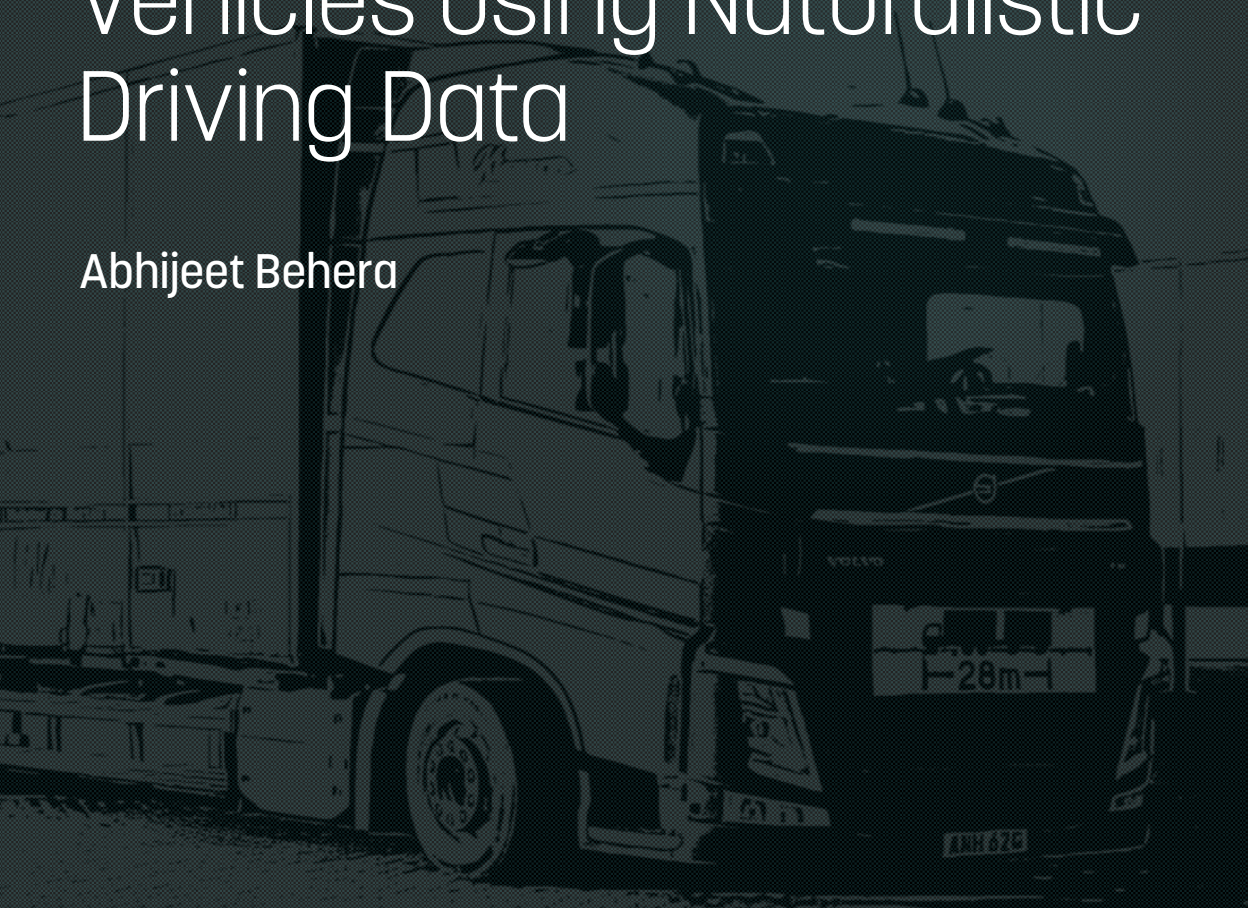# Performance Assessment of Long Combination Vehicles using Naturalistic Driving Data

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Performance Assessment of Long Combination Vehicles using Naturalistic Driving Data

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Cover picture: The background photo shows the DuoCAT combination, whose
performance is analysed in this thesis.

It's a never ending battle of making your cars better and also trying to be better yourself.

DALE EARNHARDT

Populärvetenskaplig sammanfattning

Introduceringen av långa fordonskombinationer (LCV) pågår för närvarande i Sverige vilket ger en möjlighet att minska driftskostnader samtidigt som bränsleeffektiviteten förbättras och koldioxidutsläppen per ton-km reduceras. LCV avser tunga fordon som är längre än 25,25 meter, vilket är den konventionella längdgränsen enligt svenska regler. Trots fördelarna är en fråga hur dessa fordon presterar på väg. Den här avhandlingen studerar och analyserar den frågan med hjälp av naturalistisk kördata (NDD) från experiment med LCV.

Prestandabedömningen görs med hjälp av prestandabaserade standarder (PBS). PBS är ett regleringssystem för tunga fordon, såsom LCV, som kvantifierar och kravställer fordonets beteende. De huvudsakliga PBS-måtten som används i denna avhandling är bakåtförstärkning, spåravvikelse och svept area i låg hastighet. Bakåtförstärkning representerar förstärkningen av rörelser från den främre till den bakre delen av en fordonskombination, vilket relaterar till dess stabilitet, och de två återstående indikerar det utrymme som fordonen upptar i olika scenarier. Dessutom används styråtervändningshastigheten (SRR) för att beräkna förarnas kognitiva arbetsbelastning vid låga hastigheter, exempelvis vid körning i rondeller och korsningar.

Två LCV varianter studeras i denna avhandling, en A-dubbel bestående av dragbil-påhängsvagn-dolly-påhängsvagn/dragbil-påhängsvagn-släpvagn samt en Duo-kärra bestående av en lastbil som drar två släpvagnar med centrerade axlar. Fyra scenarier är av intresse för denna avhandling: filbyten, manövrering genom rondeller, svängning i korsningar och körning i snäva kurvor. Avhandlingen presenterar tre bidrag som beskriver analysmetoderna och efterföljande resultatdiskussioner.

I det första bidraget utvecklas en algoritm för att extrahera filbyten från naturalistisk kördata av LCV fordon där metoden används på data från A-dubbelfordon. Resultaten indikerar att A-dubbelfordon håller sig till föreslagna säkerhetsgränser under filbyten.

I det andra bidraget bedöms prestandan hos ett A-dubbelfordon i rondeller med hjälp av NDD. Olika rondeller med olika radier studeras. Fordonet upptar mer utrymme i rondeller med mindre radie jämfört med rondeller med större radie och det upptagna utrymmet ligger i alla undersökta fall under den föreslagna säkerhetsgränsen. För mindre rondeller än de som tas upp i denna studie kan styrbara axlar behövas. Dessutom visas att förarens kognitiva belastning varierar med rondellens radie där förare som navigerar större rondeller har en lägre kognitiv belastning.

Det tredje bidraget handlar om prestandautvärdering av Duo-kärrafordon över fyra scenarier, följt av jämförelsen med A-dubbelfordon. Resultaten indikerar att både A-dubbelfordon och Duo-kärrafordon är stabila och har god spårningsprestanda i de flesta fallen. A-dubbelfordon observeras vara något mer stabil i filbyten, medan Duo-kärrafordon har något bättre manövrerbarhet vid låghastighetsscenarier som rondeller och korsningar.

Abstract

The deployment of long combination vehicles (LCVs) is currently in progress in Sweden. LCV refers to heavy vehicles that are longer than 25.25 m, which is the conventional length limit in Swedish regulations. LCVs reduce operational costs, improve fuel efficiency and reduce CO_2 emission per ton-km. Despite their numerous advantages, a question that still revolves around these vehicles is how they perform on the road. Although this question has been answered using simulations, an analysis using real traffic data is still missing.

This thesis assesses the performance of LCVs using naturalistic driving data (NDD). The performance assessment is done using Performance-based standards (PBS) measures. PBS is a regulatory scheme for heavy vehicles, such as LCVs, that includes performance measures with a quantified required level of performance. The main PBS measures used in this thesis are rearward amplification, low-speed swept path, high-speed transient offtracking, and high-speed steady-state offtracking. Rearward amplification represents the amplification of motions in the rear end of a vehicle combination, which relates to its stability, and the remaining three are indicative of the space that the vehicles occupy in different scenarios. The steering reversal rate is also employed to compute the cognitive workload of the drivers in low-speed scenarios.

Two LCV combinations are considered for analysis, namely an A-double composed of a tractor-semitrailer-dolly-semitrailer/tractor-semitrailer-full trailer and a DuoCAT composed of a truck hauling two centre-axle trailers. Four scenarios are of interest to this thesis: lane changes, manoeuvring through roundabouts, turning in intersections and negotiating tight curves. The thesis presents three contributions outlining the analysis methodologies, followed by a discussion of the results obtained from the analysis.

The first contribution involves developing an algorithm to extract lane changes from the NDD of LCVs. The algorithm is used against the data obtained from A-doubles. The results indicate that A-doubles adhere to proposed safety limits during lane changes.

The second contribution assesses the performance of A-double in roundabouts using NDD. Various roundabouts with different radii are considered. The vehicle occupies more space with lower radius roundabouts than higher radius roundabouts. The space occupied in all the cases is below the proposed safety limit. However, steerable axles might be needed for smaller roundabouts than those considered in this study. Additionally, the driver's cognitive workload is found to vary with the roundabout's radius, with drivers navigating higher-radius roundabouts more easily.

The third contribution deals with the performance evaluation of DuoCAT across four scenarios, followed by the comparison with A-double. The results indicate that the A-double and the DuoCAT are stable and have good tracking performance in most cases. The A-double is observed to be slightly more stable in lane changes, whereas the DuoCAT has slightly better manoeuvrability at low-speed scenarios such as roundabouts and intersections.

Acknowledgments

I have always believed that a PhD is not just about earning a degree; it's a transformative experience that enriches every facet of a person doing it. As I hit the halfway mark of this PhD, I am filled with gratitude for the people who have helped shape me into the person I am today. To each of you, I want to express my heartfelt thanks for your influence on my growth.

First and foremost, I would like to appreciate the efforts put in by both of my supervisors, Sogol Kharrazi and Erik Frisk, to guide me in difficult situations. The insightful comments of Erik combined with the professional expertise of Sogol helped me to get into the depth of the research questions handled in this thesis. Not to forget the SRS/ERS (Sogol/Erik review system) for all the publications, which has brought a substantial difference between the first and the last draft. It has not only improved the quality of publications but also taught me to handle criticism of my work. Moreover, I would like to thank Lena Larsson from Volvo Trucks, Daniel Bäckborn from Provinn and their corresponding teams for coordinating the data collection campaigns.

I have been fortunate to be a part of two workplaces, VTI and LiU. At VTI, I would like to thank Anders, Bo, Florian, Johanna, Krister, Kristoffer, Lennart, Magnus and Sogol for some stimulating fika discussions that always seemed to be like parliamentary debates, covering diverse topics such as economics, health, society, and politics. Also special thanks to Lisa, Florian and Bo for those refreshing 'after-lunch promenad'. At LiU, I would like to thank my amazing colleagues, specifically Jian (flexible), Shadi (happiness), Arman (rice), Oskar (haha), Theodor, Arvind, Arezou, Amina, Ola and Ipek for some amazing afterworks and Friday lunches. Except for teaching, they never made me feel that I am not a university-employed PhD student. I am also grateful to Jian for collaborating with me in many courses and giving me a cookie every time I visit his office. Special thanks to Arvind and Shadi for providing me with information on the essential things during the initial days of my PhD. I am also thankful to other senior researchers, both at VTI and LiU, who have provided me with valuable comments on my project on different occasions.

A part of my motivation to start the PhD came from my group of close friends in the Netherlands, Vivek, Sambit Praharaj and Arnab, who were pursuing their PhD when I was doing my masters. I learnt many skills from their experiences which has been fruitful in many of my situations. Lively night outs, discussions on crypto and stocks, or the conversation on sea station and rail port, many such countless memories with these friends never fail to bring a smile to my face. Over the years, they have become more than just friends; they are my family away from home. I would also like to acknowledge another close friend over the Atlantic, aka mathematician, Sambit Senapati. Not only has he been my go-to guy for math help whenever I have needed it, but he has also been there to calm my nerves during some of the most frustrating moments of this journey.

Finally, my acknowledgement is incomplete without mentioning my girlfriend, Sneha, and my parents. Although I live a continent away from them, there has hardly been a day when I have not received a call from them. Irrespective of how my day went, they made sure that I stayed relaxed, focused and motivated. Their love, care and support have kept me going on many stressful days.

There is still a long way to go until I finish this PhD. I am sure there are more beautiful memories and moments awaiting. Until then, many thanks again to all who have been a part of my journey and sincere apologies to someone if I have missed to mention here.

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Linköping, March 2024
Abhijeet Behera

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Funding

Contents

List of Acronyms

LCV	Long Combination Vehicle
HCT	High Capacity Transport
CAT	Centre Axle Trailer
NDD	Naturalistic Driving Data
PBS	Performance-Based Standards
RWA	Rearward Amplification
HSTO	High-Speed Transient Offtracking
HSSO	High-Speed Steady-State Offtracking
LSSP	Low-Speed Swept Path
SRR	Steering Reversal Rate
DGPS	Differential Global Positioning System
IMU	Inertial Measurement Unit
OSM	OpenStreetMap

Chapter 1

Introduction

Over the past decade, Sweden has experienced significant growth in its logistics network due to increased globalisation. Among various forms of inland logistics, road freight has emerged as the leading contributor, with its contribution increasing every year in the last decade [1]. Consequently, this upsurge has increased road congestion, transportation emissions and fuel consumption. To address these challenges, the Swedish government started the High-capacity transport (HCT) program in 2012. HCT vehicles refer to heavy vehicles with a gross load of more than 64 tonnes or a length of more than 25.25 m. These limits apply to heavy vehicles in Sweden and can be different in other countries. Backed by extensive research on HCT vehicles in Sweden, the government increased the gross combination weight of heavy vehicles from 64 tonnes to 74 tonnes in 2018 [2]. The 74 tonnes-vehicles are driven on roads with the new bearing capacity of BK4 [3]. Despite the increase in weight, the length of the vehicle remained capped at 25.25 m. In Sweden, HCT vehicles longer than 25.25 m are termed Long combination vehicles (LCVs). Several research on LCVs in Sweden and other parts of the world have shown the potential of these vehicles to reduce operational costs, and greenhouse gas emissions per ton-km, and to improve fuel efficiency [4–6]. Motivated by the benefits of LCVs, the Swedish government extended the permissible length of vehicles from 25.25 m to 34.5 m in 2023 [7], and allowed them to operate on a designated part of the road network.

While the deployment of LCVs may seem economically and environmentally beneficial, their length can present potential challenges to other road users. An approach to ensure the safety of LCVs is to use Performance-based standards (PBS). PBS is a regulatory scheme for heavy vehicles that requires the vehicles to have a quantified level of performance in certain scenarios, instead of just mandating length and weight limits [8]. Previously, PBS has been successfully implemented in Canada [9], New Zealand [10] and Australia [11]. In Sweden, the PBS requirements were introduced for 74 tonnes vehicles in 2018 [2] and

are yet to be formalised for LCVs. Nevertheless, a PBS-descriptive approach is established for the first phase of the LCV introduction. In this approach, dimension envelopes based on PBS have been used.

A PBS scheme includes different performance measures with the prescribed limits that the vehicle must comply with. Previous research on PBS has classified performance measures into multiple categories: traction, low-speed tracking, high-speed tracking, low-speed stability, high-speed stability and braking [12]. Note that the term 'tracking' has a different interpretation compared to what it is in other fields such as robotics. Here, the tracking measures give an idea of how close the paths of two units of a heavy vehicle combination are to each other. Hence, it is representative of the space that the vehicle occupies on the road.

Extensive research has been conducted worldwide and in Sweden to evaluate the stability and tracking ability of LCVs in different traffic scenarios using measures listed in PBS. In [13], simulations are conducted using the single-track vehicle models of LCVs to assess the performance in lane changes and roundabouts. These models are validated using test-track experiments. In [14], the performance of different LCVs is evaluated in Swedish roundabouts of varying dimensions using a multibody dynamics vehicle model. A review of the research related to the performance assessment of LCVs in Sweden can be found in [15]. These investigations predominantly involve simulations where validated vehicle models of different fidelities are employed to assess the performance of LCVs. Although the simulations allow for a detailed understanding of the influence of parameters on the performance measures, the parameter variation in real-world traffic is difficult to replicate in a simulation environment. Consequently, an understanding of the performance of LCVs in real-world traffic is missing.

Up until 2023, the period when the vehicle's length was capped at 25.25 m, several LCVs were granted exemptions for trial purposes on specific roads across Sweden. This thesis will utilise data obtained from trials of two combination types to evaluate their performance in real-world traffic. The first combination is an A-double, consisting of a tractor-semitrailer-dolly-semitrailer/tractor-semitrailer-full trailer, and the other one is a DuoCAT which has a truck hauling two centre axle trailers. Two vehicles of A-double type and one of DuoCAT are used for data collection, see Figure 1. These vehicles are driven across different parts of Sweden, as shown in Figure 2.

| (a) A-double 1 | (b) A-double 2 | (c) DuoCAT |

Figure 1: A-double and DuoCAT combinations used for data collection.

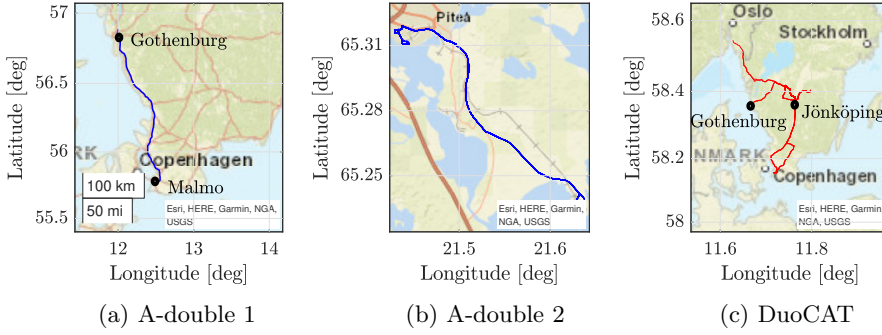(a) A-double 1   (b) A-double 2   (c) DuoCAT

Figure 2: Route maps of vehicles.

The data from the trials are collected unobtrusively as the vehicle navigates in real-world traffic. The data, which is otherwise known as naturalistic driving data (NDD), measures the unbiased response of the drivers to different scenarios [16]. Some of these scenarios may lead to safety-critical situations. Previous research on heavy vehicles has shown that scenarios like lane changes and negotiating curves are susceptible to safety-critical situations due to loss of control [17]. It is reasonable to assume that these two scenarios have the potential to create safety-critical situations for LCVs as well. Furthermore, road infrastructures like roundabouts and intersections also increase the complexity of manoeuvring for LCVs, influencing tracking abilities. Hence, four scenarios are of interest to this thesis: lane changes, manoeuvring through roundabouts, turning in intersections and negotiating tight curves.

1.1 Research question and Objectives

The selected scenarios have been studied extensively in the context of passenger cars. For example, see [18] for lane changes, [19] for roundabouts, [20] for intersections and [21] for curves. These studies primarily concentrate on assessing the behaviour of drivers. On the contrary, there are limited studies which comment on the performance of LCVs in these scenarios. Moreover, the existing studies are performed using simulations. For example, see [12], [14] and [22]. While these simulations are valuable for analysing performance across a broad spectrum of driver responses, it is essential to note that real-world responses may differ from simulated ones. This is because the response will be influenced by uncertain traffic around it. Consequently, the performance of LCVs may differ from what is predicted from the simulations. This thesis aims to evaluate the performance of two LCV types, namely A-double and DuoCAT, in the selected scenarios in real traffic. Therefore, the primary research question is formulated as,

How do A-double and DuoCAT perform in lane changes, roundabouts, intersections and tight curves in real traffic with regard to stability and tracking?

The primary question can be broken down into 8 cases, each looking at how well each of the two vehicles performs in each of the four scenarios. The answers are obtained by fulfilling the following objectives for a given vehicle and scenario:

- Identify the intervals in the recorded data of the vehicle corresponding to the scenario of interest.

- Evaluate the performance of the vehicle in the identified intervals using measures listed in the PBS scheme.

Chapter 2

Methodology

In last few years, the availability of various kinds of sensors has made data collection seamless and efficient. This fact led to many naturalistic driving data (NDD) campaigns in the automotive sector in the past two decades. Examples of famous studies which recorded a significant amount of NDD are Shrp2 [23], SeMiFOT (both 1 and 2) [24] and EuroFOT [25]. The Shrp2 consists of data logged from 2500 vehicles over three years. It is mostly used for driver behaviour and accidental analysis. In both SeMiFOTs combined, data is logged from 23 vehicles over one year. It focuses on validating the driver assistance systems. EuroFOT has the same focus as SeMiFOT. However, it is a relatively large study and is composed of 130 vehicles logging data over one year.

The NDD used in this thesis is smaller than the above-discussed studies in terms of logged data volume and lacks video streams. It comprises three vehicles, two of which are A-doubles, collectively traversing approximately 5,000 km over three months. Additionally, a DuoCAT covers approximately 35,000 km over nine months. Figure 1 presents the schematic of the data analysis process adopted in this thesis.
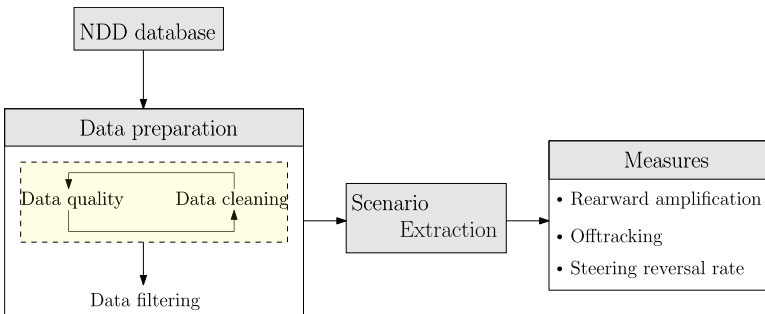
Figure 1: Schematic of data analysis.

2.1 NDD database

The NDD database is composed of files from two data sources, DGPS (Differential GPS) and IMU measurements from the OxTS RT3000 sensor package [26], and CAN signals. The sensor package has a positional accuracy of 1 cm under a clear sky and logs measurements at a frequency of 100 Hz. Two sensor packages are used in each of the vehicles, one in the first unit and the other in the last unit of the vehicles. Some of the relevant signals are steering wheel angle, vehicle speed, positions, translational/angular velocities and accelerations, and accuracy estimates of positions.

2.2 Data preparation

Data preparation aims to make the data consistent and appropriate for the scenario extraction step, using data quality analysis (DQA), data cleaning (DC) and data filtering. DQA finds inconsistencies in the data, whereas DC is associated with removing or fixing inconsistent data. The following steps are employed to make the data consistent which are inspired by the FESTA quality assurance approach [27].

1. Fixing corrupted data: Sensor produces `NaN` values upon their start and intermittently within the measurements. These instances of `NaN` are either removed or substituted with linearly interpolated values based on the length of missing data.

2. Reasonable data values: Data files with random or unreasonable magnitudes in DGPS and IMU measurements are discarded from further analysis.

3. Data dynamics over time: Some data files have IMU signals logged at a different frequency than the sampling frequency. In such cases, IMU signals are discarded, and DGPS signals are instead used to calculate orientation, velocities, and accelerations.

The consistent data is then filtered using a low-pass second-order Butterworth filter with a cut-off frequency of 1 Hz to suppress the higher-order dynamics and make it appropriate for the next step. Figure 2 shows an application of the filter on the raw yaw rate signal.
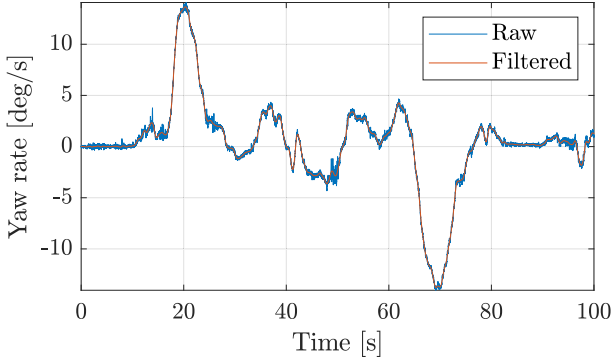
Figure 2: Raw and filtered yaw rate signal.

2.3   Scenario extraction

The processed data is used to extract scenarios of interest. There are a total of four scenarios considered in this thesis: lane changes, manoeuvring through roundabouts, turning in intersections and negotiating tight curves.

Lane changes

NDD generally includes video data. Previous research like [28] uses image processing and machine learning to perform automatic extraction of lane changes. In the absence of video data, integration methods are used to extract lane changes where IMU signals like yaw rate and speed are integrated over time to find the lateral displacement [29]. However, these signals have noise associated with them and integrating them leads to drift. In this thesis, a simple algorithm is proposed that uses road data, GPS and IMU signals to extract lane changes from NDD. The first step of the algorithm deals with identifying the oscillation pattern of the yaw rate within NDD. The second step deals with calculating lateral displacement based on the position estimates of vehicle and road data. Paper I explains this algorithm in detail.

Roundabouts and Intersections

Several research in the autonomous vehicle field have focused on detecting roundabouts and intersections. The methods employed in previous research require real-time access to camera and lidar data [30, 31]. However, when such data is unavailable, openly available geographical maps offer an alternative. This thesis utilises OpenStreetMap (OSM) to identify these infrastructures. OSM tags ('junction=roundabout') help detect roundabouts, while intersections are

detected using the fact that in OSM they are the nodes shared by multiple roads. With the locations of the roundabouts and intersections known, the intervals in NDD when the vehicle passes through a certain roundabout or intersection are extracted. Paper II and III address roundabouts and intersections.

Tight Curves

Considerable research has been dedicated to curve identification, with many studies relying on GIS (geographic information system) and commercial satellite imagery, as demonstrated in prior works such as [32], [33], and [34]. In contrast, this study utilises publicly accessible road data from the Swedish Transport Administration database [35] instead of using proprietary sources like GIS. The curvature of the road data is computed, and subsequent limits are applied to extract tight curves. Once the relevant curve locations are determined, intervals in NDD during which the vehicle traverses these curves are extracted. For a detailed explanation of the curve extraction process, please refer to Paper III.

2.4   Measures

The previous step provides intervals in NDD for each of the scenarios. In the following, the vehicle's performance is assessed using PBS measures in extracted intervals for all the scenarios. The measure rearward amplification (RWA) is employed to assess stability, while offtracking is used to evaluate the vehicle's tracking ability. The measures low-speed swept path (LSSP), high-speed transient offtracking (HSTO) and high-speed steady-state offtracking (HSSO) are variations of offtracking, which are used in this thesis. For roundabouts and intersections, the steering reversal rate (SRR) is also computed in these intervals. It is a measure of the cognitive workload of the driver.

Rearward amplification

RWA is the amplification of a motion variable of interest at the last unit compared to the first unit. The most commonly used variables are yaw rate and lateral acceleration. Mathematically, it is defined as the ratio of the last unit's peak yaw rate (or lateral acceleration) to that of the first unit in the extracted interval [11], i.e.,

$$\text{RWA} = \frac{\max |\text{Yaw rate of last unit}|}{\max |\text{Yaw rate of first unit}|}. \tag{2.1}$$

Offtracking

Offtracking is defined as the difference in the path traced by the centre of the first and last axles of the vehicle under consideration. The maximum difference in the path is termed as maximum offtracking. Maximum offtracking is alternatively

known as HSTO in high-speed transient manoeuvres like lane changes, and HSSO in high-speed steady-state manoeuvres like curves. LSSP is qualitatively the same as the maximum offtracking except for the fact that the extremities of the vehicles are traced instead of the centre of the axles.
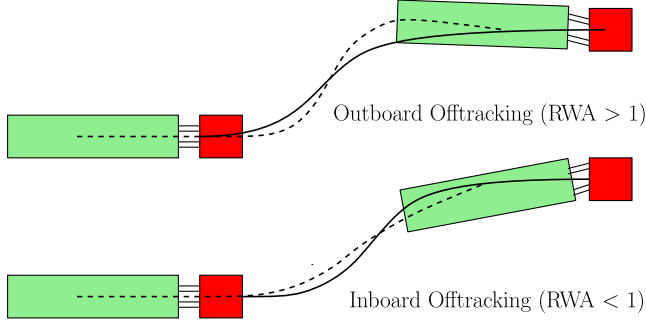

Figure 3: Different types of offtracking.

Two different kinds of offtracking are depicted in Figure 3. At the top, it is outboard offtracking where the last unit is displaced outwards of the turn. It is observed at high speed and corresponds to RWA > 1. At the bottom, inboard offtracking is shown, where the last unit is displaced inwards of the turn. It is observed at low speed and corresponds to RWA < 1.

Steering reversal rate

SRR is defined as the number of steering wheel angle reversals per minute larger than a certain minimum angular threshold. The algorithm to calculate SRR is made up of the following four steps [36].

1. Low pass filtering: A low-pass second-order Butterworth filter, with a cut-off frequency of 1 Hz in this thesis, is applied to the steering wheel angle signal to suppress the high-frequency noise.

2. Finding stationary points: A stationary point is the local maximum or local minimum of the filtered steering wheel angle signal where the steering-wheel rate is either 0 or about to pass 0.

3. Finding reversals: Steering wheel reversals are identified by examining previously calculated stationary points. A reversal occurs whenever the difference between a local maximum or minimum point and its consecutive one exceeds the threshold. Motivated from [37] where SRR is computed for a heavy vehicle, the threshold is fixed at 3 deg in this thesis.

4. Calculating SRR: It is the ratio of the total number of reversals in the steering wheel angle signal to the signal's total length in minutes.

Figure 4 illustrates an application of the algorithm. The steering wheel signal belongs to an A-double which manoeuvres through a roundabout. There are 5 reversals in approximately 24 seconds resulting in an SRR of 12.5.
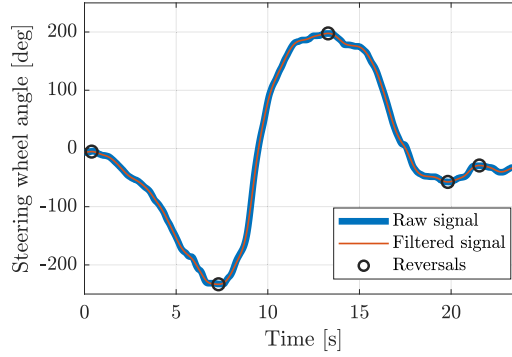

Figure 4: Steering-wheel angle profile with corresponding reversals.

Calculation of PBS measures in extracted scenarios

This section briefly explains the process behind the analysis of a few PBS measures. The approach used for computing some of the variables which influence these measures is also addressed in this section.

Lane changes

When performing a lane change, offtracking and rearward amplification are affected by variables such as steering amplitude and frequency, speed, lateral displacement, temperature, precipitation amount and load variation across and within the trailers. Some of them are used to analyse low-speed lane changes, whereas some are for high-speed lane changes.

The chosen categorizing speed for separating high-speed and low-speed lane changes is motivated by simulations. Figure 5 shows the variation of yaw rate RWA and maximum offtracking obtained from lane change simulations of an A-double. These simulations are conducted using a steering amplitude of 10 deg and frequency of 0.12 Hz for a given speed for an A-double. It is evident that maximum offtracking first decreases and then increases with speed. Inboard offtracking is observed until 70 km/h and then it switches to outboard offtracking around 75 km/h when RWA crosses 1. Hence, the categorizing speed is 75 km/h. However, simulations only provide a rough estimate of the categorizing speed, and in reality, it will be affected by the diversified driver inputs. Thus, the rough categorizing speed from simulations is adjusted for each vehicle type by examining the driving data. Categorizing speeds of 65 km/h and 60 km/h are used for the A-double and the DuoCAT respectively.
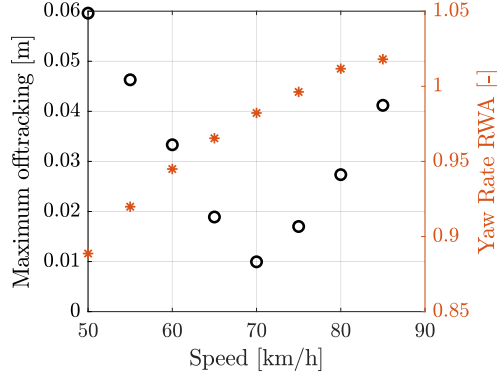
Figure 5: Variation of RWA and maximum offtracking with speed in lane change. Simulations are performed using Volvo Transport Model libraries of A-double.

Figure 6 shows the speed variation during a real-world lane change and the associated yaw rate of the first and last units of an A-double. Considering an average speed in the entire manoeuvre $(X - Y)$ to represent a lane change is not appropriate, particularly in these kinds of cases where the speed varies significantly between X and Y. In Paper I, the speed at which the maximum offtracking happens is used instead of the average speed in the entire manoeuvre. A notion of speed variation as in if the vehicle accelerates, decelerates or stays at a constant speed during the lane change is also added to the analysis conducted in Paper I. The speed at a given instance during a lane change may not directly correlate to the observed offtracking (or RWA) at that instance, specifically when the speed during a lane change is not constant. Hence, the described approach may not be always suitable for analysing offtracking or RWA. Paper III improves
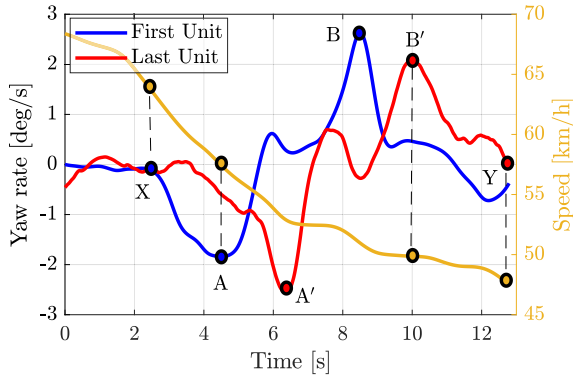

Figure 6: Rearward amplification and speed in lane change.

upon the previous method by considering the average speed during the first yaw rate peak of the first unit and the last yaw rate peak of the last unit. For example, the average speed in $A - B'$ is computed for the lane change shown in the figure. This interval is expected to have the highest influence on the performance of the vehicle. Moreover, the speed variation is not as high as the entire manoeuvre.

Additionally, the calculation of RWA has been changed from Paper I to Paper III. According to (2.1), the maximum absolute yaw rate of both the first and last units must be considered for the ratio. In Paper I, RWA is calculated as the maximum of the two ratios obtained from two sets of consecutive peaks, i.e. A, A' and B, B' in Figure 6. While this method is representative of how the peak yaw rate of the first unit influences the corresponding peak yaw rate of the second unit, it is not consistent with the definition of RWA in [11, 12]. Hence, in Paper III, the more common approach is used, where the ratio of the maximum yaw rate of the two units in the entire lane change is considered. For example, in the figure, the maximum yaw rate of the first unit happens at B and that of the last unit happens at A'. The ratio of these peaks denotes RWA.

Roundabouts and Intersections

The radius of the roundabout and instantaneous radius are used to understand the variation of low-speed swept path and steering reversal rate in roundabouts. The vehicles generally do not follow the roundabout concentrically. In these cases, the radius of the roundabout is not representative of the low-speed swept path obtained from the roundabout. Instead, the instantaneous radius is computed by considering the average radius around the location where the maximum LSSP is obtained. This gives an idea about the effect of the curviness of the path on LSSP for a given roundabout. The steering reversal rate is dependent on the entire manoeuvre and not just a specific location. Hence, the radius of the roundabout is more appropriate than the instantaneous radius. A similar approach is used in intersections, where the radius of turn is defined as the maximum instantaneous radius obtained in the turn. This maximum radius is averaged over a few indices around its location.

Tight curves

The radius of curves and speed are employed to understand the variation of high-speed steady state offtracking. The radius is computed using the path of the vehicle, instead of the road data. This choice is because the vehicle may not concentrically follow the curves, and the curve radius can be different from the radius of the followed path. Similar to lane changes, a speed is chosen which filters the cases with outboard offtracking.

Chapter 3

Research contributions

The schematic of the contributions made in this thesis are summarized in Figure 1. Paper I evaluates the performance of A-double vehicles during lane changes. In Paper II, an analysis is conducted to assess the performance of A-double vehicles in roundabouts. Paper III includes the performance analysis of a DuoCAT in all four scenarios and compares its performance with that of A-double vehicles. The A-double analyses related to lane changes and roundabouts are used from the previous papers, whereas intersections and curves are studied for the first time in Paper III.
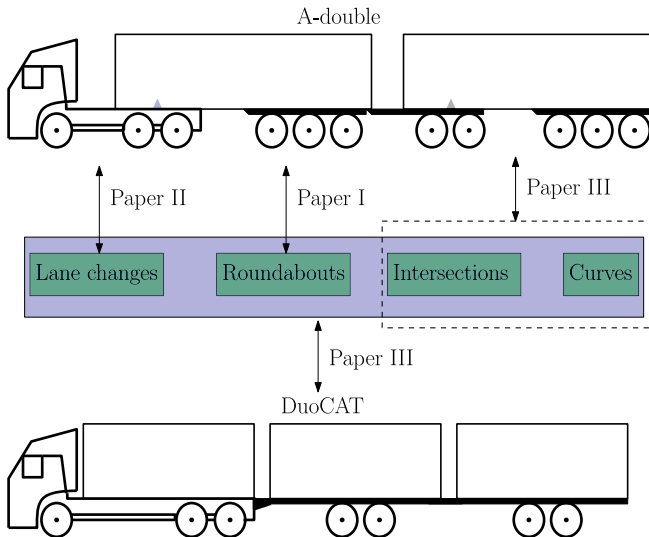

Figure 1: Scenarios addressed in different papers.

3.1   Summary of papers

Paper I: Extraction of lane changes from Naturalistic Driving Data for performance assessment of HCT vehicles

Abhijeet Behera, Sogol Kharrazi and Erik Frisk.
In: *28th IAVSD Symposium on Dynamics of Vehicles on Roads and Tracks, Ottawa, Canada, 2023.*

Paper I investigates the performance of the A-double combination during lane changes. An algorithm is proposed to identify lane changes from the NDD of LCVs by using GPS, road data and IMU signals. Subsequently, the performance of the A-double is assessed in the identified lane changes using PBS measures such as RWA and maximum offtracking. The measures show dependency on the vehicle's speed, load, and lateral displacement. The assessment concludes that the A-double satisfies the requirements set by the Swedish PBS project [12] and is driven safely in the extracted lane changes.

Paper II: Performance analysis of an A-double in Roundabouts using Naturalistic Driving Data

Abhijeet Behera, Sogol Kharrazi and Erik Frisk.
In: *17th International Symposium on Heavy Vehicle Transport Technology, Brisbane, Australia, 2023.*

In Paper II, the performance of the A-double combination is evaluated in a few roundabouts in Sweden. The steering and speed patterns are analysed to understand the driving behaviour around the roundabouts. The steering reversal rate is employed to measure the cognitive workload associated with the drivers when they manoeuvre the vehicles in the roundabouts. The SRR is found to vary mildly with the roundabout's radius and shows that drivers navigate higher-radius roundabouts more easily. The performance analysis shows a strong dependency of the low-speed swept path on the instantaneous radius obtained from the vehicle's path and travel direction in the roundabout. The magnitude of LSSP in all the roundabouts is below the proposed safety limit [12] and corresponds well with simulation results. However, steerable axles might be needed for smaller roundabouts than those considered in this study.

Paper III: How do long combination vehicles perform in real traffic? A study using Naturalistic Driving Data

Abhijeet Behera, Sogol Kharrazi and Erik Frisk. Manuscript.

Paper III evaluates the performance of both A-double and DuoCAT in all four scenarios: lane changes, roundabouts, intersections and tight curves. The considered PBS measures are rearward amplification, low-speed swept path, high-speed transient offtracking, and high-speed steady state offtracking. The metric steering reversal is also employed to estimate the cognitive efforts of the driver in

roundabouts and intersections. In the case of the A-double, the intersections and the tight curves are addressed for the first time in this paper. As discussed in Section 2.4, different approaches than Paper I are employed to compute the speed and RWA during lane changes in Paper III. The analyses conducted using the measures indicate that the A-double and the DuoCAT are stable and have good tracking performance in most cases. A disparity in the number of extracted cases from the A-double and the DuoCAT is found across some scenarios. Nevertheless, the results suggest that the A-double has a slightly better performance than the DuoCAT in lane changes. In roundabouts, both combinations have similar tracking performance in straight crossings, whereas the DuoCAT performs slightly better than the A-double in left turns. In intersections, the tracking performance of both vehicles is not as good as it is in the roundabouts. However, it is not a concern as the junctions at intersections have adequate space to accommodate these vehicles. Due to the limited number of cases with the A-double in curves, only the DuoCAT is assessed in curves. The assessment of the DuoCAT indicates a good tracking performance in tight curves. Furthermore, both vehicles demand comparable cognitive efforts from the driver, with the DuoCAT requiring a little less than the A-double.

3.2 Future work

The research presented in this thesis has increased the understanding of the performance of selected LCVs in real-world traffic. Nevertheless, there exists a substantial scope for further research to enhance our knowledge of LCVs, addressing various aspects that have not been explored in the current work. The following research directions outline specific areas for future investigations.

1. In this thesis, high-grade sensor packages (OxTS RT3000) are used to collect the necessary data for the performance assessment. They provide accurate measurements, which is essential to calculate position-based quantities. However, they are costly and are not cost-effective in studies involving a lot of LCVs. Hence, alternative methods are needed which can provide a comparable level of accuracy in positional measurements. A potential future research direction involves the use of relatively cheaper sensors for the performance assessment of LCVs. The positional estimates from these sensors are not accurate. Hence, the sensor fusion techniques can be applied to improve the estimation.

2. The data is collected during the spring and summer seasons for the A-double, while for the DuoCAT, data collection spans from fall to summer. Having a generic overview of the performance of the vehicles is not possible from this data and requires data from the remaining seasons of the year. For example, can the A-double be driven safely on the snowy road? a question that can not be answered from the available data and needs data from the winter season. Future work can encompass comprehensive data

campaigns, encompassing both the collection and analysis of data across all seasons, to provide a more nuanced understanding of vehicle performance under diverse environmental conditions.

3. The research in this thesis helps to understand the influence of driver inputs, road infrastructure and weather conditions on the performance of the selected LCVs. Another important aspect is the surrounding traffic. The reaction of LCVs to the surrounding vehicles is implicitly captured by the driver inputs. However, it is equally important to understand how the surrounding vehicles manoeuvre around LCVs. In AutoFreight 2 project [38], cameras are installed on two A-doubles. A potential next step could involve analysing the collected data using computer vision techniques to gain insights into the behaviour of surrounding traffic.

4. In this thesis, the data obtained from trials of the A-double and the Duo-CAT is used for performance assessment. Similar investigations can be performed on other combinations such as a B-double with a long link, or an AB-double.

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