A REVIEW OF MORE THAN A DECADE OF RESEARCH AND FIELD TESTS ON LONGER VEHICLE COMBINATIONS IN SWEDEN THAT SUPPORTED ROAD APPROVAL

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Abstract
For more than a decade, Longer Vehicle Combinations (LVCs) have been tested in Sweden on roads and test tracks and studied in simulations. Based on the outcomes of this research, the government in Sweden has decided to open part of the road network for LVCs with a length up to 34.5 m. Necessary regulatory framework should be in place before this change can be applied. Thus, the LVCs are not expected on the roads before winter 2023-2024. This article reviews outcomes of the extensive research which has been performed on High Capacity Transport (HCT) to support introduction of LVCs in Sweden. Summary of studies on various aspects of HCT, such as regulation, safety, maneuverability, electrification, and emissions, are presented.

Keywords: High Capacity Transport, Longer Vehicle Combination, Regulatory framework, Performance Based Standards, Safety, Maneuverability, Accident Analysis, Driver behavior, Traction, Electrification, Efficiency, Modal shift

1. Introduction

Subsequent to allowing heavier vehicle combinations up to 74 ton in 2018, the government in Sweden has now decided to also open part of the road network for Longer Vehicle Combinations (LVC), with a length up to 34.5 m. This is about 9 m increase in length, compared to the current regulations in which the heavy vehicle lengths are limited to 25.25 m. Due to the required preparatory actions, the LVCs are not expected on roads before winter 2023-2024.

The government decision is based on the outcome of extensive research which has been performed on High Capacity Transport (HCT) vehicles in Sweden by authorities, industries, universities, research institutes, and other stakeholders. A large part of these research efforts has been conducted under a unique umbrella research program, called “HCT program” (Asp and Berndtsson 2016). An annual report on HCT program has been published since 2014, which can be found on the webpage of Closer, the host platform of the HCT program (Closer 2021). These efforts have also led to roadmaps for realization of HCT in Sweden (Asp et al. 2019) and numerous technical reports and scientific publications.

For more than a decade, LVCs have been tested in Sweden on roads and test tracks and studied in simulations. A summary of these efforts and the research outcomes are presented in this review article. The timeline of HCT progress and the gross combination weight (GCW) development in Sweden are shown in Figure 1 and Figure 2. This review is focused on the research on longer HCT vehicles during the time period shown in Figure 1. So, the efforts of pioneers in the field such as Aurell and Wadman (2007), whose report on the modular concept included analysis of prospective LVCs, is acknowledged here in the introduction.

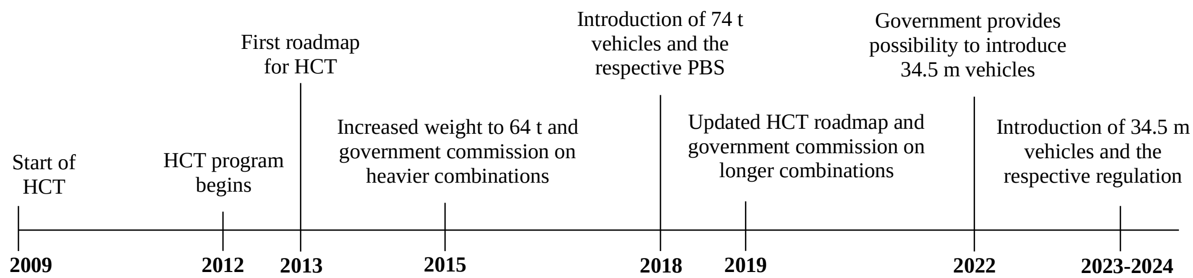

Figure 1 – Timeline of HCT progress in Sweden

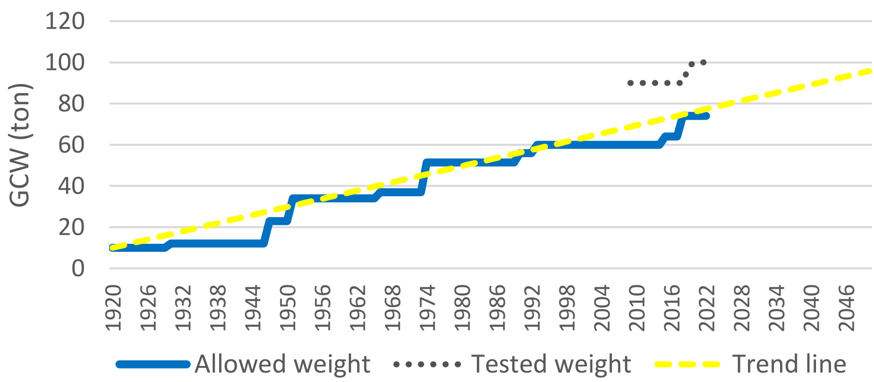

Figure 2 – GCW development in Sweden

2. Trials in Sweden

Exemptions have been issued for several longer vehicle combinations in Sweden in the form of trials for the purpose of safety and efficiency analysis, technical developments, and improvements of logistic solutions. Up till 2018, when the possibility to receive exemption for only weight was removed, 80 different vehicle combinations were part of the trials. About half of these vehicles (39 combinations) were LVCs with lengths up to 34 m, which participated in about 15 different trials, see Figure 3. Examples of such trials are:

- Different versions of the ETT vehicle, truck-dolly-link-semitrailer combinations (AB-double), tested in forest industry since 2009 (Sveaskog et al. 2013, Larsson et al. 2017, Asmoarp et al. 2018).
- The A-double combination, referred to as DOU-trailer, driven between Gothenburg and Malmö since 2010 (Cider and Ranäng 2014, Bergsten et al. 2017).
- The A-double within Scania Transportlab initiative, driven between Södertälje and Malmö
- The A-double within the Volvo Autofreight projects, driven between Gothenburg and Borås since 2017 (Larsson and Vesmes 2022).
- The A-double carrying containers for Jula company, tested between rail station in Falköping and industrial area in Skara.
- Truck with two center axle trailers, referred to as DUO-CAT, which started to roll on the roads between Gothenburg and Helsingborg in 2015 (Bergsten et al. 2017), and has also been used on a transport route between Kinnarp and Skillingaryd.
- The DUO-ETT combination (tractor-semitrailer-full trailer), transporting timber in northern Sweden since 2020.
- The B-double combination with a long link-trailer, carrying up to two 45 foot containers, tested in Gothenburg, between Arendal and APM harbor terminal since 2021.

Figure 3 – Examples of tested LVCs in Sweden
From left to right: ETT vehicle, DUO-trailer, DUO-CAT

3. Regulatory framework

Performance based standards (PBS) is a way of regulating HCT vehicles and their access to the road. In a PBS approach the performance required from the vehicle is specified, instead of just prescribing length or weight limits. Canada, New Zealand, and Australia have been pioneers of implementing PBS for HCT regulations (VWDS 1987, LTSA 2002, NTC 2008). In Sweden two national projects on PBS, with a focus on Swedish road conditions, have been carried out since 2012 (Kharrazi et al. 2014, Kharrazi 2018). The aim of the first project was to propose a PBS scheme for Sweden, including the performance measures, the required limits, and suggestions for the assessment methods (Kharrazi et al. 2015, Kharrazi et al. 2017). The second project was focused on the development of standard tire models to be used in the PBS assessment of HCTs in Sweden (Kharrazi et al. 2023). Outcomes of these projects have been used by the Swedish Transport Agency to determine the “technical requirements” for the 74 ton vehicles (TSFS 2018). It will also be used when determining the “technical requirements” for the LVCs, which will be allowed on part of the Swedish road network in the near future.

A web-based assessment tool has been developed at Swedish Transport Agency, called lastbilskalkylator (which translates to “truck-calculator”) as a supporting tool for vehicle manufacturers, transport companies, and police for assessing HCT vehicles performance (Lastbilskalkylator). The tool has been specifically developed for 74 ton vehicles with lengths up to 25.25 m and needs to be further developed to cover LVCs and the potential performance measures required for them. An alternative that is being considered is to use the OpenPBS tool developed during the PBS projects as a base for the next version of the lastbilskalkylator (Jacobson et al. 2017, Jacobson et al. 2023). However, to speed up the process of introduction of LVCs in Sweden, a PBS/prescriptive approach, in which dimension envelopes based on PBS requirements are defined for two vehicle combination types of A-double and AB-double, has been proposed by the Transport Agency. This is inspired by the PBS approach in Canada (VWDS 1987) and is proposed as the first phase implementation and is currently under referral.

In parallel to the regulation adjustments, extensive work has been carried out at the Swedish Transport Administration on categorization of the roads in Sweden. A part of the Swedish road network, about 4500 km of roads, has been selected to be opened for LVCs in the first phase. Other roads that can be opened in later phases, after necessary modifications and adjustments, have been identified as well (Trafikverket 2019). Furthermore, inspired by the Intelligent Access Program (IAP) in Australia (Cai et al. 2010), implementation of IAP in Sweden for compliance assurance of both longer and heavier HCT vehicles has been investigated (Wandel & Asp 2021).

3.1. ISO standards

Sweden has been also involved in the efforts for the development and introduction of international standards that can support regulatory frameworks for HCT vehicles. In many PBS schemes, vehicle dynamics simulations are used in the assessment procedure. Accordingly, the following ISO standards have been developed, led, and supported by members of the ISO working group ISO/TC22/SC33/WG6 and the Swedish Institute for Standards (SIS):

- ISO 19585:2019 Heavy commercial vehicles and buses - Vehicle dynamics simulation and validation - Steady-state circular driving
- ISO 19586:2019 Heavy commercial vehicles and buses - Vehicle dynamics simulation and validation - Lateral dynamic stability of vehicle
- ISO 21233:2021 Heavy commercial vehicles and buses - Vehicle dynamics simulation and validation - Closing-curve test

Another ISO standard under development led by SIS members concerns generic tire models, which is an essential part in vehicle dynamics simulation. The title of the prospective standard is "Heavy commercial vehicles and buses - Vehicle dynamics simulation and validation - Tyre model for lateral estimation of heavy vehicle combinations operated at dry paved road surface".

In addition to simulation related standards, other assessment methods have also been considered. In the PBS project a modified analytical model for the calculation of steady state rollover threshold (SRT) was proposed, which has recently been introduced as an ISO standard as well: "ISO 22135:2023 Heavy commercial vehicles and buses - Calculation method for steady-state rollover threshold". The developed method for calculation of SRT is an extension of the ECE R111 regulation (UNECE 2001), incorporating the tire lateral stiffness, with a considerable influence on the effective track width and consequently on SRT.

4. Safety and maneuverability

In addition to the aforementioned PBS projects, various aspects of the safety and maneuverability of LVCs have been studied in several projects. For instance, the swept path of several LVCs in roundabouts has been studied using simulations by varying the roundabout dimensions and the turn angle. The results have been published as a Nordic Road Association (NVF) report (Larsson and Pettersson 2022) and presented at HVTT16 (Larsson et al, 2021). One of the main outcomes was that most of the considered vehicles can turn in a roundabout with outer/inner dimension of 12.5/2.0 m, which is the existing Swedish legislation for modular-based heavy vehicles longer than 24 m (TSFS 2012). Furthermore, it was highlighted that liftable and steerable axles can be used to reduce the swept path so that all the vehicle combinations pass the test. In another extensive study, the performance of HCT vehicles, including LVCs, was simulated and compared with respect to common performance measures in a PBS scheme (Fröjd et al. 2021), a summary of which was presented at HVTT15 (Larsson et al. 2018). In a more recent study, two A-double vehicles and a Duo-CAT have been equipped with sensors and their performance will be analyzed while driving in real traffic on Swedish roads, with a focus on offtracking and rearward amplification (Behera et al. 2023a, Behera et al. 2023b).

Coupling strength is also an important aspect for LVCs safety. A failure in the coupling of a heavy vehicle can have a devastating effect if it occurs while driving. However, all the potential LVCs configurations are not covered in the existing ISO standard on coupling strength requirements (ISO 2013). Therefore, two additional LVC configurations, and how their coupling strength can be regulated for ensuring safety, have been investigated in a research project financed by the Swedish Transport Agency (Augusto et al. 2021).

In addition to the passive safety of LVCs, the use of active safety for improved performance has been investigated in different projects in Sweden. For instance, active steering for reducing the rearward amplification and offtracking in high speed maneuvers has been studied in two PhD projects resulting in several publications (Kharrazi 2012, Kati 2018). Even driving automation of LVCs for a given operational design domain has been investigated (Nilsson 2017).

4.1. Driver behavior and interaction with other road users

Driver behavior while driving an LVC and their perception of LVCs safety has been another topic of interest, where motion-based driving simulators have been a useful tool (Augusto et al. 2016). For instance, in a driving simulator study, drivers' actions prior to a mandatory lane change maneuver in dense highway traffic were investigated (Nilsson et al. 2018). In another simulator study, two different automated driving systems for an A-double were tested, both of which were appreciated by the drivers, with a slight preference of the more advanced lateral control system (Sandin & Nilsson 2014). In a more extensive study with 55 truck drivers, LVCs and conventional heavy vehicles were driven and compared. The study results showed that controlling and driving an LVC is not necessarily more difficult than driving a conventional heavy vehicle; if the vehicles have similar performance values, they can be equally easy to drive. Furthermore, the achieved results illustrated that using performance measures is a sound approach for assessing heavy vehicles safety and it correlates well with the drivers' perception of the vehicle performance (Kharrazi et al. 2019).

To obtain more knowledge about the drivers' perspective, interviews with the drivers of HCT vehicles on trial in Sweden have been conducted. For instance, in 2015, an interview with a focus group of drivers was carried out, which included drivers of three LVCs. According to the interviewed drivers, driving LVCs requires more planning, for instance when driving through roundabouts and intersections. But it does not cause a safety concern (Sandin 2016).

The time required to overtake an LVC and its effects on traffic safety have been investigated in driving simulator studies, as well as field tests. Andersson et al. (2012) performed a driving simulator study to compare overtaking situations on a 2+1-lane highway with LVCs and conventional heavy vehicles. The results did not show any drastic negative effects on traffic safety by introducing LVCs. Also, a field-study with video-recorded overtaking maneuvers of an LVC and a conventional vehicle combination has been conducted on a 50 km 2-lane country road in north of Sweden for 6 months. The difference in average meeting margins between the two combinations was not statistically significant - nor was the difference in average overtaking speeds. The results should be interpreted with great caution though, as the number of analyzed overtaking maneuvers was limited (Sandin et al. 2012).

4.2. Accident analysis

To assess the impacts of LVCs on safety, accident databases have been used as well. However, since the current regulations in Sweden do not allow LVCs on the roads, the analysis has been performed on the longest existing combinations in Sweden in comparison with shorter combinations. The results showed that "long" combinations (from 18.76 to 25.25 m) had lower rate of fatal or severe accidents per billion vehicle kilometers travelled compared to medium and short vehicles (Sandin et al. 2014).

Furthermore, the accidents in which the HCT vehicles on trials in Sweden have been involved, has been followed and analyzed as well. According to Sandin (2016), during the Swedish trial operations between 2010 and 2016, two accidents with LVCs had occurred. However, the additional length was not the main cause of the accidents.

In a more recent study, the accident involvement and accident risk of conventional heavy vehicles are calculated using accident data for a ten-year period between 2009 and 2018. The purpose is to use the results to estimate how LVCs would affect the accident rates by replacing a portion of conventional heavy vehicles which are used for goods transports.

5. Traction and electrification

Traction aspects such as resistance forces, distributed propulsion and electrification have been investigated in different projects. For instance, the magnitude of air and rolling resistance for LVCs was compared with shorter combinations in a study by Cider et al. (2021). It was shown that the rolling resistance becomes larger than air resistance for LVCs around 80 km/h, which highlights the importance of liftable axles for reducing rolling resistance. Advantages of liftable axles for increasing the load on the drive axles for hill climbing have been studied as well. In the Duo2 project, an increased load of 5.5 t on the drive axle was measured by lifting the first axle of the semitrailer and third axle of the tractor. Also, startability on slopes of 12% have been studied in the Duo2 project (Cider at al. 2018). The use of a smart dolly that can be propelled (and steered and braked) for improved startability and gradeability on wet and slippery roads have been discussed in the study by Kati et al. (2014). Furthermore, a PhD project has been conducted on distributed propulsion in LVCs for safe and energy efficient driving. In this thesis, optimization has been used to select the best vehicle in terms of the size, propulsion system, and driving system for a given transport assignment. The results of the optimizations revealed that battery electric and hybrid heavy vehicle combinations exhibit the lowest total cost of ownership in certain transportation scenarios. Further, it was shown that automation helps the adoption of battery electric heavy vehicles in freight transport (Ghandriz 2020).

6. Socioeconomic aspects

The LVC research in Sweden has also addressed socioeconomic aspects, such as the effects on emissions, noise, energy and transport efficiency and modal shift. A few of these studies and their outcomes are presented in this section.

The forecasts suggest that the freight transport work on Swedish roads (driven kilometers) will increase by approximately 140% by 2050; however, with the introduction of HCT vehicles, the increase is expected to slow down to 117-130%. The greater effect estimate is for the case of introducing both heavier and longer combinations, compared with only introducing heavier combinations (Trafikverket 2019).

One of the main advantages of LVCs is energy efficiency and the consequent reduced emissions and fuel consumption. According to the Sweden HCT road map from 2019, HCT vehicles reduce the energy consumption per ton-km by about 10% (Asp et al. 2019). In another report by the Swedish Transport Administration this reduction is estimated to be about 13% (Trafikverket 2019). Larger savings, 15-20%, have also been reported, for instance in the ETT vehicle projects (Von Hofsten 2021, Enström et al. 2021).

In addition, noise emissions of LVCs have been compared with conventional vehicles, using a simulation tool in a study by Sandberg et al. (2018). Based on this study, the noise emission from the considered LVC is higher than the conventional vehicle, per vehicle passage. But as the number of vehicles in traffic is lower for a certain transportation volume, the resulting road traffic noise exposure is very similar.

HCT vehicles will increase transport efficiency on roads, which can result in an increase in road transport's market share at the expense of rail and sea transport. However, a study by Adell et al. (2016) shows that this modal shift would not cause a net decrease in transport volumes for rail and sea carriers, but rather a slower increase than would otherwise have occurred. This is because the total freight transport volumes will increase. In another study, the modal shift in Sweden after length increases for heavy vehicles in 1990 and 1993 was investigated to provide empirical evidence on this matter; data from the period 1985 to 2013 was used in the study. It is shown that the rail transport share was decreasing between 1985 and 1995, but the trend reversed afterwards and in 2000 the rail transport had regained the market share it had in 1990 and continued to increase. The road transport share increased from 1985 and continued this way during most of the 1990s, until it stabilized around 60-65%. Also, their results show that the level of transported goods for both road and rail had been increasing since 1990, so the modal shift did not cause a net decrease in transport volumes for rail carriers (Vierth et al. 2018). Also, in a report by Swedish Transport Administration, it is argued that the negative effects on emissions due to possible modal shift from rail to road is limited in comparison with the positive effects gained by the HCT vehicles (Trafikverket 2015). It should also be noted that complementary policy instruments and measures could strengthen the competitiveness of rail and sea transport and compensate for the shift in market share (Adell et al. 2016).

7. Future outlook

In more than a decade, extensive research has been conducted on LVCs in Sweden, a summary of which is presented in this paper. The first phase of introduction of LVCs on the roads is planned for winter 2023. Sweden's efforts in this area will continue to ensure safe and efficient utilization of these vehicles. In the following, a few examples of recently started projects connected to LVCs are provided.

Driver assistance systems will be investigated in the second AutoFreight project, where real transport operations with an A-double is studied. In the first project (Larsson and Vesmes 2022), difficulties with reversing the full combination were observed and sometimes decoupling was necessary. Therefore, driver assistance systems for reversing LVCs by rearward directed cameras, which are becoming common for passenger cars, will be investigated in the second project. Logistics solutions, electrification, and required steps towards automation of HCT vehicles, are other subjects of investigation in this project.

Another important safety aspect which will be studied further is the LVCs' interaction with vulnerable road users. In an ongoing project, a pilot test has been performed for investigating perceived safety/danger by a cyclist when overtaken by an LVC; further tests with several cyclists are planned. The parameters which might affect safety, such as distance to the cyclist, vehicle speed, and length of the vehicle will be analyzed by measuring the air pressure imposed on the cyclist, as well as subjective assessment.

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