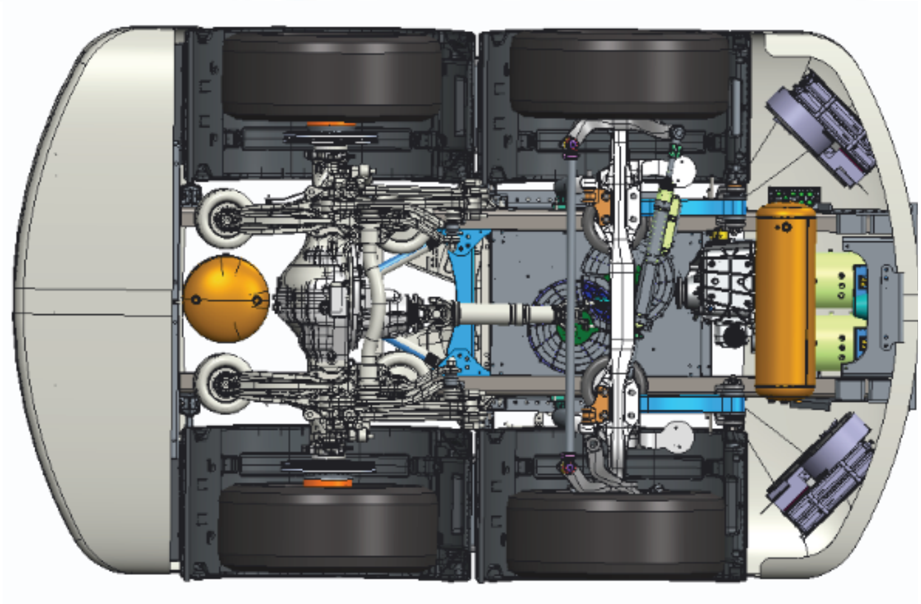
Final report for project “iDolly”

Using an iDolly for distribution of container trailers from a dry port to local logistics terminals

Public report



Project within **FFI – EUTS**

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Last modification Date: 2021-10-28

FFI Fordonsstrategisk Forskning och Innovation

Content

1 Summary

1.1 Summary in English

Electromobility and automation will bring about major changes in how heavy road transport is carried out. One area that is affected is the transport of containers from the ports where they have arrived by boat for further transport to their final destination inland. Rail and truck are primarily used for these transports. To make truck transport more efficient, the introduction of High Capacity Transport (HCT) is being studied in several different projects where longer and heavier vehicles are used. This means that congestion, energy consumption and thus carbon dioxide emissions can be significantly reduced per tonne and cubic meter of goods transported. Connecting several vehicle units for HCT transport also means new challenges in the transport nodes. When the long truck arrives, it usually has to be disconnected and new ways of performing the "last mile" transport to the end customer's logistics terminal need to be developed. In this project, we have studied the use of an intelligent (self-driving) dolly (called "iDolly") for such local distribution of containers from a so-called dry port (transhipment site) to end customers in the immediate area.

A dolly is a two-axle vehicle with a turntable and drawbar that is often used to connect a semi-trailer in heavy vehicle combinations. Normally it is "passive" and just rolling, but in this case the dolly has been equipped with both propulsion and steering, as well as some "intelligence" to be able to drive by itself, or via remote control, at low speed. This allows it to tow semi-trailers with containers to end customers in the immediate area. This in turn means that the tractor used for transport from the port can be used more efficiently for the on-road transports.

In the project, we have studied how the iDolly concept could work in a real case, linked to the research project Autofreight, where containers are transported from the port of Gothenburg to the industrial area Viared outside the city of Borås. With the help of this case, the project has been able to study the requirements that must be met for iDolly to work well in the transport system. Furthermore, the technical design of iDolly has been studied with special focus on automation of this type of local transport. Automatic connection of semi-trailer is an important part of the automation that has been tested in real vehicles. Requirements and impact on the infrastructure have also been studied.

The project has contributed with valuable knowledge both in terms of the design of a logistics system and technical solutions for automated transport. One of the conclusions is that there are advantages to electrifying "last mile" transports, but that full automation is further ahead, if it is even desirable. The need for advanced support systems and (costly) system integration and adaptations, and thus limited flexibility, makes the benefits of full automation more questionable. Despite this, the project has yielded a number of interesting results that can be applied to semi-automated systems, for the development of electrified solutions and more efficient logistics. Knowledge and technical solutions from the project have also been further developed within one of the partner companies into a commercial product.

The project has been carried out in collaboration between Volvo Technology, Chalmers, VBG, Borås Municipality, Ellos, Kerry Logistics, Speed Group and Volvo Buses. Due to several project manager changes and the corona pandemic, the project had to be extended and lasted between 2017-10-26 and 2021-08-31.

1.2 Sammanfattning på Svenska

Elektromobilitet och automatisering kommer att medföra stora förändringar för hur tunga vägtransporter genomförs. Ett område som påverkas är transport av containers från de hamnar dit de har kommit med båt för vidare transport till sin slutgiltiga destination inåt landet. För dessa transporter används i första hand järnväg och lastbil. För att göra lastbilstransporterna mer effektiva studeras i flera olika projekt införandet av High Capacity Transport (HCT) där längre och tyngre fordon används. Det gör att trängsel, energiförbrukning och därmed utsläpp av koldioxid, kan reduceras avsevärt per transporterat ton och kubikmeter gods. Att koppla ihop fler fordon för vägtransporten innebär samtidigt nya utmaningar i transportnoderna. När den långa lastbilen kommer fram måste den oftast kopplas isär och nya sätt att utföra ”last mile” transporten till slutkundens logistikterminal behöver utvecklas. I det här projektet har vi studerat användningen av en intelligent (självkörande) dolly (kallad ”iDolly”) för sådan lokal distribution av containers från en så kallad torrhamn (omlastningsplats) till slutkunder i närområdet.

En dolly är ett tvåaxligt fordon med vändskiva och dragstång som ofta används för att koppla till en semitrailer i tunga fordonskombinationer. Normalt är den ”passiv” och bara rullar med, men i det här fallet har dollyn försetts med både drivning och styrning, samt viss ”intelligens” för att kunna köra själv, eller via fjärrstyrning, i låg hastighet. Därmed kan den själv dra semitrailers med containers till slutkunderna i närområdet. Det gör i sin tur att dragbilen som används för transporterna från hamnen kan användas mer effektivt för just vägtransporter.

I projektet har vi studerat hur konceptet iDolly skulle kunna fungera i ett riktigt case, kopplat till forskningsprojektet Autofreight, där containers transporteras från hamnen i Göteborg till industriområdet Viared utanför Borås. Projektet har med hjälp av caset kunna studera vilka krav som måste uppfyllas för att iDolly ska fungera väl i transportsystemet. Vidare har den tekniska utformningen av iDolly studerats med särskilt fokus på automatisering av den typen av lokala transporter. Automatisk tillkoppling av semi-trailer är en viktig del av automatiseringen som har provats i verkligt fordon. Även eventuella krav eller inverkan på infrastrukturen har studerats.

Projektet har bidragit med mycket värdefull kunskap både vad gäller utformningen av ett logistiksystem och tekniska lösningar för automatiserade transporter. En av slutsatserna är att det finns fördelar med elektrifiering av ”last mile” transporter men att full automatisering ligger längre fram i tiden, om det ens är eftersträvansvärt. Behovet av avancerade stödsystem och (kostsam) systemintegration och anpassningar, och därmed begränsad flexibilitet gör att vinsterna med full automatisering blir mer tveksamma. Projektet har trots detta gett en rad intressanta resultat som kan tillämpas på semi-automatiserade sy-

stem, för utveckling av elektrifierade lösningar och effektivare logistik. Kunskap och tekniska lösningar från projektet har också utvecklats vidare inom ett av partnerföretagen till en kommersiell produkt.

Projektet har genomförts i samverkan mellan Volvo Technology, Chalmers, VBG, Borås kommun, Ellos, Kerry Logistics, Speed Group och Volvo Bussar. På grund av flera projektledarbyten och coronapandemin så fick projektet förlängas och pågick mellan 2017-10-26 och 2021-08-31.

2 Background

A dolly (or converter dolly) is a type of vehicle commonly used for pulling a semi-trailer. Figure 1 illustrates how a dolly is often used in a vehicle combination. In this project we have studied the possibilities for making a dolly "intelligent" (i.e. in this case self-driving), thus the use of the notation "iDolly". In this section we provide some background elaborating on the potential need for and use of iDolly in logistics operations, as well as technical details and background regarding the iDolly.

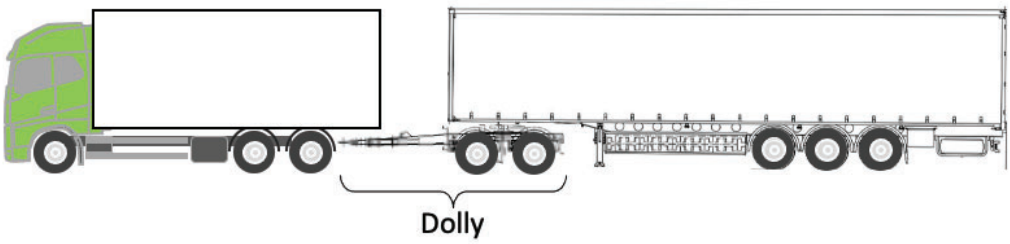


Figure 1. A dolly used to connect a semi-trailer to a rigid truck in a 25.25m long "Nordic combination".

2.1 Increasing container transports

Transport of goods is a necessity in the modern society and a function of the prosperity growth. Container transports have steadily been increasing since it started in small scale in the mid 1950's. Since 2007, the container sea transport capacity has been doubled from 10 million 20 foot equivalent (TEU) to 20 million TEU in 2017, see Figure 2. Today container transport is making up for 60% of the value of global seaborne trade. About 85% of the world trade is at some stage carried out on ships (Clarkson Research). The ship sizes have also been steadily increasing; now with loading capacity of 15000+ TEU's. This means, when the ships arrive at the sea ports, they need to be quickly and efficiently loaded and unloaded to not add cost to the remainder of the containers that will continue the journey to another port.

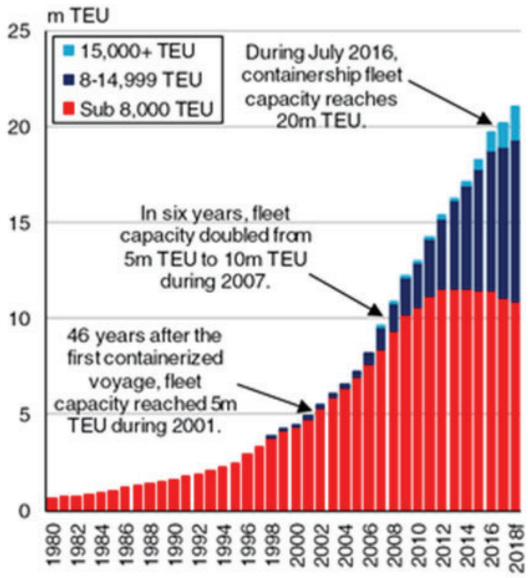
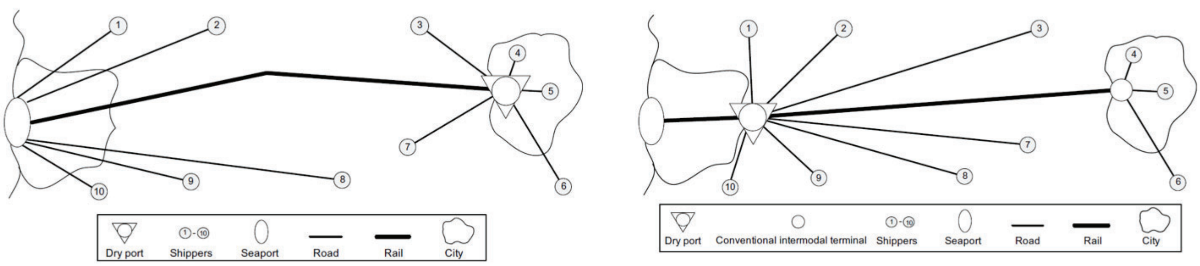


Figure 2. World container shipping capacity since 1980 to forecasted 2018 (Clarkson Research).

2.2 Establishment of dry ports for local distribution

To avoid congestion in cities with larger container ports, such as Gothenburg, there are already solutions today to connect railway to the main seaport, enabling efficient container transports into hinterland. Still many containers need to be transported on road by trucks to their destination.

One way to reduce the road transports is implementing a "dry port" where containers are transported from the seaport to an area (the dry port) located outside the city area for further distribution. In Roso et al. (2009) different dry ports concepts are analyzed including close, midrange, and distant dry ports, see Figure 3.



(a) Conventional seaport with railway and road connections.

(b) Close dry port in the rim of the city with sea port.

Figure 3. Conventional sea port layout (a) compared with a close dry port connected by electric railway (b) (Roso, et al. 2009).

To reduce emissions and road congestions in the Gothenburg area it is proposed in Roso (2007) to introduce a close dry port at Viared, Borås, connected with electric railway from Gothenburg seaport. This would, however, require a large infrastructure investment in the railway system. As an alternative, container transports can be done with automated and electrified road transports. One idea is that the transports to the close dry port could be conducted during nighttime, which would optimize the usage of the existing road infrastructure, with lower top-speed around 40-50 km/h. This would save energy and reduce risk for congestions at daytime. The AutoFreight project (see Wermström, 2016) addresses the technical challenges involved in automated transport of container trailers between Gothenburg seaport and Viared dry port. By using A-double vehicle combinations (see Figure 4) the energy consumption and emissions for the road transports between the seaport and the dry port can be significantly reduced. However, the scope of the AutoFreight project does not include the challenges associated with (automated) *local* distribution of container trailers from Viared dry port to the local logistic terminals. Therefore, the project described in this report makes an important complement as it focuses on the challenges associated with the automation of local distribution from the dry port to the logistics terminals in Viared.

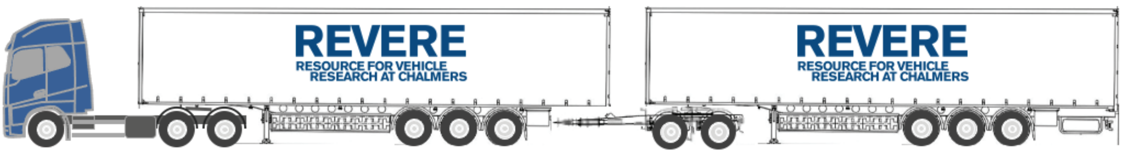


Figure 4. The type of A-double combination studied in the Autofreight project. A 6x4 tractor is coupled with a semi-trailer, a dolly and a second semi-trailer.

2.3 Introducing the ”iDolly” concept

A converter dolly (or just “dolly”) is a relatively small vehicle used in heavy vehicle combinations. The fifth wheel on top of the dolly enables it to be connected to the king pin of a semi-trailer. The semi-trailer - dolly combination can then be connected to a truck via a drawbar (see Figure 5). Normally the dolly is just pulled by the truck, and it has neither propulsion nor steering (though there are brakes). Hence, the dolly only acts as a slave unit in the vehicle combination.

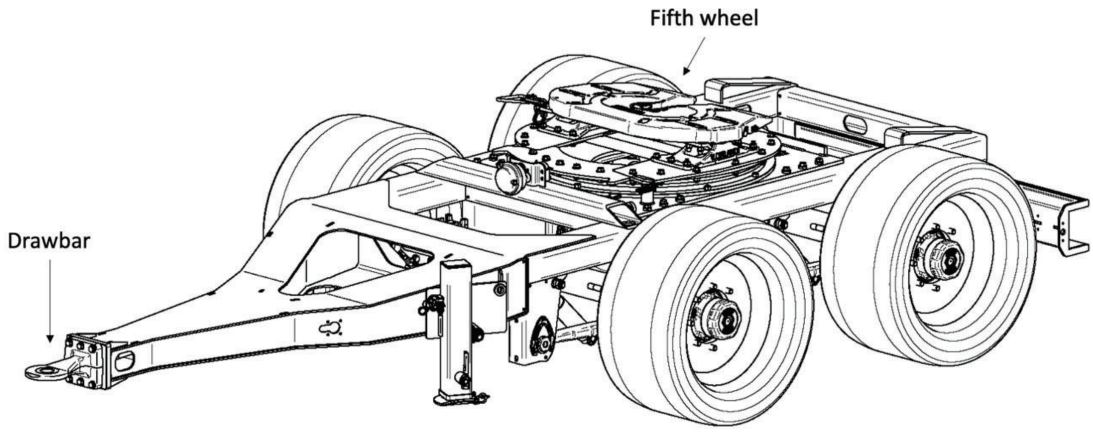


Figure 5. Converter dolly (courtesy of AutoComp AB).

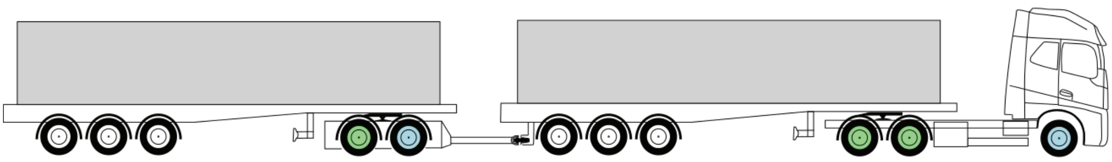
In this research project, however, an alternative concept has been studied where the dolly is equipped with (electrical) propulsion and steering, as well as some capabilities for autonomous driving. It is therefore referred to as an iDolly (intelligent dolly). This enables the dolly to act on its own as an individual unit. It can also perform different transport missions by connecting to and moving semi-trailers. In this way the iDolly can be used for the distribution of containers from a dry port to local customers.

At the outset of the project a hypothesis was that compared to a standard tractor and semi-trailer combination, the iDolly with a semi-trailer used for local distribution of containers could reduce the operating cost with around 30-50%, due to reduced energy consumption and driver cost. However, there will likely be other additional costs for support systems and system integration that is required when the human driver is removed. Depending on how the electrical energy used to power the iDolly is produced, the concept can also reduce up to 100% of CO_2 and NO_x emissions.

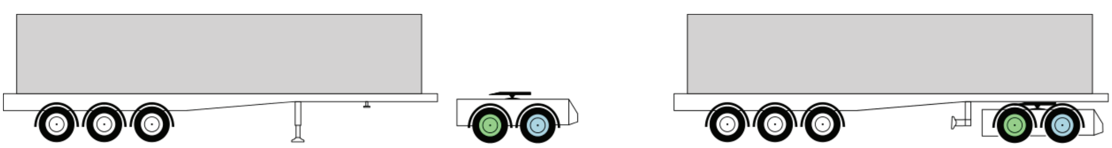
The idea of autonomous transport of containers is, however, not new. Automated Guided vehicles (AGV's) (see e.g. Liu & Ioannou, 2002; Kim & Bae, 2004) are to date state-of-the-art technology used in modern advanced sea ports for the transportation of containers (see Figure 6). This technology is, however, not suitable for the dry port since in that case the container is already loaded on to a semi-trailer container chassis. To use an AGV the container would need to be transferred from the semi-trailer to the AGV, and also be unloaded from the AGV at the final destination. This would require extensive investments in crane systems at the dry port as well as at customer terminals. Moreover, AGV's are made for use in confined areas, while the distribution of containers from the dry port to local customers involves transportation on public roads. Therefore, the proposed iDolly technology would in this case be more suitable. With iDolly there is no need for expensive crane systems and the trailers with containers can be moved by the iDolly for docking at the dedicated logistic terminals where the trailers can stand still for a longer time (the investment cost for a semi-trailer is much lower than for an AGV) while unloading/loading the container.

Figure 6. An AGV for transport of containers (courtesy of Kalmar Industries).

The iDolly has many similarities with the eDolly (electric dolly) that is studied in other projects (for example the FFI project HELPED). There is one big difference though. While the iDolly can act autonomously the eDolly is intended mainly as a slave unit in a larger vehicle combination (see Figure 7). The propulsion on the eDolly enables a hybrid drive train for the vehicle combination as a whole (e.g. in combination with the tractor's internal combustion engine) and can also provide additional traction when needed. The steering on the eDolly enables improved low speed maneuverability and better high-speed stability for the vehicle combination (see Islam, et al., 2015). While the eDolly and iDolly concepts are made for different use cases it is of interest to study what technical similarities and differences this implies.



A-double combination vehicle with an eDolly acting as a "slave" unit.



Semi-trailer and iDolly coupling / decoupling with changing height and landing gear lifting. iDolly acting on its own as a "master" unit.

Figure 7. Applications of dollies (green color represents propulsion and blue represents steering)

With the automation of the iDolly comes the "usual" challenges regarding, for example, suitable sensor setup (such as cameras and lidar), perception system (i.e. how the vehicle shall be aware of, understand and interpret the surroundings), positioning system (e.g. GPS), and vehicle control system (for propulsion, steering etc). Many results from the previous research project "C2VC" (see Laine, 2016), where a "control B-matrix" for actuator coordination as master/slave was developed provided valuable input for this project.

These systems need to be capable of handling not only the stand alone iDolly but also the iDolly with a coupled semi-trailer. This is a challenge in itself since trailers are different and there are many old trailers (some are 20+ years) in the logistics system with no on-board support for autonomous driving.

The coupling and uncoupling of semi-trailers to the iDolly also adds several challenges that have an impact on the possibilities for full automation. First, the iDolly must be able to locate the desired semi-trailer and, in particular, find out the position of the semi-trailer's king pin. When the king pin is connected to the fifth wheel on the iDolly, the air and electrical connections (that are critical for brakes and light functions) between the two vehicle units must be established. A semi-trailer also has support legs that need to be lifted from the ground before it can be moved.

Taken together, the concept of using an iDolly provides many potential benefits for the local distribution of containers from a dry port, but there are also several challenges that need to be managed.

3 Purpose, research questions and method

3.1 Purpose

The purpose of this project has been to conduct research on the automation and improved efficiency of the local distribution of containers from a dry port to local logistics terminals by using an iDolly.

3.2 Research questions

With reference to the potential gains and challenges outlined in the background section above the following research questions (RQ) have been investigated in the project.

RQ1 – Investigate how an iDolly can be implemented in a logistical system and what potential **challenges** need to be handled

RQ2 – What specific **technical** requirements need to be considered when designing an iDolly? For example, electrical propulsion, automatic trailer coupling and similarities/differences between an iDolly and an eDolly.

RQ3 - What specific solutions regarding the **automation** of an iDolly need to be developed? For example, systems for perception, positioning and vehicle control, including the maneuvering with a connected semi-trailer.

RQ4 – What changes to the **infrastructure** are required for using an iDolly for logistics operations around a dry port? For example, road adaptations, implementation of charging infrastructure and support for localization of semi-trailers.

In section 5 Results and Deliverables, the outcome of the project is described in relation to these research questions.

3.3 Method

The project has used a range of research methods for the collection of various types of data and evaluation of different technical designs. The collection of qualitative empirical data has played an important role for the analyses.

Different **theoretical studies** constitute the basis for the work performed within areas like vehicle automation, modelling and control. For example, different control strategies were evaluated with regard to the different requirements posed on the iDolly in its operational design domain.

Modelling and **simulation** have been used for the study and analysis of individual vehicles as well as for vehicle combinations (such as iDolly connected with semi-trailer) and also for some system level studies (e.g. maneuvering of the iDolly with semi-trailer within a logistics terminal area).

In order to reduce the time between development loops and hence speed up the learning process, **scale model vehicles** were used to perform various vehicle tests inside the REVERE vehicle lab at Chalmers. The scale model has full actuation (propulsion and steering) and is also equipped with different sensors. Thereby, the modelled and simulated concepts could be tested and evaluated under fairly realistic conditions in a controlled environment. This method also made it easier for persons that do not have a truck driving licence to perform vehicle testing in a smooth way.

Several different tests and demonstrations were also carried out using **full scale vehicles**. This enables test and validation under completely realistic conditions. While data collection was carried out with these vehicles on site at Viared, the autonomous operations including vehicle actuation had to be tested in confined areas as this would otherwise require a special permit. The initial intention was to use an electrically driven dolly originally developed by Volvo for eDolly research. However, as the build of the eDolly (for reasons not connected to this project) was delayed, a Volvo 6x4 tractor with possibilities for full actuation (acceleration, braking and steering) was used instead. In fact, when adjusting for some parametrical differences (like wheelbase and fifth wheel position), and if the driver cabin is ignored, the tractor is not that different from a driven and steered dolly (at least for low speed testing). Also different semi-trailers adapted for automation and equipped with sensors were used for testing different operations at logistical terminals.

In addition to the researchers from academia and industry that were directly working on the development and research activities, the **network** of other organizations involved throughout the project has played an important role. It has provided empirical data and valuable knowledge input regarding, for example, logistical operations requirements at Viared, vehicle configurations requirements, as well as economic considerations. This was fundamental to achieving a good understanding of realistic logistics operations at Viared. In addition, the project was connected to the High-Capacity Transport steering group, where it has been reviewed on a regular basis along with other similar research projects.

4 Objectives

In the project application the following vision for the project was formulated:

The overall vision is to develop an automated iDolly technology for future state-of-the-art green terminals and local distribution of container trailers.

The following objectives were outlined for the project (slightly re-phrased to be aligned with the terminology used in this report). Each objective is followed by a short comment within brackets "(…)" regarding any changes to the objective during the project.

- Develop and implement future transportation technology using iDolly for container transports with minimal investment on infrastructure. (No change of objective)
- The iDolly at the dry port will be an appropriate equivalent and cost-efficient alternative to AGV's at sea ports. (No change of objective)
- Automation of local distribution using the i-dolly during night-time and early hours, so the road network is used efficiently. (Objective has changed as the project results showed this was not a viable strategy)
- Electrification along with automation will ensure the energy efficiency and environmental friendliness within the dry port and local distribution network. The entire transportation task will be completed with iDolly together with the AutoFreight and Optimal Distributed Propulsion projects. (No change to objective, however, electrification and automation could not be demonstrated on site at Viared as intended due to delayed build of eDolly and restricted possibilities to test vehicle automation on public roads).

In addition to the objectives listed above it is worth noting that the desired Technology Readiness Level (TRL) was set to 4-5 in the project application. The overall conclusion, based on the actual project results and deliverables (see section 5), is that this TRL target has been met.

5 Results and deliverables

In this section an overview of the results and actual outcomes of the project is provided. For more detailed results we refer to the different publications referenced in the text.

5.1 Goods flows at the dry port

This section mainly addresses the first research question:

> ***RQ1*** *– Investigate how an iDolly can be implemented in a logistical system and what potential* ***challenges*** *need to be handled.*

Studying a real use case with on-going logistics operations provided much value to the project. This has been very important for achieving a profound understanding of how an iDolly can be designed and used in a real logistics system. The case in focus in the project has been the transport of containers from the sea harbor in Gothenburg to Viared industrial area near Borås, in Sweden. The distance is about 70 kilometers (see Figure 8), and a major part of the transport is on highway. At Viared the containers are delivered to different customer companies by placing each semi-trailer with container at the customer's loading dock for un-loading.

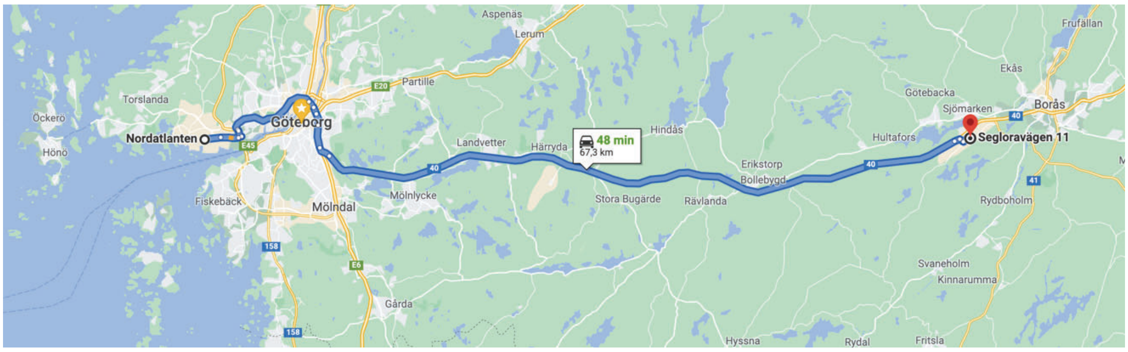


Figure 8. The transport between Gothenburg harbor and Viared near the city of Borås, in the south western part of Sweden.

An A-double is used for the road transport between the harbor and Viared, enabling two 40 foot containers to be transported each trip. By using such an A-double instead of two individual tractor plus semi-trailer combinations the fuel consumption and carbon dioxide emissions can be reduced by around 25% per transported ton of goods. When arriving at Viared, the vehicle units of the A-double need to be de-coupled. The relatively tight space at many customer terminals does not allow for a full A-double combination to be reversed all the way to the loading dock. Therefore, the access to the dry port area is important. At the dry port, the tractor plus first semi-trailer of the A-double are decoupled from the dolly plus second semi-trailer. Then the tractor can pull the first semi-trailer with container to its destination. If possible, the tractor can then couple another semi-trailer with an empty[1] container and bring it to the dry port area. Back at the dry port, the tractor will be used to disconnect the dolly from the second semi-trailer, couple the second semi-trailer and bring it to the customer's loading dock. The tractor is equipped with a drawbar coupling so, in some cases, the dolly plus semi-trailer combination can be

[1] Most companies at Viared are importing goods, meaning rather few loaded containers are transported from Viared to the harbor. Volvo Buses, one of the project partners, is an exception. Bus chassies are transported from their Viared plant to the harbor in Gothenburg for export. The ambition is to increase the transports of loaded containers from Viared to the harbor over time.

pulled by the tractor to the customer. When arriving back at the dry port for the second time (with another semi-trailer loaded with an empty container), the A-double combination is formed again and the journey back to the harbor can start. In a normal working day two such round trips between the harbor in Gothenburg and Viared can be performed (see Figure 9).

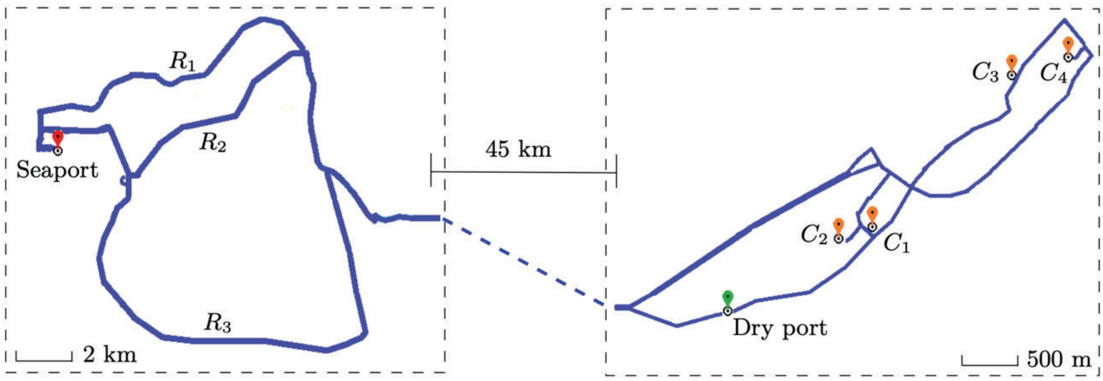


Figure 9. Mapping of transport routes in Gothenburg and Viared (Ghandriz, 2020).

The use case clearly shows that while the use of an A-double helps to significantly reduce the energy consumption for the road transports, there is room for improvement when it comes to the last mile transports at Viared. In comparison, when using two tractor plus semi-trailer combinations instead of an A-double[2], these tractors can directly bring their respective semi-trailers with containers to the right loading dock.

That is where the iDolly comes into the picture. With an iDolly in the system, the vehicle units in the A-double combination arriving from the harbor can be de-coupled at the dry port and then the iDolly will take care of the distribution of the semi-trailers with the loaded containers to the local customers. The iDolly can also bring semi-trailers with empty containers back to the dry port. These semi-trailers with empty containers are then coupled to form a new A-double combination heading for the harbor.

The project clearly shows that such use of an iDolly would make last mile transports more efficient. There are several reasons for that. The tractor used for the A-double combination is generally over-dimensioned for the local (low speed) single semi-trailer transports. Its capacity is better used for the road transports between the harbor and Viared. By reducing the time spent at Viared for local container distribution it may be possible to introduce a third round trip per day. However, the case also shows that one critical factor for the efficiency of the transport system is the waiting time at the harbor. While the pandemic has led to relatively smaller container volumes and thus less cues for loading containers at the harbor, some longer waiting times can be expected when going back to "normal". As the iDolly is off-loading work from the A-double truck driver at Viared it may play an important role for the transport system as a whole. This is also connected to the fact that the truck driver's driving time is strictly limited. If too much time is spent

[2] Many container transports to Viared are still carried out with tractor plus semi-trailer combinations.

cueing for containers to be loaded this may have a big impact on what transports can be carried out during the rest of that day.

The project also looked into the possibility of using an iDolly for transporting only one of the two semi-trailers coming with the A-double (the second one in the combination) to its destination at Viared, while letting the tractor pulling the A-double bring the first semi-trailer in the A-double combination to its destination. That would reduce the need for de-coupling and coupling semi-trailers (and dolly) at the dry port. However, the results show that this would also mean the tractor would spend relatively more time at Viared (compared to using the iDolly for all last mile distribution). Also, the business case for using an iDolly would be somewhat eroded as the iDolly utilization rate would be reduced.

Even though developing a business case for the iDolly was not really part of the project, some economical aspects were studied. Since an iDolly is not commercially available as a product it is somewhat difficult to define the investment cost for it. However, for example, AGV's and experience from Volvo's project "VERA" (Volvo, 2019) could provide some guidance. It is also difficult to estimate the cost for integrating the iDolly into the transport system, which is a requirement for fully utilizing the potential gains with automation. It also depends on to what level the iDolly can operate on its own and how much human intervention (e.g. coupling vehicles, handling transport documentation, transport planning etc.) that adds cost would be needed. One should still remember that logistics is much more than just "driving", and all different activities must be considered for a system analysis. While no details of the calculated costs can be included here for secrecy reasons, the business case analysis done clearly shows that the utilization rate of the iDolly is critical. With only two round trips, i.e. four semi-trailers with containers arriving at the dry port per day, the iDolly would be standing still for about 40-60% of the time. So, one important conclusion is that to make an iDolly economically viable higher container volumes is needed. There is a plan to extend the A-double transports with one or more A-double combinations in the future, meaning the amount of last mile transports will increase.

Another economical aspect that was discussed in the project is the business model or, who should pay for the iDolly operation. The simple answer is of course the users, but still some new business model would need to be developed detailing who to make the investment (and thus take the risk), who to operate it and so on. Due to many unknown variables no "concrete/viable" business model could be developed in the project, but the input from the involved companies provided much valuable information. The Autofreight project has already shown that much can be done to, for example, enable improved transport planning. Several companies have joined forces for a joint transparent transport booking system. Initiatives like that could also be implemented to enable local distribution of containers with an iDolly.

Another important aspect of using an iDolly for last mile distribution of containers is flexibility. As described above the iDolly would help off-loading the tractor, implying a bit more flexibility can be achieved with respect to when containers are delivered to the respective customer. In the application for the project, one hypothesis was that the iDolly would enable last mile distribution of containers during nighttime. In this way containers can be placed at the customer for unloading early in the morning, and the iDolly moving at a relatively low speed (<30 km/h) would cause fewer disturbances to on-road traffic in the Viared area. Also, since the iDolly does not have a driver and is thus not influenced by driving time regulations, it could (theoretically) operate more or less 24/7 (if there are enough containers to be distributed). The project and the studied case, however, showed that this would be difficult to obtain. In most cases, the customers want their containers delivered as quickly as possible. They don't want a container to be waiting at the dry port for delivery one day later. Already today there have been some difficulties filling up the second round trip with containers on the A-double because most customers want their containers delivered with the first tour in the morning (around 07.00am). Further, not all customers' terminals are accessible during night as the gates are closed. Leaving containers at the dry port overnight may also be an issue due to the risk of theft. Different solutions with fences around the dry port etc were studied but this also implies considerable additional investments impacting the business case.

5.2 iDolly technical design considerations

This section mainly addresses the second research question:

> ***RQ2*** *– What specific* ***technical*** *requirements need to be considered when designing an iDolly? For example, electrical propulsion, automatic trailer coupling and similarities/differences between an iDolly and an eDolly.*

As briefly described in the introduction chapter a dolly is a two-axle[3] vehicle that is commonly used for pulling a semi-trailer behind a truck by coupling the semi-trailer king pin to a fifth wheel and coupling the dolly drawbar to the rear of the truck. While the iDolly that has been of special interest in this project has many similarities with a conventional dolly, there are also many differences (see Figure 10). In this section results and learnings regarding the technical design of an iDolly are described in some more detail.

[3] There are also dollies with, for example, one or three axles depending on transport application.

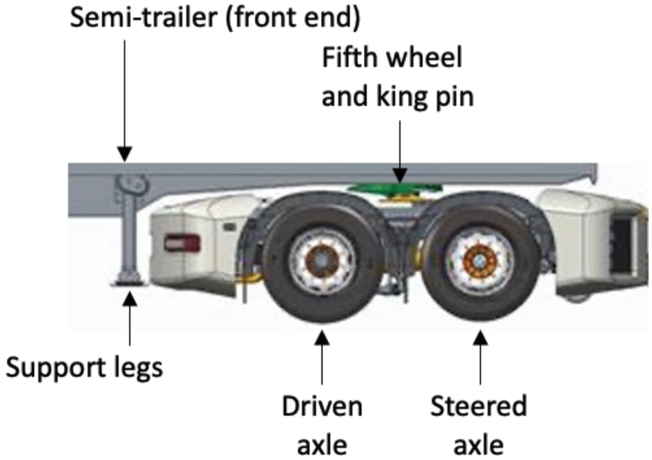


Figure 10. An iDolly and some main components.

5.2.1 Electrical propulsion

While the electrical propulsion is a key function of the iDolly, it is studied in more detail in other projects (see for example Jacobson, 2021) and therefore this technology received less attention in this project. However, an initial hypothesis was that maybe the same electric drivetrain could be used for both iDolly and eDolly. However, calculations and simulations for iDolly and eDolly respectively quite quickly showed that this was not the way to go. The main reason for this is the quite dissimilar use cases to be managed. The eDolly is mainly intended as a slave unit making up one complementary part of the drivetrain in a long multi-vehicle combination, such as an A-double, that is driven at relatively high speeds (up to 80 km/h) and long distances. The iDolly, on the other hand, should be designed to function as an individual (master) unit that can be used for precision driving (e.g. semi-trailer shunting operations) and it is mainly operating at low speeds (up to 30 km/h, and relatively flat roads). An eDolly can make sense also without steering, while steering is necessary on an iDolly. These differences pose very different demands on the energy storage capacity, power electronics, the need for gears and the design of electrical machines, steering and braking, and the master/slave control. Thus, eDolly and iDolly are quite different with regard to the electrical propulsion.

5.2.2 No drawbar

Another thing that makes the iDolly and the eDolly different is the front drawbar. While a drawbar is very much needed for the eDolly, it is inconvenient when operating the iDolly. In the beginning of the project, the possibility of first using an eDolly as an integrated part of an A-double, then disconnecting it to instead take the shape of an iDolly that can move a semi-trailer on its own while the tractor pulls the other trailer to its destination was studied. In this way, the combined eDolly/iDolly could make both on-highway and last mile transports more efficient. To enable automated coupling and decoupling of the dolly drawbar to the truck a “MFC” coupling from Swedish supplier VGB was successfully tested (see Figure 11). This coupling also enables automated connection of electrical and air supply between the truck and the dolly. A special communication interface was provided by VBG, enabling the complete coupling procedure to be fully automated.

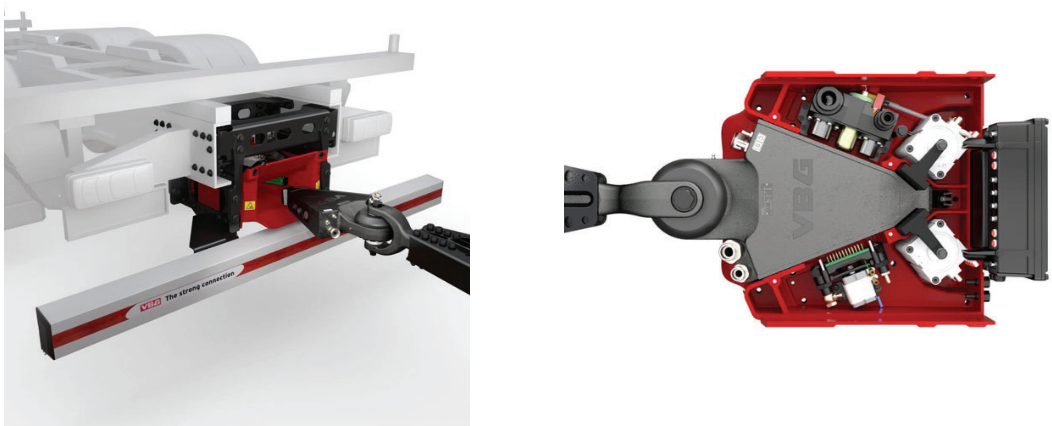


Figure 11. VBG ”MFC” automatic trailer coupling (courtesy of VBG Group Truck Equipment)

However, the drawbar in front is an obstacle when changing to iDolly mode. The drawbar sticking out in the front limits the maneuverability in tight spaces and raises concerns regarding traffic safety when driving on public roads. Therefore, different concepts for foldable drawbars were studied (see illustration in Figure 12), but this makes the design more complex, heavy, and expensive. Also, as concluded above, the eDolly drivetrain is not optimal for iDolly operation (and vice versa). The main conclusion was therefore that it is better to make the iDolly design dedicated for last mile operation only with no drawbar.

Figure 12. Illustration of iDolly with foldable drawbar.

5.2.3 Automated semi-trailer coupling and de-coupling

A vehicle that shall be coupled to a semi-trailer, in this case the iDolly, needs to be equipped with a so-called fifth wheel. By reversing the iDolly under the semi-trailer the fifth wheel locking mechanism will lock with the semi-trailer king pin and thus make a secure connection between the two vehicles. The king pin can still rotate, thus functioning as an articulation point between the iDolly and the semi-trailer. On most tractors the coupling (and de-coupling) operation is manual, requiring intervention by the truck driver.

To make the iDolly fully autonomous, however, an automated fifth wheel is needed. In the project a prototype system from German fifth wheel supplier JOST called "KKS" was used for that purpose (see Figure 13). It was installed on the Volvo FH16 tractor that was used in the project to emulate an iDolly. The KKS system detects when the fifth wheel is close enough to the semi-trailer (coupling height is critical) and it also provides fully automated fifth wheel locking and un-locking. Normally, the KKS is operated by the truck driver from inside the cab via a control panel. With a specially designed control panel a CAN communication interface was provided by JOST, enabling full fifth wheel control by the vehicle's automation control system. Also, the air suspension on the tractor was included in this control loop enabling precise fifth wheel height adjustment.

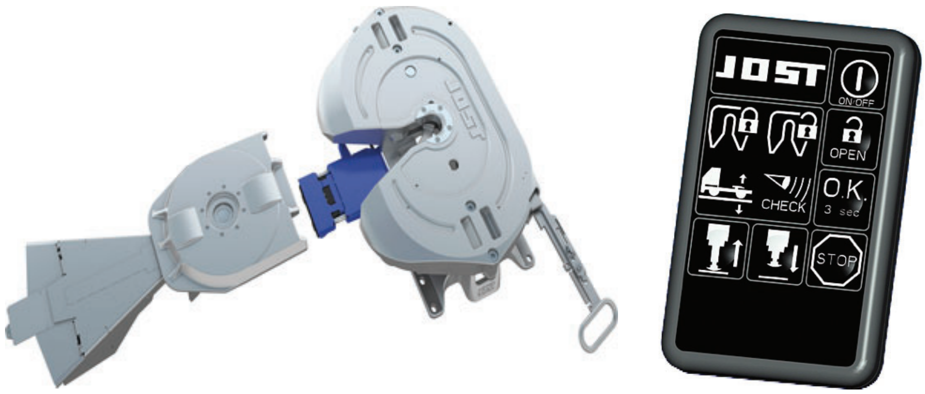


Figure 13 – Trailer unit with king pin and fifth wheel for the KKS system (left). The blue part is the automatic connector for air and electrical supply, mating with the triangular part on the trailer side when coupling the semi-trailer. Control panel in cabin for the KKS system (right). Courtesy of JOST.

Another valuable feature of the KKS system is the fully automated connection of electrical and pneumatic couplings between iDolly/tractor and semi-trailer. Connecting electrical cables and pneumatic hoses is also an operation that is normally carried out by the truck driver. However, while the automated locking function for the fifth wheel can be used with any (old or new) standard semi-trailer, the automation of electrical and pneumatic connections requires the trailer to also be equipped with the KKS system.

A semi-trailer does not have any wheels at the front so, when parked dedicated support legs must be used. Normally the truck driver uses a crank on the trailer to move the support legs up or down. In the project the semi-trailers used for testing were equipped

JOST's electrically powered support legs, which can also be maneuvered from the same control panel as the KKS. In this way, also the operation of the support legs can be fully automated.

The project showed that with this type of equipment installed it is possible to make the coupling and de-coupling of semi-trailers fully automated. However, since logistics is a complex operation with many different (old and new) vehicles involved, the demand for having specific equipment installed on semi-trailers (e.g. electrically powered support legs) may cause problems. In harbor operations special terminal tractors (tuggers) are used for moving trailers. They are equipped with hydraulically liftable fifth wheels (see Figure 14). This enables the terminal tractor to move a semi-trailer without first lifting the support legs. This could maybe be a solution for the iDolly as well, but the challenge with electrical and pneumatical connectors remains. Another solution can be to use only semi-trailers equipped with e.g. KKS and electrically powered support legs in a "closed system", however, this may have considerable negative impact on system flexibility.

Figure 14. A Terberg terminal tractor with hydraulically liftable fifth wheel (courtesy of Terberg).

5.3 Automation and control

This section mainly addresses the third research question. While vehicle automation is a huge area in itself, this project has been focused on automation specific for iDolly operation.

> *RQ3 - What specific solutions regarding the **automation** of an iDolly need to be developed? For example, systems for perception, positioning and vehicle control, including the maneuvering with a connected semi-trailer.*

5.3.1 Motion planning and Path following

In the project, several different approaches to motion planning and control were studied. In this section some high-level descriptions are provided.

The main objective of an autonomous driving system is to achieve transportation from one point to another. One of the initial steps is then to find a way to arrive at the destination, starting from the current position. If Volvo's ambitions are to become reality, the need of a path planning algorithm is essential. Therefore, in the study done by Olesen et al (2019) an algorithm is implemented in which a trajectory is produced that ensures feasibility with respect to constraints on both control inputs and vehicle dynamics. Currently the popular algorithms such as Rapidly exploring random tree (RRT) and RRT* only constructs feasible paths for vehicles with very simple dynamics. An attempt to solve this was to extend the RRT algorithm with kinematic constraints. Although this algorithm can find a path, it's highly random and the generated paths are inefficient. This created an interest in alternative methods for path planning. Thus, a new approach for robot path planning has been explored using MPC that with multiple consecutive cost functions successfully can find a path that the vehicle can follow to reach the end state where the end state consists of the vehicle's position and orientation. Using MPC for path planning instead of RRT works well in many cases, performing complex maneuvers that satisfy all the constraints of the goal state.

Another maneuver that needs to be automated is docking with a semi-trailer (see Olofsson and Wadman, 2020). To perform a successful docking/coupling maneuver, the truck/iDolly will have to be moved into a certain position and orientation that allow the docking equipment on the truck/iDolly and semi-trailer to dock. To be able to control the iDolly to a desired position, a motion planning algorithm is needed. The motion planning algorithm need to know the current position and the goal position. The problem is broken down into two separate tasks, the motion controller and a localization algorithm (see Figure 15). The motion controller algorithm has the purpose of generating a path and moving the iDolly into a desired position and orientation at a desired velocity. The localization algorithm is developed for estimating the position and orientation of the combination with respect to the goal position. The motion controller can be used for example for reversing the iDolly to a semi-trailer for automatic coupling or reversing the iDolly and the semi-trailer combination to a desired location for docking at a terminal.

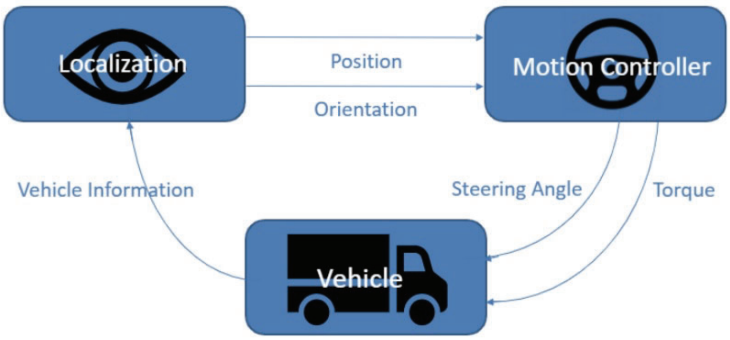


Figure 15. Overview of the interactions between the localization procedure, the motion controller and the vehicle. The position and orientation of the truck/iDolly is measured with respect to the trailer.

The idea of the motion controller is to generate a feasible path between the combination (iDolly or iDolly – semi-trailer) and the goal position. One idea studied in the project was to generate paths consisting of either a circle or a clothoid curve, describing a continuous path. The generation of the path is updated at each time instant in a receding horizon fashion until the unit has reached the end goal. The dolly is steered to follow the generated path. The motion controller was evaluated using a high-fidelity model with reasonable initial conditions. The final offset and orientation error between the unit and the end goal remained well within the specifications, achieving centimeter precision. These results were better compared to when a simple path tracking method was used. The motion controller could be calculated in real-time on an ECU with no convergence issues. The results, of course, depend a lot on the how good is the positioning of the dolly unit and the localization of the end goal.

The motion controller needs to know, as mentioned before, the current position and the goal position to generate a path. The localization is made in relative coordinates instead of in global coordinates. The disadvantage with global coordinates is that it requires GPS position measurements of not only the units but also the end goal and it is also more error sensitive. A relative localization method used is based on a camera system mounted on the dolly and markers mounted on the end goal, the semi-trailer, or the docking station. Two different approaches were investigated for solving the problem of estimating the position and orientation of the camera using these points. The first approach solved the Perspective-n-Point problem using the direct linear transform method followed by Levenberg–Marquardt optimization. The second approach used inverse plane mapping to estimate the position and template matching to estimate the orientation. The Perspective-n-Point approach was the more successful one, but both methods could be used in a full-scale system. If a camera-based system is supposed to be used, there are of course some problems that needs to be solved, the problem with dirt is the most evident, both on the camera blocking the field of view and on the markers.

Another studied approach covered in this project is GPS-based path-following control (see Lundqvist et al., 2018). A controller is implemented that allows the iDolly to follow a reference path with GPS coordinates. The controller used in the project is a nonlinear Lyapunov-based controller that minimizes the error between the iDolly’s position and the desired coordinates along the reference path. It is assumed that the iDolly will operate at low speeds only (<30 km/h). The iDolly is modelled using a standard kinematic model often referred to as the bicycle model. In the proposed approach, the path planner compares the current position of the vehicle with the trajectory and calculates the next desired position. The error between the estimated and the desired position is put in the Lyapunov controller which forwards an action in the form of a velocity and a heading rate. A nonlinear Extended Kalman Filter is also used to weigh together the estimated position from the kinematic model, GPS-measurements, and the input from the controller to provide a better estimate for the planner and error calculations. An overview of the controlled system is depicted in Figure 16.

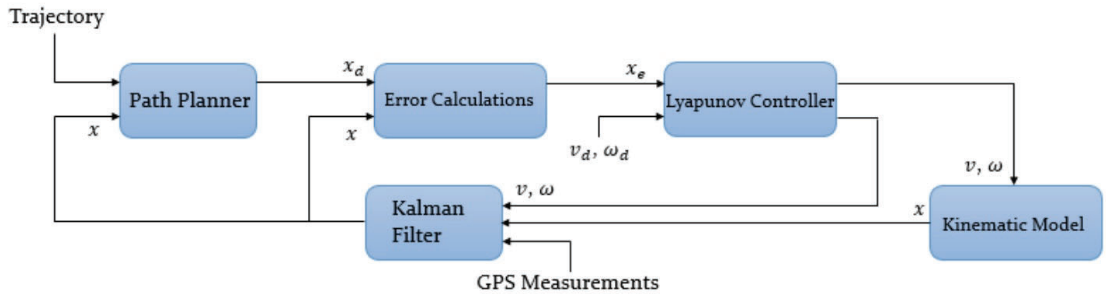


Figure 16. Overview of the complete system. The control signal x is the state vector that consists of x and y coordinates and the vehicle's heading θ.

Simulations of the vehicle successfully following different paths were presented in this project. The coupled vehicle follows the reference well - the trailer has an off-tracking of at most 4.6 m during a 90 degrees turn with radius 12.5 m and the iDolly has a deviation of approximately 2.5 cm from the reference path.

Zhang (2020), designed and implemented a GPS-based path-following control in the simulation software VTM (Virtual Truck Model). The controller is designed as low-speed independent and works well to make the single unit vehicle tracks the given trajectory closely. The controller is formulated based on a kinematic model and an error dynamic model of the states and afterwards verified using VTM. In this work, the autonomous vehicle drives up to 9 m/s forward and -3 m/s backwards to follow the given path with high precision. Based on the given predefined trajectory, a smoothing algorithm has been investigated and implemented to represent the trajectory to make the simple linear controller perform better along the path. Thus, a spline fitting approach is chosen as the way to represent the given trajectory since it provides a compact and smoother path for the vehicle tracking. The reverse motion control for tractor/iDolly with semi-trailer is the most tricky part. VTM is non-linear and there are also lots of constraints that affect the stability and controllability of the reverse motion controller compared with forward moving. Therefore, Jacobian linearization and the LQR controller is investigated and implemented to solve the problem. Figure 17 shows the overview of the whole controlled system.

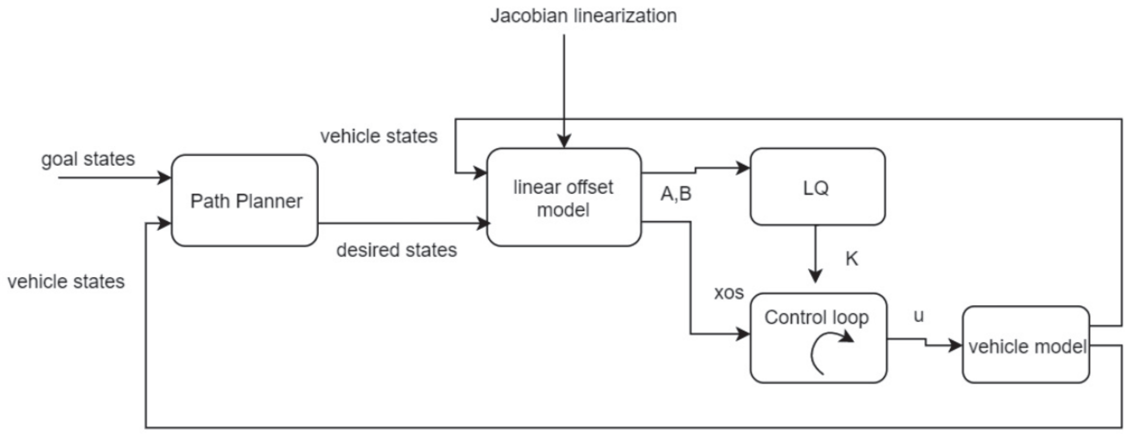


Figure 17. Complete control algorithm overview

The controller is designed to be speed independent and simulation results using VTM show that the controller works fine up to 9 m/s in forward motion and to -3 m/s in reverse motion. A precision of less than 4 cm and less than 4.5 cm are achieved when driving at 3 m/s in forward and at -3 m/s in reverse, respectively.

5.3.2 Positioning

Accurate and reliable positioning is critical for successful vehicle automation. As already described in the previous section, the positioning method play an important role for how a reliable motion planning function can be achieved. Detailed aspects of positioning have already been covered in numerous other research projects and was therefore not specifically in focus in this project. However, some additional aspects of positioning specific to the iDolly concept are worth mentioning here.

For the iDolly to function properly at a logistics terminal it is critical to not only know the position of the iDolly itself, but also the position of the semi-trailer(s) to be coupled and moved around. As described in the previous section, one method for locating a semi-trailer is using cameras on the iDolly and specific markers on the trailer (and on terminal docks).

Another method that was briefly investigated in the project is to rely on GPS positions only. Quite quickly it turned out to not be a feasible method. First, the position of the iDolly itself and, specifically, the position of the iDolly fifth wheel needs to be determined. In theory the relative position of the fifth wheel can quite easily be calculated with the help of the iDolly position and its heading angle. When tested on a 6x4 tractor the method turned out to be somewhat unreliable due to the relatively large distance (3.2m) between the GPS antennas and the fifth wheel. The maximal acceptable lateral error (approximately 0.1m) of the fifth wheel position will be exceeded when the heading angle error comes close to 2 degrees. That problem should, however, be smaller on an iDolly where the distance between GPS antennas and fifth wheel is smaller.

Moreover, as the iDolly becomes more or less completely "hidden" when coupled to the semi-trailer, the GPS position accuracy will be further reduced, see Figure 18. This is believed to be a major challenge for the iDolly concept since localization to some extent will be dependent on GPS and the antennas cannot be placed on top of the semi-trailer or container for proper visibility to satellites.

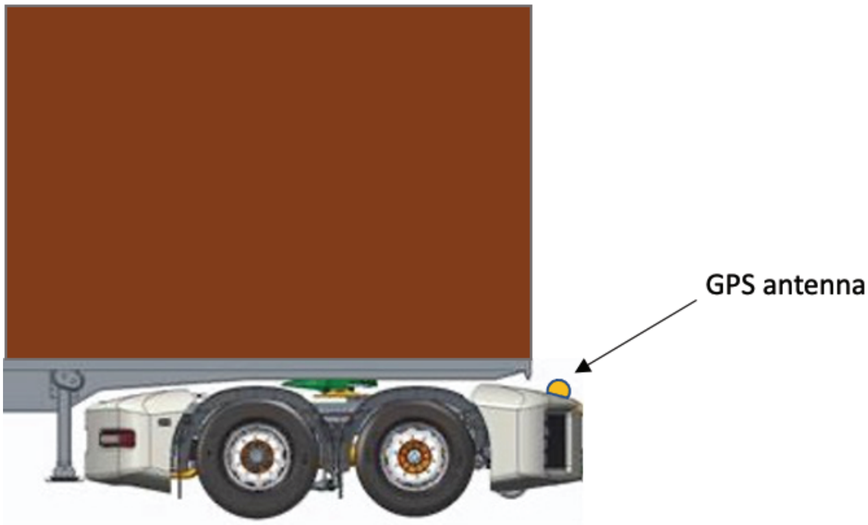


Figure 18. GPS antenna coverage partly occluded by trailer and (45 foot) container.

Another challenge is for the iDolly to get exact information about where the semi-trailers to be coupled are positioned. In particular, the position of the semi-trailer *king pin* needs to be known. If a semi-trailer has been left at a terminal by another truck, the information about the semi-trailer position needs to be transferred to the iDolly via some form of system. Thus, relying on GPS positioning only seems to not be a viable solution for realistic iDolly operation.

Another way of positioning tested in the project is based on the use of an overhead camera. This method is also using markers on the vehicles and is thus similar to the method described in the previous section. The overhead camera was tested and demonstrated inside the REVERE research lab using 1/14 scale model vehicles (see section 6.2.2 for more details). After some calibration with regard to specific camera lenses etc. the positioning method functioned well. In a real setting, for example at a logistics terminal, the overhead camera(s) could be placed on a tall lamp post or similar. However, the system will always be limited to the viewable area on the ground that can be covered by the cameras. The markers are relatively inexpensive and don't require any system connection onboard the vehicles, making them easy to use. However, when transporting containers, it will be difficult to place markers on top since containers are continuously being swapped out.

Taken together, especially when considering the specific use case studied, accurate positioning can be a quite challenging task. This far, positioning of vehicles by use of GPS and cameras mounted on the iDolly and markers mounted on trailers and loading docks (and other objects that needs to be positioned) seems to be the most feasible solution, but this needs to be investigated and developed further.

5.3.3 Perception system

The perception system is the vehicle's ”eyes and ears” enabling an understanding of where it is and what is happening around the vehicle. This information is used as input for the vehicle motion planning. The perception system setup applied for this project is in most respects quite “standard” when comparing with what is generally used for vehicle automation. It is therefore not described in detail in this report. Instead, some aspects of perception unique to the iDolly concept will be in focus.

In the project, the Volvo FH16 tractor used to emulate an iDolly for the tests, was equipped with several different sensors. Cameras provide image input and in the front of the vehicle a stereo-camera setup also enables information about depth/distance to identified objects (see Figure 19). Different camera setups have also been tested for viewing what is behind the vehicle, which has proven to be a challenging task. More about that later. The vehicle was also equipped with a 32-layer lidar providing geometrical information about surrounding objects (point cloud with detailed information about the distance to objects), a high precision GNSS positioning system (using GPS), and an Inertial Measurement Unit (IMU) providing information on vehicle acceleration/rotation. The vehicle was also equipped with one radar unit on each side, but for different reasons these could not be made operational during this project.

Figure 19. Cameras mounted on the test vehicle.

Thus, this perception system is quite similar to what is often used on, for example, autonomous passenger cars. However, the main difference, and also challenge, with the iDolly perception system is the positioning of the sensors to get a good coverage around the vehicle. The positioning of cameras can be used for illustrating this. In Figure 20 four cameras are used for covering the areas beside and behind the iDolly with coupled semi-trailer when making a turn (front cameras are not included in this picture). The two cameras placed close to the front wheels of the iDolly provide a view that is similar to what can be seen in the rear-view mirrors on a truck. The two cameras placed in the rear end of the iDolly provide important complementary information.

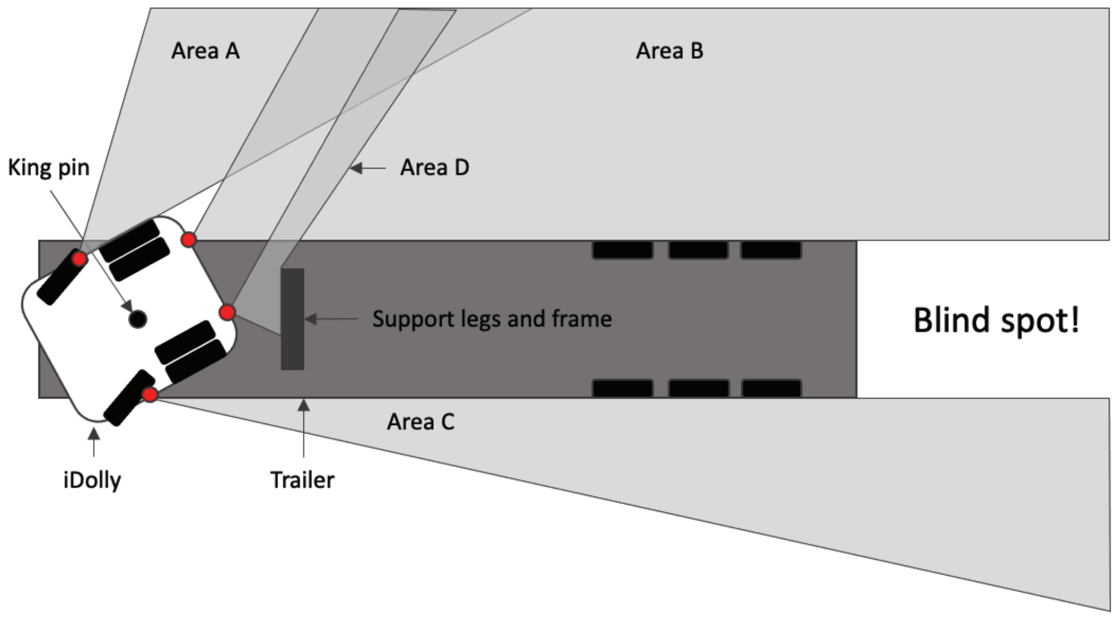


Figure 20. Illustration of camera coverage behind the iDolly when making a turn with coupled semi-trailer. Red dots illustrate camera positions.

It is a well-known fact that when making a turn with a tractor – semi-trailer combination there will be large blind spot areas beside the semi-trailer (most of Area B). This blind spot can largely be avoided with the cameras placed on the rear end of the iDolly. However, as illustrated in the picture, when making a left turn the left rear end camera view is largely constrained by the support legs and the semi-trailer's frame structure. Figure 21 shows an example of how cameras were mounted on the rear end of a dolly for testing the camera view under and beside the trailer.

Figure 21. Cameras mounted on the rear end of a dolly for testing camera views.

When driving straight forward, the two rear end cameras will have a limited field of view due to the support legs and semi-trailer frame structure. Depending on what camera lens and thus view angle is chosen, they may still contribute with relevant information.

It is also evident that independent of where cameras are placed on the iDolly, the usual blind spot right behind the semi-trailer will remain. The rear end cameras on the iDolly may provide some information based on what can be seen under the semi-trailer (between its wheels) but that is usually very limited. While there are proposals for making reversing cameras mandatory on semi-trailers, old trailers without reversing cameras will remain in operation for many years. In logistics systems where a limited number of "known" semi-trailers are used, there is a possibility to retrofit them with rear view cameras (that also requires an analog/wireless/ethernet interface or similar between semi-trailer and iDolly). However, in many cases, like a dry port where many different semi-trailers are used by different transporters, that is not a viable option. Therefore, an alternative strategy for securing these blind spot areas was discussed in the project. The idea is to manage the situation in a similar way as truck drivers do it every day when reversing trucks. When entering an area like a terminal, where the truck driver knows some reversing will soon take place, objects (such as other trucks, fences, pedestrians etc.) that will potentially be in the way when reversing the truck are identified. Then the truck driver will keep track of any objects moving in or out of that zone. When e.g. pedestrians have left and if no new objects enter the zone where the reversing should take place, there should be no objects behind the truck when reversing.

Further, when turning the iDolly – semi-trailer combination, smaller or larger parts of the semi-trailer will be visible for the cameras. To detect what object is actually seen by a camera i.e., the "own" semi-trailer or another object, the information from the king pin angle sensor combined with information about the semi-trailer geometry proved useful. With some simple trigonometric calculations, the system would be able to judge whether a detected object is the "own" semi-trailer or another object.

Another blind spot, not illustrated in Figure 20 is above/on top of the iDolly – semi-trailer combination. To cover that area some form of camera arm that can be raised from the iDolly to see over the semi-trailer chassis was briefly discussed. However, also in this case the solution was to handle this in a similar way as a human truck driver would do it. When entering an area, such as a logistics terminal, the free height is checked (can be done with the lidar on the iDolly) to make sure there are no roofs or similar that are too low for the vehicle combination. While inside the area it is assumed that these conditions will not change.

This section has mainly covered the use of cameras on an iDolly. Other sensors like radar and lidar are quite similar to cameras in the sense that comparable blind spots occur. Cameras (and some radars) are quite inexpensive and lidars are (still) more on the expensive side, meaning it is easier to add some cameras around the vehicle. However, cameras can be used only when there is light that can be detected by the camera sensor and cameras easily get dirty (especially when placed close to the ground as on an iDolly). Therefore, radar and lidar (and potentially other types of sensors) that are operational under different conditions (e.g. darkness and fog) are important complements to cameras.

5.4 Infrastructure adaptations

This section mainly addresses the fourth research question:

> ***RQ4*** *– What changes to the* ***infrastructure*** *are required for using an iDolly for logistics operations around a dry port? For example, road adaptations, implementation of charging infrastructure and support for localization of semi-trailers.*

Although it was not as thoroughly studied as the vehicle technical parts, the project also explored some different aspects of (hardware and software) infrastructure adaptations needed when implementing an iDolly into a logistics system.

In the research application for the project the potential need for adapting the road infrastructure was brought up. Ideas like adding road markings or magnetic strips for guiding the iDolly were mentioned. The project showed, however, that this type of support should not be needed. This is in line with other research on vehicle automation where the use of digital maps, SLAM, GPS positioning and proper perception systems should be sufficient. The relatively low speed at which the iDolly is moving also makes this much easier. The project also created some digital maps of the Viared area using high precision GPS. Such GPS traces would be useful for guiding the iDolly between the dry port and the destination terminals. Although no demonstration could be performed at Viared in this project with a fully actuated vehicle, similar GPS way points were used for testing the method at a test track.

At the terminal areas, where a higher positioning precision is required (e.g. to accurately locate a loading dock or a semitrailer-king pin) some adaptations like markers may be needed. These are, however, inexpensive and need to be firmly secured so they don't move out of position (e.g. being hit by a fork lift).

One way of positioning vehicles already mentioned earlier is the use of overhead cameras. This would thus require additional infrastructure in the form of cameras mounted (high) above the area to be monitored. If available, tall lamp posts can be used for that purpose, otherwise some form of (more or less expensive) mast would be needed. This type of solution also requires some form of system to convey the positioning information via a wireless link to the iDolly. While this type of systems and communication links introduces additional potential risks of failure, also some potential benefits were identified. As described earlier, covering the blind spots, especially right behind the semi-trailer, when reversing with the iDolly and a coupled semi-trailer can be very difficult. With an overhead camera most such blind spots can be covered and the information about surrounding objects can be conveyed to the iDolly.

Whether sensors external to the iDolly are used or not, the iDolly would in any case require a (wireless) connection to a transport planning and supervision system. Although this would not have to be a real-time system, the iDolly regularly needs to receive information about, for example, what semi-trailers to pick up, their position, as well as their destination. The iDolly would also need to provide the system with information about what semi-trailers have been handled and so forth, as well as information about its own "health status" (e.g. battery state of charge).

The iDolly is electrically driven and therefore regularly needs recharging. Since the iDolly would be operating within a fairly limited geographical area, the exact location of a charging station is of less importance. Since the iDolly would come back to the dry port on a regular basis it was concluded that this would also be a good place for a charging station. If this for different reasons, such as availability of high-power electric connections, turns out to not be a viable solution, the charging station can be placed somewhere else within Viared. The City of Borås have recently started a project to investigate how a charging infrastructure for heavy vehicles could be implemented at Viared. The project will cover different aspects such as technical solutions, flexibility for future expansion, business model, organization, and mapping of logistical flows. That is of great interest since the number of heavy electrical vehicles is expected to increase over the coming years and an iDolly would not be the only consumer in such a system.

5.5 Learnings and ideas for new projects and technologies

The project resulted in valuable learnings regarding technology as well as how an iDolly needs to be designed to fit into a real transport system.

Knowledge and experience from the project contributed to a new product developed by Swedish truck coupling manufacturer VBG that is also one of the project partners. The new system includes radar units that measure the angle between a truck and a dolly/trailer that is pulled by the truck, see Figure 22. This can be of great help when coupling the trailer to the truck and also help to further improve safety.

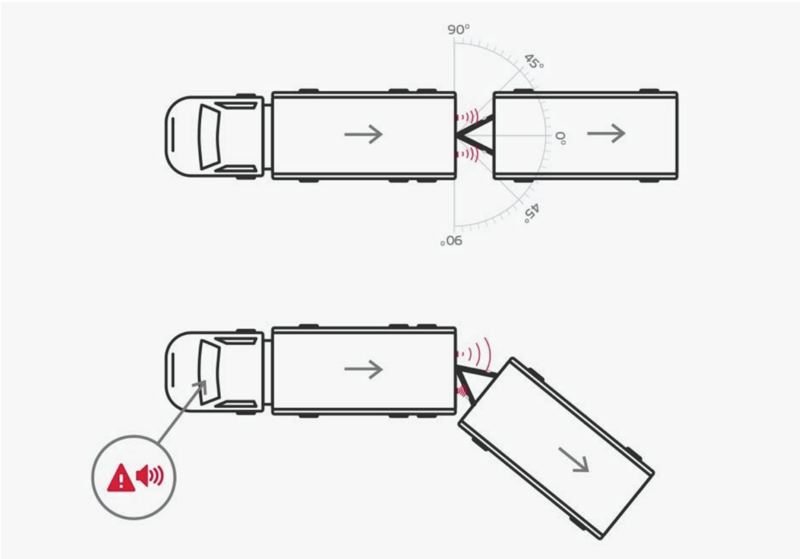


Figure 22. Radar system for drawbar angle measurement.
Courtesy of VBG Group Truck Equipment).

Further, several areas relating to vehicle automation studied in the project need further research and development. That includes, for example, remote control of (semi) autonomous vehicles, methods for reliable vehicle positioning, how to enable automatic coupling of "old" semi-trailers, and how to manage some more tasks that are currently performed by the truck driver (e.g. logging of container ID numbers). For last mile distribution of containers, that is performed at low speed, more can probably also be learned from areas like assembly plant logistics and robots.

The limited size of the iDolly and the fact that it more or less disappears under the trailer may make it interesting for use in applications where the maneuvering space is very limited. One such application could be using the iDolly concept for loading semi-trailers on to Ro-Ro ships. Today quite much deck area cannot be utilized because terminal tractors need some maneuvering space around and between trailers.

6 Dissemination and publications

6.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	Much knowledge has been gained regarding iDolly design and technology as well as how it can be incorporated in a logistical system. Knowledge has been shared among the project partners,
Be passed on to other advanced technological development projects	X	The iDolly project has provided input to other development projects like Volvo's VERA project. It has also provided valuable input for the Autofreight project regarding, for example, the understanding of how a dry port can be operated and how to support a driver reversing a truck.
Be passed on to product development projects	X	Volvo's VERA project will continue and take some solutions further. Valuable input to projects on new couplings and connections for electrical, communication and pneumatics interfaces to semi-trailers.
Introduced on the market	X	The iDolly concept needs more research and development before market introduction. However, VBG has developed a new product for drawbar angle measurements partly based on project results.
Used in investigations / regulatory / licensing / political decisions	X	The project has provided valuable input to future standards regarding semi-trailer electrical connections and communication protocols

6.2 Demonstrations

The project results have been demonstrated in different ways during the project. The initial plan was to conduct demonstrations using the electrified dolly built by Volvo as an eDolly (with a drawbar at the front), however, the build of it was delayed and instead the Volvo FH16 tractor available at the REVERE lab at Chalmers was used. Even if it had been nicer from a demo point of view to use a driven dolly, this had less impact from a research point of view. The project also set out to perform a demonstration at Viared. However, as it turned out, driving at Viared (public road) with a self-actuated vehicle would require a special permit for testing of autonomous vehicles. Therefore, the demonstrations were done at test tracks and in a lab environment instead.

6.2.1 Automated semi-trailer coupling and uncoupling

In August 2019 the fully automated coupling and de-coupling of a semi-trailer was successfully demonstrated at the IAVSD 2019 conference, at the Astazero test track. A Volvo FH16 6x4 tractor was used to emulate the iDolly. The tractor could be actuated via a computer enabling acceleration, braking (including parking brake), steering and air suspension adjustment. The tractor and the trailer were also equipped with the JOST KKS system for fully automatic locking of fifth wheel to semi-trailer king pin as well as automated connection of electrical and air supply to the semi-trailer. The trailer was also equipped with electrically maneuvered support legs. To increase the audience's understanding of what was demonstrated, a big screen was also set up outside showing the status of the fifth wheel lock, support leg position etc.

The demonstration is illustrated in Figure 23. It started with the tractor reversing towards the semi-trailer (1). When the fifth wheel touches the underside of the trailer the automated fifth wheel system is automatically activated. If needed, the fifth wheel height can be adjusted with the help of the truck's air suspension. When the king pin has reached the correct position, the fifth wheel locks around the semi-trailer king pin (2). At this demo the truck was reversed along a straight line. Thus, locating the trailer king pin (i.e. lateral positioning) was not part of this demo. At the same time as the king pin reaches its designated position in the fifth wheel the air and electrical connections to the semi-trailer are established. When the king pin is locked the parking brake is applied. Then the support legs can be safely lifted from the ground.

Next, the tractor semi-trailer combination was driven a short distance forward (3) to demonstrate that it was now ready for road use. It then stopped again and the parking brake was applied (4), which is a condition for enabling the support legs to be lowered and the fifth wheel to be unlocked again. When the unlocking procedure was completed, the tractor could move forward again (5) and the air and electrical supply to the semi-trailer was automatically disconnected. All steps 1-5 (except shifting gear from reverse to forward) were performed autonomously.

The demo was appreciated by the audience and clearly showed that truck automation is much more than just driving on a road. The demo also contributed with many interesting learnings for the project regarding, for example, challenges to couple the trailer at the right speed and setting the right fifth wheel height (that is even more difficult on uneven ground).

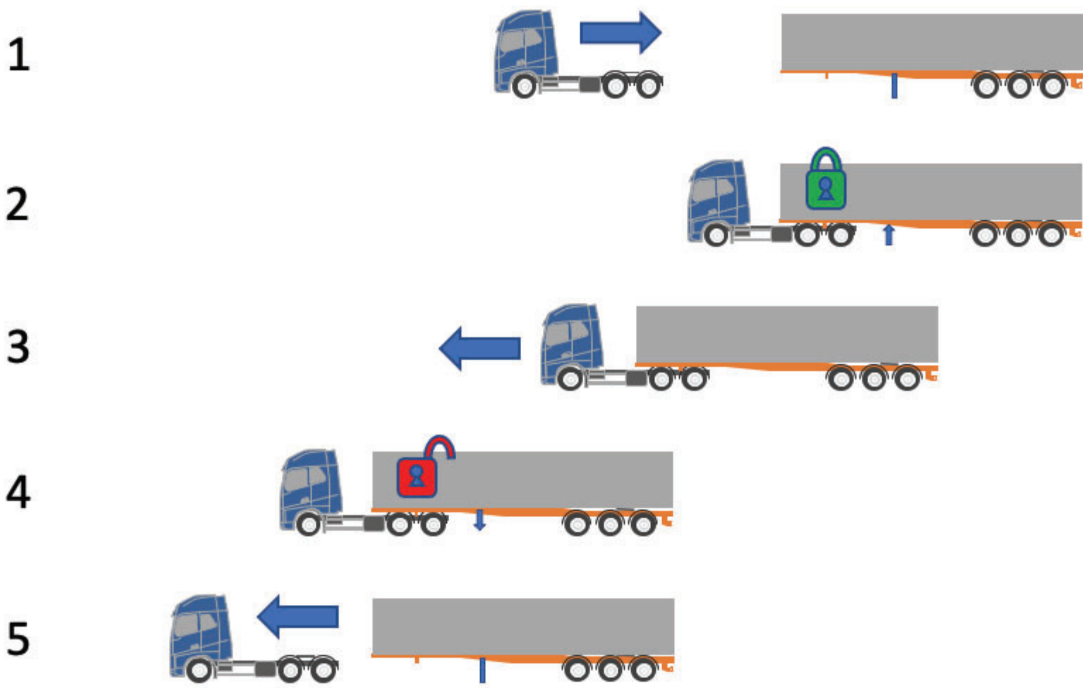


Figure 23. Demonstration of automated coupling and uncoupling of a semi-trailer.

6.2.2 Autonomous semi-trailer coupling and shunting at terminal

As described in previous sections, the positioning of iDolly and semi-trailer to enable coupling and shunting operations is of central importance. For that purpose a reversing algorithm was developed by Kachhawah and Rahul Misquith (2021) (see Figure 24).

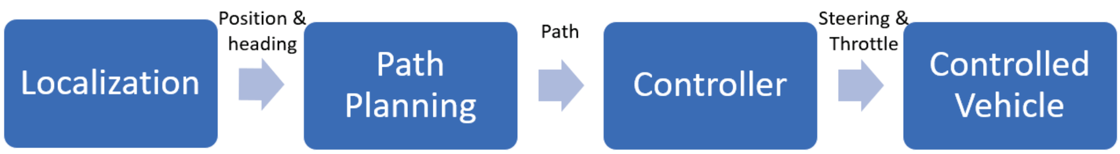


Figure 24. Basic building blocks for the reversing algorithm.

It was then tested and demonstrated on a 1/14 scaled down tractor – semi-trailer combination model, which is shown in Figure 25. Here instead of an iDolly, a truck is used and any reference to iDolly is considered to be the truck. For the purpose of keeping the demonstration as realistic as possible, the two rear axles were merged and treated as one as the loading on the rear axles are equal.

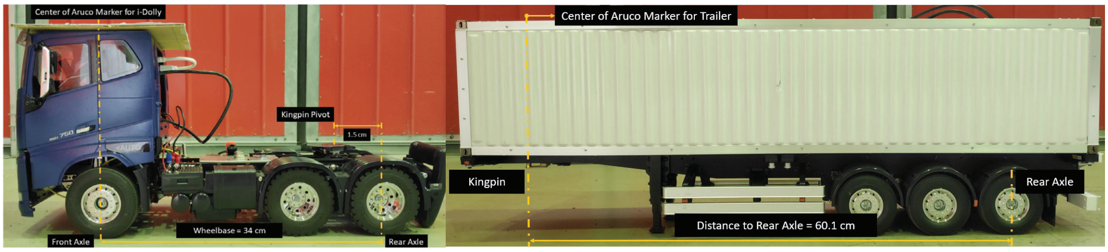


Figure 25. Scaled down model used for the test and demonstration

The testing was also done in a scaled environment with reasonable assumptions of vehicle speed and the precision and accuracy which comes with scaling down. For the purpose of localization and tracking of the scaled down model, an overhead downward-facing camera along with ArUco markers were used as seen in Figure 26.

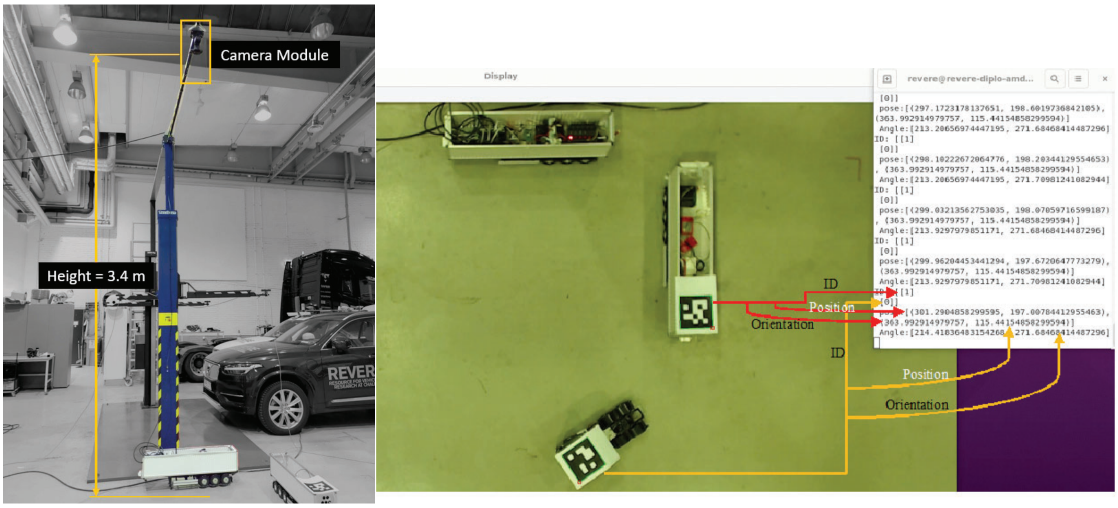


Figure 26. Overhead camera placement (left) and tracking using ArUco markers (right).

The ArUco markers were affixed upon the iDolly and the trailer. These markers allowed the tracking of X and Y coordinates in a 2D plane as well as the orientation with respect to the virtual x-axis. The benefit of using this method is the reduced complexity and that it mimics the real-life combination of GPS-IMU-odometer fused data.
The maneuver starts with stopping the iDolly near the trailer (iDolly stopping zone) and then the iDolly reversing begins as shown in Figure 27 below.

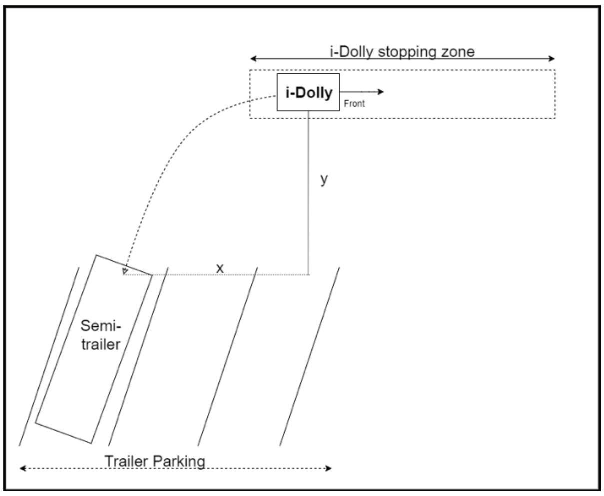


Figure 27. iDolly reversing to couple a semi-trailer.

The start position is the current position of iDolly and the orientation is considered to be the opposite of heading as it is reversing. The end point is the semi-trailer king pin whose exact location is known as the ArUco marker is kept directly above it. As the position of the fifth wheel wheel is fixed with respect to the iDolly, by measuring its distance from the centre of the ArUco marker, the fifth wheel can be tracked as well. A Stanley controller was used to control the vehicle's movement till it reaches the end position (see Figure 28).

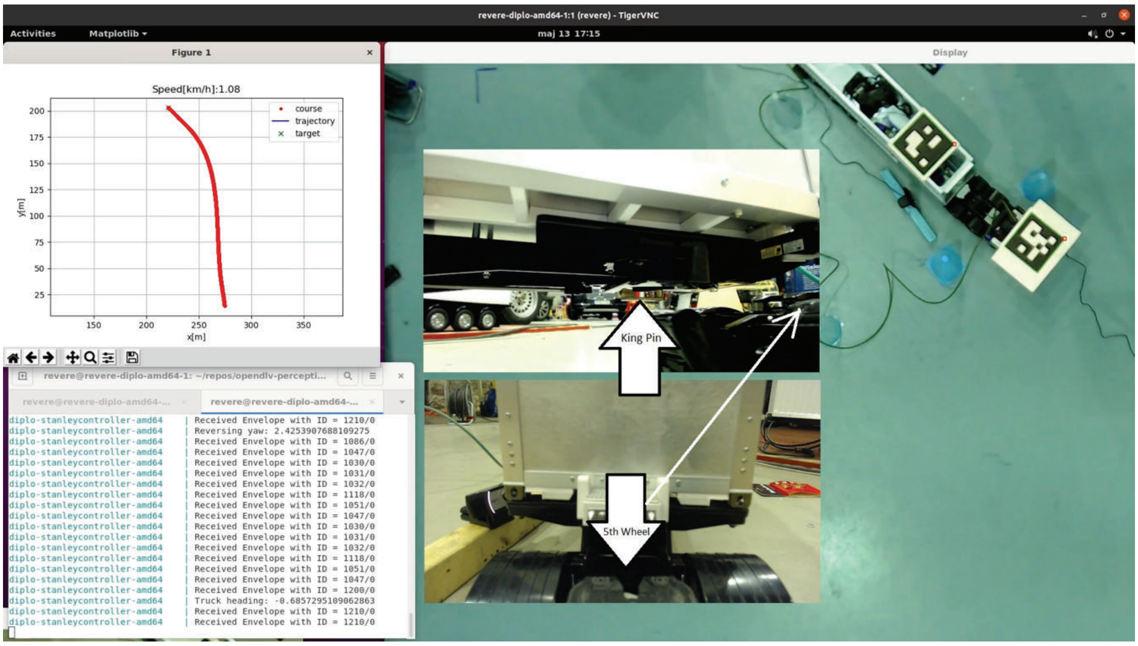


Figure 28. Different camera views showing the fifth wheel approaching the semi-trailer king pin.

The reason for using a scaled down model was to replicate the possible real-life problems which can come up but might not be noticeable in simulations. The Stanley controller was a simple, yet effective controller used for path following. In real life applications there may not be an overhead camera, but the ArUco markers could be placed on the front face of the semi-trailer and using a reversing camera on the iDolly (as described in previous sections), enabling a similar maneuver to be performed. This method, with some changes (i.e. including semi-trailer dynamics and using cameras mounted on the iDolly) can be applied for reversing into the goods terminal as well.

6.3 Publications

Ghandriz, T., Jacobson, B., Nilsson, P. et al (2020) Computationally Efficient Nonlinear One-and Two-Track Models for Multitrailer Road Vehicles IEEE Access, 8: 203854-203875

Ghandriz, T., Jacobson, B., Laine, L., Hellgren, J. (2020).”Optimization data on total cost of ownership for conventional and battery electric heavy vehicles driven by humans and by Automated Driving Systems”, Journal article

Ghandriz, T. (2020). “Transportation Mission-Based Optimization of Heavy Combination Road Vehicles and Distributed Propulsion, Including Predictive Energy and Motion Control”, Doctoral thesis, 2020

Ghandriz, T., Jacobson, B., Laine, L. et al (2020) Impact of automated driving systems on road freight transport and electrified propulsion of heavy vehicles Transportation Research, Part C: Emerging Technologies, 115

Ghandriz, T. (2018). “Transportation Mission Based Optimization of Heavy Vehicle Fleets including Propulsion Tailoring”, Licentiate thesis, Chalmers University of Technology.

Jacobson, B. et al., Section *4.5.2.2 Articulated Vehicles*, in *Vehicle Dynamics Compendium*, https://research.chalmers.se/publication/513850, 2019.

Kachhawah, N. and Rahul Misquith, C. (2021) ”Propelled and steered converter dolly for improved shunting of semitrailers at goods terminals”, Master thesis, Chalmers University of Technology 2021.

Laine, L. et al. (2020). “AutoTransform and auto-reconfigure vehicle unit and vehicle combination for the mission. E-dolly can transform itself to VERA or e-dolly”, 23 Jan 2020, Filed Patent P2020-0045, 2020

Laine, L. et al. (2020). “AutoTransform and auto-reconfigure vehicle unit and vehicle combination for the mission. E-dolly can transform itself to VERA or e-dolly”, 21 Jan 2020, Filed Patent P2020-0036, 2020

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Sadeghi Kati, M. et al, Distributed Control Allocation for Multi-trailer Commercial Heavy Vehicles, In preparation 2020

Zhang, H. (2020) ”GPS-based path-following control of i-dolly usedfor local distributions”, Master thesis, Chalmers University of Technology

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Liu, C. I., & Ioannou, P. A. (2002). “A comparison of different AGV dispatching rules in an automated container terminal”.

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Volvo (2019) Veras första uppdrag: Volvo Lastvagnar presenterar en självkörande transportlösning mellan ett logistikcenter och en hamn, https://www.volvotrucks.se/sv-se/news/press-releases/2019/jun/pressrelease-190613.html

7 Conclusions and future research

The project has studied how last mile transports of containers can be electrified and automated using an iDolly. By continuously referencing a real use case where containers are transported using HCT vehicles many useful learnings could be obtained about the logistical system requirements.

One conclusion is that electrical vehicles are suitable for the type of last mile transports studied in the project. The distances are relatively short and since the vehicle is regularly coming back to the same place the charging should not be an issue. A new project has already been started for studying this specific subject in more detail at Viared industrial area.

When it comes to automation of the last mile transports the picture is somewhat more complex. Some level of automation can definitely help to improve the efficiency of logistics, but the implementation of full automation seems to lie quite far ahead, if it is at all desirable. This conclusion is largely based on the knowledge and learnings gained by studying the potential implementation of an iDolly in the real use case at Viared. It is evident that making an iDolly function in such a logistics *system* implies so much more than just driving the iDolly from A to B. There are many challenges to overcome before it will work smoothly. Some of these challenges include coupling and moving all types of semi-trailers (including older trailers with no adaptations for automation), how to locate the semi-trailers to be picked up and how to log and report the ID's of the transported containers. This will require quite advanced and integrated support systems and also some physical adaptations.

Even if the project results propose that full automation of the last mile container transports should not be the main goal, the project has yielded a number of interesting results that can be applied to semi-automated systems, for the development of electrified solutions and more efficient logistics. As a first step it is proposed that the last mile transports are done using a full electric but manually driven tractor. With forecasted increasing volumes of containers transported to the dry port with HCT vehicles there should soon be viable a business case for it. As a next step, new driver support systems can be developed, for example aiding the driver with coupling and reversing semi-trailers. Then semi-automated transports, e.g. with remote control, can be implemented. By doing this step by step the logistics system can also be adapted over time, enabling the integration of technology, business models, organization and logistical flows that is necessary for system efficiency.

8 Participating parties and contact persons

The project was carried out in cooperation between several different organizations, see the table below.

Organization		Contact person
Volvo Technology AB	VOLVO	Lena Larsson lena.larsson@volvo.com
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