},f}, x_1, x_1, x_1, \delta] \\
u &= [\alpha_{x\text{vi},d\text{es}}, \delta]
The states $v_{yv1f}$, $\psi$ and $\dot{\psi}$ are the lateral velocity, yaw angle and yaw rate of the first vehicle axle.

$\Delta \psi_1, \Delta \psi_2, \Delta \psi_3, \Delta \psi_4$ are the articulation angles and the rate of the articulation angles of the towed units.

$v_{xv1f}, a_{xv1f}$ are the longitudinal velocity and acceleration of the first vehicle axle. $s_1, s_11, e_1, e_11$ are the distances and the perpendicular distances of the first and the last vehicle axles projected on the lane geometry. The variables $\kappa_{R,1}, \kappa_{R,4}, \theta_{R,1}, \theta_{R,4}$ are the road curvature and heading angles of the first and last vehicle axles. The parameter $\tau$ is a constant for the longitudinal dynamics. The inputs are the longitudinal acceleration of the first vehicle axle $a_{xv1f,des}$ and the road wheel steering angle $\delta$.

Figure 26. Parameters of the one-track model with linear tire slip.


Appendix II: Questionnaires (in Swedish)

Version 4 2013-02-03  Datum: ______________  FP nr: _____

### A. Upplevelse av köring i simulatorn

1. Hur realistisk tycker du köringen i simulatorn var totalt sett?
   - Inte alls realistisk
   - Mycket realistisk
   
   1  2  3  4  5  6  7

2. Hur realistiskt upplevde du:

<table>
<thead>
<tr>
<th></th>
<th>Inte alls realistisk</th>
<th>Mycket realistisk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vägmuljön?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
<td></td>
</tr>
<tr>
<td>Interiörsinringar?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
<td></td>
</tr>
<tr>
<td>Accelerationer?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
<td></td>
</tr>
<tr>
<td>Ljudet (från vindbrus, motor, däck)?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
<td></td>
</tr>
<tr>
<td>Lastbilens tjäderingsrörelser (vertikalt och kragning)?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
<td></td>
</tr>
<tr>
<td>Vibrationer i lastbilshytten?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
<td></td>
</tr>
<tr>
<td>Styrsens och motstånd i ratten?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
<td></td>
</tr>
<tr>
<td>Manöverbarhet och korogenskaper vid styrning?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
<td></td>
</tr>
</tbody>
</table>

Kommentar: __________________________________________

____________________________________________________

3. Hur väl kunde du hålla din önskade hastighet?
   - Inte alls ☐ ☐ ☐ ☐ ☐ ☐ ☐       - Mycket bra
   
   1  2  3  4  5  6  7

Kommentar: __________________________________________

____________________________________________________
4 Hur realistiskt upplevde du att köra på vägen när det gäller

<table>
<thead>
<tr>
<th>Inte alls realistiskt</th>
<th>Mycket realistiskt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Utseende på vägen?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
</tr>
<tr>
<td>Ömgivning (t.ex träd, gräs, diken)</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
</tr>
<tr>
<td>Vibrationer från vägen?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
</tr>
<tr>
<td>Vägsträckor med gropig/pågjämn väg?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
</tr>
<tr>
<td>Upphöjdbackar</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
</tr>
<tr>
<td>Nedförhöjdbackar?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
</tr>
<tr>
<td>Väglutning i sidled?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
</tr>
<tr>
<td>Kvaror?</td>
<td>☐ ☐ ☐ ☐ ☐ ☐ ☐</td>
</tr>
</tbody>
</table>

Kommentar: ____________________________________________________________

__________________________________________________________

__________________________________________________________
**B. Upplevelse av körning jämfört med vanlig lastbil**

5 Om du jämför med den lastbilskombination du oftast kör, hur stor skillnad var det att köra den extra långa lastbilen i simulatorn?

<table>
<thead>
<tr>
<th>Inne skillnad</th>
<th>Mycket stör skillnad</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

- Vid interomningar?
- Vid acceleratöner?
- I ljudet (från vindor, motor, däck)?
- Lastbilen tjädergrörele (vertikalt och krängning)?
- Vibrations i lastbilshytan?
- Styrmåla och motstånd i ratten?
- Manöverbart och körregelnskaper vid styrning?

Kommentar: ________________________________


6 Hur idag tykte du det var att hålla dragbil och alap inom korrektet?

<table>
<thead>
<tr>
<th>Inte alls svårt</th>
<th>Mycket svårt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

- På raksträckor?
- I högkurvor?
- I väntelkurvor?
- I uppstörbockar?
- I nedstörbockar?
- På vägstäckor med gropig/öjnm väg?

Kommentar: ________________________________


7. Hur god tyckte du sikten var i den extra långa lastbilen?

<table>
<thead>
<tr>
<th></th>
<th>Inte alls god</th>
<th>Mycket god</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

Framåt?

Bakåt?

Åt varirt?

Åt höger?

Kommentar:______________________________

______________________________

8. Om du upplevde att sikten var begränsad, skulle kammaror eller radsensorer undantas?

Ja □ Nej □ Vet ej □

Kommentar:______________________________

______________________________

______________________________
C. Upplevelse av automatiskt körsystem nr ___

9 Vad är din spontana kommentar till det automatiska körsystemet? Vad är bra och vad är mindre bra?

__________________________________________________________________________________________________________________________________________

10 Hur bra tycker du att det automatiska systemet positionerade sig i körhastighet generellt?

1 2 3 4 5 6 7

Inte alls bra □ □ □ □ □ □ □ mycket bra

11 Hur tycker du att det automatiska körsystemet klarade av att köra:

<table>
<thead>
<tr>
<th>Inte alls bra</th>
<th>Mycket bra</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

På radsträckor?

[□ □ □ □ □ □ □]

I högerkurvor?

[□ □ □ □ □ □ □]

I vänsterkurvor?

[□ □ □ □ □ □ □]

I uppförskonter?

[□ □ □ □ □ □ □]

I nedförsen?

[□ □ □ □ □ □ □]

På vägsträckor med groprigjort väg?

[□ □ □ □ □ □ □]

Kommentar: ________________________________________________________________

__________________________________________________________________________

12 Ville du ta över kontrollen vid något/några tillfällen?

[□] Ja  [□] Nej

Om ja – namn några tillfällen: ________________________________________________

__________________________________________________________________________
13 I verkligheten skulle jag vilja använda det automatiska körsystemet

<table>
<thead>
<tr>
<th></th>
<th>Inte alls otta</th>
<th>Mycket otta</th>
</tr>
</thead>
<tbody>
<tr>
<td>På motorväg?</td>
<td>□ □ □ □ □ □ □</td>
<td>□ □ □ □ □ □ □</td>
</tr>
<tr>
<td>Landeväg?</td>
<td>□ □ □ □ □ □ □</td>
<td>□ □ □ □ □ □ □</td>
</tr>
<tr>
<td>I stadstrafik?</td>
<td>□ □ □ □ □ □ □</td>
<td>□ □ □ □ □ □ □</td>
</tr>
</tbody>
</table>

Kommentar (varför/varför inte?): __________________________________________


14 Jag tror jag skulle känna mig trygg med systemet i verkligheten och i samma körsituation som jag kört i simulatör.

<table>
<thead>
<tr>
<th></th>
<th>Inte alls trygg</th>
<th>Mycket trygg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>□ □ □ □ □ □ □</td>
<td>□ □ □ □ □ □ □</td>
</tr>
</tbody>
</table>

Kommentar (varför/varför inte?): __________________________________________


15 Jag tror jag skulle känna mig trygg med systemet i verkligheten och i samma körsituation som jag kört i simulatör och då andra fordon befinner sig inom synhåll, men inte i omedelbar närhet?

<table>
<thead>
<tr>
<th></th>
<th>Inte alls trygg</th>
<th>Mycket trygg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>□ □ □ □ □ □ □</td>
<td>□ □ □ □ □ □ □</td>
</tr>
</tbody>
</table>

Kommentar (varför/varför inte?): __________________________________________
D. Upplevelse av automatiskt körsystem nr____

16 Vad är din spontana kommentar till det automatiska körsystemet? Vad är bra och vad är mindre bra?

________________________________________________________________________

________________________________________________________________________

17 Hur bra tycker du att det automatiska systemet positionerade sig i körfältet generellt?

1 2 3 4 5 6 7

Inte alls bra □ □ □ □ □ □ □ Mycket bra

18 Hur tycker du att det automatiska körsystemet klarade av att köra:

<table>
<thead>
<tr>
<th>Kommentar:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>På raktäckor?</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>I högerkurvor?</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>I väntkurvor?</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>I uppförstavkar?</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>I nedförravkar?</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
<tr>
<td>På västraockor med gropig/jamn väg?</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>

19 Vill du ta över, eller tog du över kontrollen vid något/några tillfällen?

□ Ja □ Nej

Om ja – namn några tillfällen: ____________________________________________

________________________________________________________________________
20 I verkligheten skulle jag vilja använda det automatiska körsystemet

<table>
<thead>
<tr>
<th>Inte alls ofta</th>
<th>Mycket ofta</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

På motorväg? □ □ □ □ □ □ □
Landsväg? □ □ □ □ □ □ □
I stadstrafik? □ □ □ □ □ □ □

Kommentar (varför/varför inte)?

________________________________________________________________________
________________________________________________________________________

21 Jag tror jag skulle känna mig trygg med systemet i verkligheten och i samma körsituation som jag kört i simulatorn.

<table>
<thead>
<tr>
<th>Inte alls trygg</th>
<th>Mycket trygg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

Kommentar (varför/varför inte)?

________________________________________________________________________
________________________________________________________________________

22 Jag tror jag skulle känna mig trygg med systemet i verkligheten och i samma körsituation som jag kört i simulatorn och då andra fordon befinner sig inom synhåll, men inte i omedelbar närhet?

<table>
<thead>
<tr>
<th>Inte alls trygg</th>
<th>Mycket trygg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

Kommentar (varför/varför inte)?

________________________________________________________________________
________________________________________________________________________

23 Det automatiska körsystemet du fick prova i simulatorn är en tidig prototyp. Vilka krav och förväntningar skulle du ha på ett mer utvecklat system?

________________________________________________________________________
________________________________________________________________________
24 Hur ofta skulle du använda ett automatiskt körsystem som motsvarar din krav och förväntningar?

<table>
<thead>
<tr>
<th>Inte alls ofta</th>
<th>Mycket ofta</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

På motorväg?
Landsväg?
I stadsstrafik?

Kommentar: __________________________________________________________

25 Jag tror jag skulle känna mig trygg i verkligheten med ett automatiskt körsystem som motsvarar mina krav och förväntningar.

<table>
<thead>
<tr>
<th>Inte alls trygg</th>
<th>Mycket trygg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
</tbody>
</table>

Kommentar: __________________________________________________________
### E. Bakgrund

26 Vilket åter är du född? ______
27 □ Man □ Kvinn
28 Vilket år tog du dina körkort?
28.1 B: ______
28.2 C: ______
28.3 CE: ______
28.4 D/D: ______
29 I genomsnitt, hur många mil kör du per år med lastbil? ______ milår.
30 På att unga är, hur många dagar per vecka kör du lastbil? ______ dagar/vecka.
31 Vilken lastbilskombination kör du ofta?
   □ Dragbil med semitrailer □ Lastbil utan släp
   □ Lastbil med släp □ Annan: ______________________
   ______________________
31.1 Kör du längre lastbilskombinationer, längre än 25.25 m, som kräver specialstillstånd från Trafikverket?
   □ Ja □ Nej
   Om ja, hur ofta?
   
   1 2 3 4 5 6 7
   Inte alls ofta □ □ □ □ □ □ Mycket ofta
31.2 Hur gamla är den siste lastbil du huvudsakligen kör? ______________________
31.3 Vilken typ av gods kör du ofta?
   □ Stycke gods □ Levande gods (slaktdjur)
   □ Farligt gods och/eller flytande gods □ Bulkgod/massgods
   □ Timmer □ Avfallskrot
   □ Annan: ______________________
31.4 Hur ofta kör du lastbil:
   
<table>
<thead>
<tr>
<th>Inte alls ofta</th>
<th>Mycket ofta</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>På motorväg?</td>
<td>□ □ □ □ □ □</td>
</tr>
<tr>
<td>På landsväg?</td>
<td>□ □ □ □ □ □</td>
</tr>
<tr>
<td>I stadstrafik?</td>
<td>□ □ □ □ □ □</td>
</tr>
</tbody>
</table>
32. Brukar du köra med farthållare som håller konstant hastighet när du kör lastbil?
   □ Ja □ Nej
   Om nej, gå vidare till fråga 33.

32.1 Hur ofta använder du farthållare när du kör lastbil:
   | Inte alls ofta | Mycket ofta |
   | 1 2 3 4 5 6 7 |
   | På motorväg? |
   | På landväg? |
   | I stadsstrafik? |

32.2 Vilken är din allmänna inställning till att använda farthållare när du kör lastbil?
   | Mycket negativ | Varken eller | Mycket positiv |
   | □ □ □ □ □ □ |

32.3 Hur stort förtroende har du för farthållare när du kör lastbil?
   | Mycket stort | Varken eller | Mycket stort |
   | □ □ □ □ □ |

33. Har du någon gång kört lastbil med adaptiv farthållare (även kallad ACC som automatiskt håller avståndet till framförvarande bil)?
   □ Ja □ Nej □ Vet ej
   Om nej eller vet ej, gå vidare till fråga 34.

33.1 Hur ofta använder du adaptiv farthållare (ACC) när du kör lastbil:
   | Inte alls ofta | Mycket ofta |
   | 1 2 3 4 5 6 7 |
   | På motorväg? |
   | På landväg? |
   | I stadsstrafik? |

33.2 Vilken är din allmänna inställning till att använda adaptiv farthållare (ACC) när du kör lastbil?
   | Mycket negativ | Varken eller | Mycket positiv |
   | □ □ □ □ □ □ |
### 33.3 Hur stort förröende har du för adaptiv fartbäddare (ACC) när du kör lastbil?

<table>
<thead>
<tr>
<th>Mycket litet</th>
<th>Varken eller</th>
<th>Mycket stort</th>
</tr>
</thead>
<tbody>
<tr>
<td>☐</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

### 54 Använder du följande säkerhetsystem i den lastbil du kör ofta?

- **Antisladdsystem**
  - ☐ Ja
  - ☐ Nej
  - ☐ Vet inte
  - ☐ Finns ej

- **Kollisionsvarningssystem**
  - ☐ Ja
  - ☐ Nej
  - ☐ Vet inte
  - ☐ Finns ej

- **Avåktningsvarningssystem**
  - ☐ Ja
  - ☐ Nej
  - ☐ Vet inte
  - ☐ Finns ej
Projekt-ID:                      Datum:                      Id.nr:

**Information om forskningsstudie**

Volvo och VTI önskar din medverkan i en forskningsstudie om upplevelsen av att på en svensk landsväg köra lastbilskombinationen A-double med totalvägt 80 ton. Dragbilen är en FH16 med 750 hk och automatisk växellåda. Studien är en del i vår säkerhetsforskning och din medverkan är av stor betydelse för oss.

För att vi skall kunna samla in uppgifter kräver ditt samtycke. Accepterar du att delta måste du ta del av denna information och darafr lämna ett skriftligt samtycke på billaget blankett ”Medgivandeformulär”.

**Studiebeskrivning**

Syftet med studien är att i en körsimulator låts flera lastbilchaufförer bedöma upplevelsen av att dels själva köra lastbilskombinationen A-double på en svensk landsväg, och dels låta två automatiserade körsystem köra samma lastbil på samma sträcka.

Först kommer du att få fylla i några frågeformulär, och sen kommer du att köra en träningsdel där du får bekanta dig med simulatort, testa att bromsa, gasa, svänga etc tills du känner dig heltväl i miljen. Under alla delar av studien kommer du att få köra på en landsväg med en lit i vardera riktningen, inga andra fordon kommer att befinner sig på vägen under någon del av studien.

När du sitter i körsimulatort så får du gärna ”tänka högt” eftersom dina spontana intryk och kommentarer är värdefulla för oss. Under träningsdelen kan vi prata med varandra. Men under resten av studien så vill vi att du kör utan att prata med oss om det inte är absolut nödvändigt, dock får du gärna ”tänka högt”.

Direkt efter träningsdelen så börjar första delen i studien där du själv får köra lastbilen i 10 min. Vi vill att du försöker köra som du normalt skulle göra och köra i max 70 km/h. Självklart får du sakte ned i kurvor och köra på ett sått som känns säkert för dig. Efter den första delen får du komma ut från simulatort och fylla i ett frågeformulär.


Efter den andra delen så får du sita kvar i simulatort och besvara ett frågeformulär. Sen kommer du att få uppleva en annan variant av automatiskt körsystem som kör lastbilen på samma sträcka under 10min.

När den tredje och fjärde delen är slut så får du komma ut ur simulatort och fylla i några fler frågeformulär. Sist vill vi veta lite mer om din bakgrund, vilket du lämnar i biljetten "CICE-kort"

Under studien lagrar vi data från simulatort (hastighet, rörelse, position på vägen etc) samt från videokameror riktade framåt mot vägen, mot dig som förare samt in mot
kupén och instrumentpanel. Vi sparar även de svar som du givit i de ersätter vi ber dig fylla in.

Under analysen efter studien är klar så ligger fokus på dina erkärtar. Vi kommer även att studera fordonsinsignier från fordonet. Videofilmer används framförallt som komplement för att tolka specifika avsnitt av loggningen, t.ex. vid kurvor och köckor.

**Frivilligt deltagande**

Ditt deltagande i forskningsstudien är helt och hållet frivilligt.

**Rätten att avbryta**

Du har rätt att när som helst avbryta din medvetande i studien och begära att insamlingen av data avbryta utan att ange något skäl.

**Eventuella risker**


**Behandling av personuppgifter och data**

När du deltar i den här studien kommer personuppgifter att samlas in om dig. Utöver det som insamlas automatiskt i simuleraren (t.ex. bil, förrätte, tid och plats) kommer vi ha dig om vissa uppgifter såsom t.ex. namn, kontaktadress, ålder och kön. För behandlingen av alla uppgifter som går att hantera till dig som person följer vi personuppgiftslagen (1998:204), PUL.

Ändamålet med forskningsstudien är att utvärdera olika alternativ av ett möjligt framtida system samt samla in vanlig kördata under normal köring och automatiserad köring.

De data, inklusive videoupptagningar, som vi samlar in med din hjälp, kommer att vara tillgängliga för dem som behöver data för att arbeja i det aktuella forskningsprojektet.

Vi kan komma att publicera slutsatser dragna på statistisk nivå från en sammanvägning av data från ett antal förare, där din identitet inte kan röjas.

Du har möjlighet att samtala till att videoopptagen eller stillbilder av dig och din köring publiceras eller visas offentligt i olika sammanhang. Det kan då gälla t.ex. i forskningsrapporter, vid konferenser eller vid utbildningsställen.

All loggad nådata dvs. observerade signaler från fordonet, kommer att förvaras hos Volvo Group Truck Technology samt på VTI. Därmed är alla två parter personuppgiftsansvariga.

Du har naturligtvis själv rätt att få ta del av de data som samlats om dig och din köring. För att få tillgång till data kan du kontakta någon av personerna på nästa sida.
ViP is a joint initiative for development and application of driving simulator methodology with a focus on the interaction between humans and technology (driver and vehicle and/or traffic environment). ViP aims at unifying the extended but distributed Swedish competence in the field of transport related real-time simulation by building and using a common simulator platform for extended co-operation, competence development and knowledge transfer. Thereby strengthen Swedish competitiveness and support prospective and efficient (costs, lead times) innovation and product development by enabling to explore and assess future vehicle and infrastructure solutions already today.