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FACULTY OF ECONOMICS AND BUSINESS

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KBI_1618

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Abstract:

Vehicle automation technologies are rapidly developing and will be available soon. Businesses in the logistics industry can develop a competitive advantage when effectively adopting this new technology. However, only limited research exists about the impact of autonomous vehicles on the logistics industry. The aim of this paper is to provide a broad introduction to autonomous vehicles, after which the usage and potential consequences of autonomous vehicles in logistics is discussed. It is clear the adoption of AVs holds the promise of completely innovating the way in which mobility and transportation logistics are dealt with and many research opportunities remain unexplored.

Key words: autonomous vehicle; automated guided vehicle; logistics; secure settings; long-haul trucking; last mile

1. Introduction

The transportation of individuals and goods plays a prominent role in the economy and everyday life. The widespread introduction of motorised vehicles since the beginning of the 20th century has unarguably revolutionised the transportation industry by making the world smaller and allowing larger loads, having a vast impact on many aspects of society. Especially in the developed world automobiles are used by many on a nearly daily basis for private and work related purposes, businesses rely heavily on the usage of automobiles for their operations, and the combined effect of transport and the manufacturing of automobiles on the economy is non-negligible.

The recent technological advancements in the development of autonomous vehicles (AVs) are announced as the next revolution in mobility and the transportation sector. The introduction of AVs holds the promise of completely innovating the way in which mobility and transportation logistics are dealt with. As explained throughout this study AVs are expected to revolutionise vehicle ownership structures through on demand services, bring new solutions for bridging the first and last mile, redefine the role of connectivity and data analysis in logistics, alter transport and travel patterns, and create potential for new business models whilst ending the prospects of existing ones (Anderson, et al., 2014; DHL, 2014;

Fagnant & Kockelman, 2013; Gao, et al., 2014; Sebestyen, et al., 2014; Silberg, 2013; Silberg & Wallace, 2012; Yeomans, 2014).

Although it is still unclear when businesses, governments and consumers will be ready for large-scale production and usage of AVs, most experts and industry watchers seem to agree that the introduction of some sort of AVs in everyday operations is likely to occur within the next decade. The recent technological progressions spurred traditional automobile manufactures and new players (e.g. Google) to start working on their own AV, while several governments have started to propose legislation and issue licenses so as to create the optimal environment for heading the development of this new technology and popular media have been eagerly reporting about developments in the field of AVs. Similarly, the evolution of AV technology has encouraged the literature in the field to start dealing with a wide range of issues regarding autonomous vehicles.

Despite the increase in activities and the progress made, the idea of AVs driving around in everyday traffic within the near future is still faced with a lot of scepticism and ignorance (Shanker, et al., 2013). However, if AVs are going to be available in the next decade, presumably in logistics, it is important for logistics professionals to prepare for their arrival as the smooth adoption of the technology could allow for building a competitive advantage. Indeed, as recognised by DHL in their Trend Report on AVs in logistics (2014), logistics provides ideal working environments for autonomous vehicles. AVs have been used already for several decades in logistics, but so far only within the clearly defined boundaries of a controlled environment such as ports, distribution centres and production plants. The recent technological advancements are aimed at bringing autonomous vehicles out of these controlled settings and into the uncertain environments of everyday traffic (Piekenbrock, 2014). However, current research lags behind the technological progress that has been made and the efficient introduction of autonomous vehicles in logistics would benefit from more research (Fagnant & Kockelman, 2013).

The aim of this study is to create a concise review of the research that has been carried out so far on the introduction and implementation of autonomous vehicles of levels 3 and 4 (see Appendix A) in general and in logistics in specific. This could provide clarity as to where research stands and what further research is needed to allow for the efficient adoption of the technology. Besides, the aim is to allow scholars as well as important stakeholders in the logistics sector to get an introductory overview of the current state-of-the-art, allowing them to prepare for the introduction of the technology. To that end the term logistics in this study refers to the systems set in place by organisations in order to systematically move goods between geographical locations. The aim is not to present a comprehensive review of all aspects of AVs discussed here, but rather to present a broad overview necessary to understand the relevance and potential consequences of AVs for the logistics industry and references to publications focussing on and reviewing each of the different aspects touched upon.

The remainder of this paper starts with explaining the material and methods (i.e., way of working) used. It represents a broad introduction to AVs and related research by looking at the definitions of AVs, by describing a timeline of AV development, by discussing the expected advantages and drawbacks of AVs, and by taking a glance at popular research topics concerning AVs. The aim of this broad introduction to AVs is to provide the necessary background information necessary to fully understand the extent to which AVs can impact the logistics industry. The next section then focuses on the results of this literature review by discussing the usage of AVs in logistics and the potential consequences thereof. More specifically, this section looks at applications of AVs in secure indoor and outdoor logistics settings as well as for long-haul trucking and to solve the last mile problem. The fourth section reflects on the state-of-the-art of AVs and related logistics research. The last section summarizes the most important conclusions.

2. Material and methods: a broad introduction to autonomous vehicles

This broad introduction of AVs to logistics is based on a search of publicly available publications and information. To that end Google Scholar, Web of Science, LIBISnet and the internet were searched for the terms “autonomous vehicles”, “driverless cars”, “driverless trucks”, “automated guided vehicle”, “platooning”, etc., often in combination with other terms specifying the intended focus such as “logistics”, “supply chain”, “scheduling”, “technology”, “liability”, “last mile”, “long-haul trucking”, etc. Naturally the references in the publications found through the aforementioned searches were consulted. We started our search from 2007. Earlier relevant publications are also incorporated whenever a recent publication from 2007 or later was not available.

In order to fully understand the potential impact of AVs on logistics during the upcoming years, it is important to have a general understanding of the development and potential effects of AVs. Therefore, we added the following topics to Appendices A, B, C and D respectively: the different levels of automation as defined by the US National Highway Traffic Safety Administration (NHTSA) (we will focus on levels 3 and 4), a timeline of the development of AVs, the advantages of AVs and the disadvantages of AVs for society at large.

As the idea of autonomous vehicles became ever more realistic over the years, a literature started to develop dealing with a wide range of issues regarding AVs. Most of these research areas have no direct link with logistics. However, when trying to understand how AVs could affect logistics and be implemented in practice, it is important to be aware of the research done in these different fields. Therefore we give a brief overview of the most popular research topics concerning AVs that can be of interest from a logistics point of view. As it is far beyond the scope of this paper to give a comprehensive overview of each of these fields of research, a short description is given together with some references for further reading.

2.1 Technology

The vast majority of research that has been carried out so far relates to the technological aspects of AVs. This should not be surprising as autonomous vehicle technology has only recently been partly commercialised and still mostly resides in the development and test phases. Note, however, that many automobiles that entered the market during recent years are already equipped with some automation features (Casey, 2014) such as Forward Collision Warning (Dagan, et al., 2004; Srinivasa, 2002), Adaptive Cruise Control (Vahidi & Eskandarian, 2003) and Lane Departure Warning (Lee, 2002).

When trying to understand the basic functioning of an AV, it is important to realise that there is no such thing as a single AV technology. Rather, the capability of an AV to drive itself comes from a set of hardware and complex software technologies that together make up the system enabling autonomy. As noted by Shanker et al. (2013) it is hard to get a complete overview of the state-of-the-art of AV technologies because different players are developing an AV using their own approach whilst not being very open about it, partly because of competitiveness concerns.

Generally speaking, however, AVs consist of four essential technologies that enable them to operate autonomously in the complex environment that is everyday traffic. These components are environment perception and modelling, localization and map building, path planning and decision-making, and motion control (Siegwart & Nourbakhsh, 2004). Simply put this comes down to an AV being able to gather data about its environment, interpret these data, use the interpretation to plan the best possible AVs actions, convert these plans into actionable commands and execute the actions (Anderson, et al., 2014). Anderson et al. (2014) also note that AVs need to be equipped with significant back-up systems that monitor the performance of the different components and are able to navigate to a safe parking space in the event that any of the primary units fails.

There are two broad approaches for achieving these capabilities (Shanker, et al., 2013). The first relies heavily on V2V and V2I communication systems. The idea is that the infrastructure tells the vehicle what its environment looks like, the car adds its own Light Detection And Ranging (LIDAR) observations of the surroundings of the car and compares this information with a map database to identify differences as obstacles to navigate around. The advantage of this system is the relatively low cost of the vehicle, while the downsides are a limited ability to react to sudden changes and the burden of having to install road infrastructure. The second system does not rely on input from the environment, but rather enables the car to fully perceive and analyse its environment. The downsides of this system are the higher vehicle cost, as the vehicle needs to be equipped with a suite of cameras, radars and sensors, and the greater sensitivity to weather conditions. The advantage is the ability to react more quickly to changes in the environment and a greater degree of independence of infrastructure. Silberg and Wallace (2012) note that convergence between both approaches would result in better safety, mobility, and self-driving capability than either approach could deliver on its own, and describes the path towards convergence. It is likely indeed that the eventual AV will be a combination of both described methods.

Shanker et al. (2013) give a very brief and accessible overview of the different hardware components and their role in an AV technology system (camera, radar, LIDAR, sensor, GPS/communication, human-machine interface, domain controller and motion control system). Trible et al. (2014), on the other hand, briefly discuss the challenges developers still face with regard to perception, machine intelligence and decision-making. Cheng (2011) provides an in-depth overview of the different approaches to the various components that make up the system enabling an AV to drive itself. Veres et al. (2011) made a systematic review of decision-making methodologies for AVs and Anderson et al. (2014) briefly summarise the current state of AV technologies with a special focus on telematics and communication, because, as they argue, AVs will need those technologies not only for V2I and V2V, but also in order to update maps and software, and provide infotainment to passengers.

2.2 Liability and legislation

The need for legislative change and the liability issue are often cited as the main obstacles to the widespread adoption of autonomous vehicles as both currently assume human drivers. Consequently quite a few AV related publications deal with these issues.

Smith (2012; 2013) discusses the legal aspects of AVs in the US and concludes that AVs are most likely legal as long as a driver is at all times able to take over control of the vehicle. There are, however, difficulties as certain specifications in state law assume a human driver. The consequences of this are not always clear. For example, legislation about following distance could hinder platooning. Khan et al. (2012) look at the implications of further automation levels and conclude that these would pose major challenges to legislation and argue that a policy framework should be created that regulates, amongst other things, technical standards, safety design standards, privacy issues and usage requirements.

In the EU, on the other hand, the Treaty of Rome requires that a driver is responsible at all times for a vehicle on public roads, which creates uncertainties regarding the usage of AVs that effectively hinder their adoption (van Dijke & van Schijndel, 2012). They also point to the lack of criteria for verifying whether a system is safe enough to be licensed.

As mentioned before several EU countries and US states are adopting legislation that allows the testing of AVs. Both in the EU and the US, however, automobiles that do not enable a driver to take control at all times are not allowed on public roads. Hence current regulation assuming that the drivers are always human could hinder the adoption of AVs even if they allow a human driver to take control and a broader legislative framework would need to be developed that regulates AVs beyond the test phase.

Besides, AVs come with a liability issue, as it is not very clear-cut who is to be held accountable in the event of an accident. Generally it is expected that liability will shift away from drivers to manufacturers as automation advances. However, before vehicles with automation Level 4 become common, many vehicles will be controlled in part by both the human driver and the automation system. LeValley (2013) argues that when a vehicle is under automation control, manufactures should be held accountable to the same high standards as common passenger carriers. Gurney (2013) brings a more nuanced view in which the manufacturer is held accountable for accidents caused in autonomic mode whilst liability could shift back to the driver depending on his nature and ability to prevent the accident. Manufacturers, however, could argue in their defence that AVs are not 100% flawless and that their fault should thus be evaluated in a comparative context taking into account the safety benefits of AVs as compared to human drivers as well as safety standards set by regulators (Marchant & Lindor, 2012). It is doubtful that this manufacturer's argument will be successful though and thus it is feared that liability will be an obstacle to the adoption of AVs as long as they have a significant rate of failure, because assuming the liability risk would be very costly to manufacturers. Similarly Kalra, Anderson and Wachs (2009) explain how current liability laws on design defects could hamper AV technologies, because of which manufacturers might wait before commercialising AVs despite their social benefits. Duffy and Hopkins (2013) therefore reason that owners should be held accountable much like other chattel that can act independently, because this would suit the dual purpose of fairly assessing liability without hampering the adoption of AVs. In order to facilitate the smooth adoption of AVs, legislators will thus have to clarify the uncertainties concerning AV liability in such a way that private interests are protected fairly without discouraging the introduction of AVs and their social benefits.

2.3 Ethics

It is often noted that the decisions taken by AVs in instances where a crash is unavoidable might be questioned in court. When having to choose between hitting a deer crossing the road, colliding with a car coming from the other direction or driving into a tree, human drivers are often not held accountable for the decision they have to take in a split second. AVs, however, can take more informed decisions given their computational power. What is more, this kind of ethical decision already has to be made when programming the car. Especially when it is a group of children there is no obvious answer and thus there is a debate on how to deal with this ethical aspect of developing AVs.

Goodall (2014) explains how driving involves constant risk assessments and thus the need to make decisions that are morally and legally ambiguous. He calls for more ethics research in AV decision systems and refutes nine criticisms of the need for this research. After this he gives a brief review of the relevant work in machine ethics and moral modeling based on two main challenges in developing ethically programmed AVs. The first is to express society's value choices in a variety of complex situations. The second is to program these morals into AVs.

Also Lin (2015) discusses why it is important to carefully consider ethics in designing AVs and stresses the need for more research, as this is a new field of research with a lot of questions that remain unanswered. To explain the issue at hand Lin (2015) points out how a targeting strategy that minimises harm, at first thought a sensible approach, is often unjust. Besides, it is not so obvious whose harm should be minimised. Should the car occupant be protected or other road users? Further he describes some scenarios explaining the complexity of the AV ethics debate.

Gerdes & Thornton (2015) give an introduction to ways in which ethical considerations could be translated into mathematical cost or constraints in an optimisation function that can be programmed in AVs. In doing so they discuss the method, advantages and disadvantages of an approach based on cost minimisation and rules enforcement. They also look at the implications of strict obedience to traffic laws and pose the question: to what degree should adherence to traffic law be programmed in AVs given the fluid application of traffic laws by human drivers.

In conclusion, there is a need for more transparency and care in making these ethical choices when developing AVs. They should not be made light-heartedly, nor should they be made by manufacturers alone. Rather, the wider society should be involved or at least be made aware of the ethical decisions AVs are programmed to make. Moreover, not giving enough attention to this issue before introducing AVs on public roads could imply a serious setback for autonomous vehicles in the event of an unfortunate accident, be it because of the liability of manufacturers or because of any consequent public hostility towards the technology.

2.4 Human factors

As mentioned before, it will most likely still take a while before fully autonomous Level 4 vehicles able to drive themselves anywhere will be widely available. Rather, vehicles that can drive themselves at a certain speed, under certain conditions and on certain roads will be introduced during the upcoming years. In other circumstances these vehicles will rely on a human driver taking control. As the automation system and the human driver will share the control over the vehicle, it is important to foresee the interaction between the human operator and AV. The body of AV-related human factors research studies this issue. Part of the safety risks discussion given in Section 2.4 already tackles this issue. This section adds to that discussion and thus does not repeat what has already been mentioned.

Merat et al. (2014) report on human factor studies carried out as part of the European CityMobil and UK's EASY project. Amongst other things they studied the degree to which drivers engaged in non-driving related activities, their reaction to critical events and their ability to regain control of the vehicle. They found that performance depends on the road environment, and that it was manageable for human drivers to resume control as long as their attention was devoted to the road. Performance capacity when taking manual control, however, diminished severely when drivers were engaged in secondary tasks. The report found that drivers take approximately 40 seconds to stabilize their gaze fixations and vehicle handling when regaining control. When the transfer of control was predictable and at a regular rate, however, performance levels increased. Merat et al. (2014) thus concluded that the biggest challenge for human factor researchers is to create a successful path for the transfer of control to the human driver with sensors that can predict when human intervention will be necessary and a system that is able to provide the driver with the right information at the right time to allow a smooth transfer of control. They also stress the need for research on how to keep drivers alert and allow them to engage safely in non-driving related activities.

Trimble et al. (2014) carry out a human factors assessment of driver behaviour and performance under automation Level 2 and 3. Part of this effort is a literature review that gives a good impression of AV-related human factor research. In doing so they give an overview of the key human factor challenges facing AV developers and usage. These include negative acclimatization of human drivers because of misunderstanding of, misuse of or overreliance on the automation system, as well as inappropriate distraction from the driving task. Also the impact of AVs on the information processing capabilities, situational awareness and level of workload of drivers is of concern.

The body of research concerning the human factors of AV driving is still fairly new, but very important to anyone interested in using AVs of automation Level 2 or 3 as the impact of this research on the design of autonomous vehicles will largely impact the degree to which drivers can engage in non-driving related activities.

3. Results: usage and consequences of autonomous vehicles in logistics

The broad perspective provided in the previous section gives insight into the wider context of the introduction of AVs, thus enabling us to better understand the potential usage, impact and hurdles of the introduction of autonomous vehicles in logistics. This section focuses on the significance of autonomous vehicles for logistics. As mentioned before, logistics is understood in this paper to be the systems set in place by organisations in order to systematically move goods between geographical locations.

As seen above, the literature concerning AVs concentrates on technical aspects, potential hurdles, benefits and costs of the introduction of AVs. What is more, the main focus has been on autonomous passenger cars, thus neglecting the significant segment of road transport that consists of the transportation of goods (Flämig, 2015). Consequently little attention has been paid so far to the introduction of AVs in logistics and the consequences thereof.

Notwithstanding the minimal research, there are several reasons why AVs might be adopted sooner in logistics than in passenger transport (Ghaffary, 2014; Stromberg, 2014). First of all, as recognized by DHL (2014), logistics often provides the ideal environment for AVs. Operating AVs in controlled settings such as warehouses, production plants or harbors, and remote outdoor locations is significantly easier than in the complex setting of urban traffic. Besides, in these settings the usage of AVs is subject to fewer laws and regulations. By using AVs in these environments logistics practitioners are in familiar territory and can gain experience with the usage of AVs, thus enabling them to adopt the technology faster in everyday traffic than consumers who are unfamiliar with the technology. Secondly, it is argued that the aforementioned liability issue would be less severe when transporting goods rather than people. Thirdly, businesses are more likely to base their decision on a potential cost advantage whereas consumers could be more receptive to trust and ethical issues.

What is more, as becomes clear throughout this section, the introduction of autonomous vehicles could have a tremendous impact on logistics as it is known today. Logistics operations in the entire supply chain, ranging from the extraction of raw materials and intermediate transport over the operations in warehouses, distribution centres and production plants, all the way to systems bridging the last mile, can be affected by the adoption of AVs thereby creating potential for new business models whilst ending the prospects of existing ones.

The potential usage of AVs in logistics can be roughly split into four segments (DHL, 2014). The remainder of this section gives an impression of the research done in each of these segments in turn. First, a brief review is given of the way AVs are used in indoor settings. Secondly, AVs are discussed in secure outdoor environments. Third, research on the potential of AVs for long-distance road freight is looked at. The last part of this section gives an overview of the work done on the prospects of AVs being able to bridge the last mile.

3.1 Autonomous vehicles in indoor logistics

Material handling is a crucial activity for many production and distribution sites. Various kinds of long autonomous vehicle are used in production plants, cross-docking stations, warehouses and distribution centres to increase the efficiency of material handling activities. These controlled, structured and thus relatively simple indoor logistics settings create the ideal environment for autonomous vehicles. Consequently the usage of AVs in indoor logistics settings is one of the most developed applications of AVs in practice, acquainting the logistics industry with AVs.

So far the term autonomous vehicle has been mostly used to refer to vehicles of automation Level 3 or 4 as defined by the NHTSA and given in Appendix A. In the indoor settings discussed in this section, however, the literature typically uses the term automated guided vehicle (AGV). AGVs are described as “autonomous vehicles widely used to transport materials between workstations in flexible manufacturing systems and perform a variety of tasks that involve automation in industrial environments” (Kalinovcic, et al., 2011; Vivaldini, et al., 2015). Autonomous vehicles need to be understood in this sense to mean all kinds of vehicles which do not require a human driver to move around.

As aforementioned, for a long time AGVs have been used in indoor logistics settings. Barrett Electronics Corporation brought the first AGV, and generally the first practical application of vehicle automation, to the market in 1954 (Lagorio-Chafkin, 2014; Scribner, 2014). The vehicle, first used in a grocery warehouse, slid along an overhead wire whilst pulling a trailer much like a tow motor. Some AGVs still use similar wire technology in which the vehicle follows radio waves transmitted by a wire in the ground. Building on this, AGVs were developed using guide tape technology in which coloured, reflective or magnetic tape is integrated into the infrastructure to guide the vehicles equipped with cameras, sensors or magnets in order to detect the tape (RoboteQ, 2015). Instead of tape other visual elements can be blended in the infrastructure in order to guide AGVs. The disadvantage of these AGV technologies using infrastructural elements to guide vehicles is their limited flexibility, as these AGVs can only be used on predefined paths. Besides, many of these AGV are not capable of moving around an unexpected obstacle on their path, thus being blocked until the obstacle is removed or a human operator takes control (Vivaldini, et al., 2015). More recently AGVs equipped with vision guidance technology have come onto the market. Much like the aforementioned AV technology, these AGVs use depth cameras, lasers and sensors to constantly monitor their environment, creating a 3D map used to navigate independently of preinstalled infrastructural elements (Möller, et al., 2012). This newest generation of AGVs is thus becoming truly autonomous and capable of navigating freely on every possible path in the indoor setting, enabling more applications than ever before. At the same time the acceptance of AGV in the industry seems to be at a tipping point with increased usage by large manufacturers and distributors (Lagorio-Chafkin, 2014).

The increasing popularity of AGVs in indoor logistics settings can be recognised by looking at the advantages they offer when compared to alternatives for use in material handling. These alternatives are human operators or conveyor belts, carousels and automated storage and retrieval systems (ASRS). Compared to human operators, AGVs can achieve efficiency, productivity and accuracy gains as well as increased safety (DHL, 2014). Compared to conveyors, carrousels and ASRS on the other hand, AGVs offer more flexibility when it comes to handling disparities in size, shape, weight, volume and mechanical properties of the goods. They also offer more flexibility in adapting to changes requiring a new site layout, eliminating burdensome retrofitting. AGVs also facilitate scalability in order to adapt to growth and cope with seasonal demand. Besides, because of the modularity of AGVs the system remains operative in the event of a breakdown or need for technical maintenance of one or even several AGVs. AGVs thus achieve a middle ground between human operators and fixed transporters by striking a balance between efficiency, scalability and flexibility (Huanga, et al., 2015). Despite these advantages and the scientific work described below, the penetration of AGVs is impaired by installation costs and the difficulty of taking full advantage of AGVs. The latter is in part due to the difficulty of developing a system that is sufficiently generic to be applied to a wide range of industrial problems (Vivaldini, et al., 2015).

In the remainder of this section the dispatching, scheduling and routing of AGVs is briefly discussed followed by an overview of some applications of AGVs.

3.1.1 Dispatching, scheduling and routing

In most indoor logistics settings several AGVs are operated at the same time and thus a group of AGVs is jointly responsible for executing a set of material handling tasks. Consequently some form of cooperation and control is needed. The term AGV System (AGVS) is used to refer to a set of AGVs operating concurrently and the system ensuring the coordination between the different AGVs. An AGVS needs to execute three important functions in order to perform its tasks. These are dispatching, scheduling and routing (Vivaldini, et al., 2013; Qiu, et al., 2002). This discussion of those functions owes much to the review of Vivaldini et al. (2015) concerning the issue at hand.

Vivaldini et al. (2015) identify the challenge of an AGVS as that of servicing all transportation demands in the correct sequence and in a timely manner, whilst adhering to certain constraints such as the total time of the route, starting time, path capacity, network layout, and priority of tasks and AGVs (e.g., because of battery constraints). As this requires a high degree of integration between dispatching, scheduling and routing, an AGVS needs a controller to perform these tasks (Vis, 2006). As written by Co & Tanchoco (1991) and Lavegin et al. (1996): “Dispatching is the process of selecting and assigning tasks to vehicles, Routing is the selection of the specific paths that each vehicle will execute to accomplish its transportation tasks, and Scheduling is the determination of the arrival and departure times of vehicles at each segment along their routes to ensure collision free travel.”

There are two types of dispatching: vehicle-initiated in which a load is assigned to a vehicle when the vehicle is ready for its next assignment and workcenter-initiated when a vehicle is assigned to a new transport request (De Koster, et al., 2004; Egbelu & Tanchoco, 1984). Generally the objectives of dispatching are minimization of load waiting time, maximization of the system throughput, minimization of queue length, and guarantee of a certain service level (Vivaldini, et al., 2015). The main approaches to solving the dispatching problem are dispatching rules (Hwang & Kim, 1998), meta-heuristics (Udhayakumar & Kumanan, 2010) and integer/mixed programming (Kasilingam, 1991).

The main goal of AGV scheduling is transporting as quickly as possible to meet time constraints, but minimization of the maximum load waiting time and maximum number of items in critical queues can also be considered (Le-Ahn, 2005). Scheduling consists of two key components. The first is predictive and determines the planned start and completion time of operations. The second is reactive and monitors execution and deals with unexpected events such as breakdowns, cancellations, data changes, etc. (Akturk & Yilmaz, 1996). Scheduling can happen offline or online. In the event of the former all data need to be available prior to a planning period and all tasks scheduled at once. In the event of the latter scheduling decisions are taken dynamically based on the current system state (Le-Ahn, 2005).

The AGV routing problem can be compared to the Vehicle Routing Problem, which is covered extensively in the literature as noted by Vivaldini et al. (2015). Algorithms solving the AGV routing problem can be divided into static and dynamic algorithms. Static algorithms solve the problem based on data available before the path execution. Dynamic algorithms, on the other hand, take real time information into account. Static systems thus need to be equipped with an additional system to avoid deadlocks and collisions.

Vivaldini et al. (2015) provide an overview of the state-of-the-art techniques used to solve the scheduling and routing problem for AGVs. They conclude that the scheduling and routing issues are often studied independently, whilst being closely interrelated in practice and that their integration is a challenging problem deserving more attention in the literature.

3.1.2 Applications of automated guided vehicles in indoor logistics

The AGV market has reached a point where a multitude of businesses are developing and producing all sorts of AGVs, each with their own functionality. This section presents some typical applications of AGVs in indoor logistics and gives examples.

A first group of AGVs is designed to simply horizontally transport goods from A to B. An automated towing vehicle for example can pull one or more trailers thus forming an automated train (see for example (Egemin Automation Inc., sd)). These AGVs are generally used to transport big volumes over a relatively large distance in a production or warehouse setting. Also automated unit load carriers are used to simply transport goods. Deck AGVs, for example, can have an array of deck-top appliances to carry and transport goods. Some Deck AGVs, such as the Karis Pro System (Karlsruher institut für technologie, 2014), can connect with each other to create a flexible conveyor system. This kind of AGV is generally used to transport high throughput goods between workstations or between a warehouse and production units. When these vehicles are also capable of automatically loading or unloading themselves or when other automated machines can perform these actions, the entire material handling process can be automated. AGVs also find applications in other settings. In an office environment, for example, AGVs are being used to drive mail around and in the medical or life science world AGVs such as the RoboCourier (Swisslog, 2015) are used to securely transport sensitive loads such as laboratory samples and medicines.

A second group of AGVs is capable to not only horizontally but also vertically transport goods. This generally allows them to autonomously load and unload from and onto heights such as racks, stands and conveyors. A typical example is a forklift AGV, which is amongst the most used AGV because it is so versatile. The ability of forklift AGVs to vertically move goods broadly widens the range of tasks that can be executed as it allows for storing and retrieving loads from multi-level storage racks. In addition, forklift AGVs are compatible with many conventional storage rack systems using pallet platforms (Dziwis, 2005). This kind of AGV can thus be used not only to simply transport goods but also to take care of other aspects of the material handling process. As an example DHL (2014) described how a single employee can handle the entire receiving area of a warehouse through coordinating a fleet of automated forklifts that pick up loads, drive to the storage location and put the load in the rack before returning to the receiving area. Baylo (2015) recently took a leap in overcoming adoption hurdles by introducing MOVEBOX, a kit converting regular electronic forklifts into self-driving vehicles. Similarly, un-palletized loads can be handled by clamp AGVs.

As already illustrated, this second group of AGVs is well suited for assisted put away applications. A related popular application of AGVs is assisted order picking. DHL (2014) describes a possible use case for manual order picking in which an assisting picking cart follows a human order picker through the racks of a warehouse. The order picker instructs the picking AGV through hand gestures. When the cart reaches full capacity it is sent to the drop-off location and replaced by another cart that can be ordered to join the human picker in advance. According to DHL (2014) this scenario results in a more ergonomic and more efficient picking process. More profound applications could induce far-reaching changes in the way warehouses are operated, as described by Huang et al. (2015). In a goods-to-person (G2P) setting, for example, employees can perform picking and possible packaging tasks at a fixed location, whilst AGVs bring the good to the human pickers, thus minimizing tedious and inefficient human movements. AGVs capable of performing this task are readily available on the market (Brockmann, 2014). A famous example is the Kiva system used by Amazon, which transports entire shelves to the human picker and is thus capable of handling goods of different shape and size. G2P systems using AGVs are scalable and combine the flexibility of human pickers with the efficiency of ASRSs. Huang et al. (2015) describe the layout and working cycle of the Kiva system in a G2P organisation. The material handling process can be automated further by replacing the human pickers with picking robots, thus creating a goods-to-robot (G2R) organisation. A robot-to-goods (R2G) organisation is a different solution that eliminates the need for picking stations when compared to G2P and G2R. A R2G system can be realised by letting AGVs carry an order picking robot, thus creating an Order Picking Robotic AGV (Bastian Solutions, sd). This solution combines the automation strength of a picking robot for picking the right object with an AGVS to autonomously complete the transportation tasks in a warehouse. Huang et al. (2015) further describe two innovative warehouse designs enabled by AGVs. The first is a robotic grid warehouse in which aisle space is eliminated and the second is cellular warehouse with AGVs capable of efficiently processing different types of goods.

In order to overcome the high investment hurdle of AGVs adoption, Huang et al. (2015) argue for a logistics automation service system business model in which stakeholders share risks and benefits whilst focusing on their core competences, thus meeting the capital needs of an AGVS. The business model comes down to AGVS being installed and maintained by a technology provider at low or no cost. In return the technology provider receives a part of the revenue generated by the logistics operator by using the AGVS.

3.2 Applications in controlled outdoor environments

As mentioned before, the existing technological advancements are aimed at bringing automated vehicles out of the security of controlled settings into the uncertain world of everyday traffic. A first step in doing so is applying AVs in private outdoor terrains such as harbours, airports and logistics courtyards. The usage of AVs in these controlled outdoor environments is the topic of this section.

Just as with indoor settings, these private outdoor environments are better suited for the usage of AVs than public roads because there is significantly less uncertainty, fewer regulations apply, the liability issue is not as complex and an efficiency-driven corporate logic applies. Consequently, as will become clear in this section, AVs of various kinds are already consistently used in practice to execute material handling tasks in harbours and logistics yards. According to DHL (2014) AVs are not really used yet at airports, but cargo transporters could be more effective when using vehicle automation technology.

In any case it is easily understood that material-handling performance is crucial for the competitiveness of harbours, airports and logistics yards. For one thing ships, airplanes and trucks only generate revenue when they are underway. Turnaround times thus need to be minimised. Secondly, goods cannot be used as long as they are being transported and thus their transportation needs to be completed as quickly as possible. Given the importance of these two metrics for the competitiveness of airports, harbours and logistics yards, it is not surprising that a similar automation process can be observed to that observed in indoor logistics (Vis, 2006). Airports seem to be lagging behind, as already mentioned, but in harbours automation is the most important development trend when it comes to transportation equipment (Carlo, et al., 2014). After all, the same advantages apply as in the indoor settings. Here too AVs can eliminate human error, are highly reliable and accurate in driving, allow the continuous monitoring of goods and vehicles, reduce vehicle wear and fuel consumption and reduce labour costs (Demuth, 2012).

As in indoor settings, the term AGV is often used for vehicles that can drive without a human operator in secure outdoor logistics arenas. Comparably, similar technologies and vehicles are used to those described in the previous section. In addition, however, as distances and loads are often larger in outdoor settings, autonomous trucks are used. An example of AGV usage in harbours can be found at the Container Terminal Altenwerder (CTA) in Hamburg harbour (OELCHECK GmbH, 2009). On the quay AGVs pick up or deliver containers that are loaded off or onto ships. A network of transponders embedded in the ground is used to guide the AGVs which travel up and down between the quay and intermediate storage areas. Here too, dispatching, scheduling and routing are essential and are in part managed by a central system coordinating the fleet of AGVs. The AGVs not only move forwards and backwards, but also sideways, making them extra agile. In a similar way AGVs are used in logistics yards. A German dairy producer, for example, uses automated trucks to drive up and down between its on site warehouse and production building (Demuth, 2012). The trucks drive at low speed (6km/h) with a driving precision of 2 cm. They use laser scanners to monitor their environment and rely on transponders embedded in the infrastructure to navigate.

Currently AGVs in secure outdoor settings mostly operate at low speed and on fixed paths, guided by infrastructural elements and by on-board cameras and lasers. The recent developments in vehicle automation technology described before enable AGVs in these outdoor settings to move faster and travel more freely, independent of infrastructural elements. Amongst other things, the usage of GPS guidance increases freedom of movement at the expense of more complex traffic management that has to avoid deadlocks, collisions and congestion (Carlo, et al., 2014). The SaLsA research project aims to develop AGV for secure outdoor environments that can drive freely at high speed even with human driven vehicles and pedestrians around (Kerner, sd). These AGVs build a model of their environment based on stationary and on board sensors, as well as mapping data and processing information. This model will project the possible movements of all objects in the environment, based on which the AGV can independently plan its path. This is precisely the technology used to bring AV onto public roads.

As in indoor settings, the main challenges in operating AGVs relate to dispatching, routing and scheduling. A significant body of research thus looks at these tasks. Carlo et al. (2014) created a comprehensive review of the literature concerning transport operations in container terminals. In their paper, a discussion of research on vehicle types, the number of required vehicles, dispatching and routing, collision and deadlock avoidance, and techniques to integrate these different decision problems can be found.

Looking beyond private outdoor terrains, an intermediate step between using AVs in secure outdoor environments and in everyday traffic, is using them on desolate public terrain. It should thus be no surprise that automated trucks are already heavily used in the mining industry. A famous case is the usage of autonomous trucks by Rio Tinto (Coyne, 2015). The company currently operates 53 autonomous trucks across four mine sites, having more than 4 million kilometres on its odometer, and is planning to extend its fleet to 150 autonomous trucks. According to Rio Tinto, using AVs reduced costs and increased efficiency, but it also enhanced health, safety and environmental performance.

3.3 Potential usage of autonomous vehicles for long-haul freight transport

The logistics use cases illustrating recent developments in vehicle automation technology looked at in the previous sections, i.e. in secure private indoor and outdoor settings, are mostly an extension of already existing applications. Indeed, AGVs have already been used for some time for material handling purposes in private and deserted areas. The usage of AVs for logistics purposes in everyday traffic, however, would be truly innovating. So far no AVs have been used or even allowed on public roads, except for small-scale technological test projects executed in recent years. This section looks at what is arguably the most obvious application of AVs on public roads for logistics operations (Shanker, et al., 2013), namely long-distance intercity freight transport, which mostly consists of trucking on highways.

Several autonomous truck projects have been developed over the years, mostly focusing on platooning (see section 3.2). Platoons are often referred to as road trains. They essentially are convoys of vehicles cooperatively driving together at very small distances from each other. The first vehicle takes the lead and the others just have to follow. For example the first European projects, PROMOTE CHAUFFEUR I & II, worked on the necessary technology (IST world, 2000), whereas the KONVOI project at the University of Aachen studied the impact as well as legal and economic implications of platooning (Lenk, et al., 2011). More recently the European Commission funded the SARTRE project that further developed and tested platooning systems (Chan, et al., 2012). In Japan the Energy ITS project has similar objectives (Tsugawa, 2012). A follow-up project funded by the European Commission and led by Scania will specifically study the logistics and back-office supporting functions for platooning (Scania Group, 2013). Last year also in the US an autonomous truck project was started. (Atherton, 2014)

There are some good reasons why AVs might first be used on public roads for long-haul trucking rather than for passenger transport or on smaller roads. First of all, because the benefits of not needing a driver are especially large in the road freight industry, as in the US driver wages and benefits account for more than 30% of the total shipping costs (Fender & Pierce, 2012). What is more, there seems to be a constant struggle to find enough drivers for the trucking industry (Walsh, 2013). Secondly, autonomous vehicle technology will most likely first be ready for driving on highways as this environment is much more predictable and less complex than, for example, city streets (Stromberg, 2014). Third, when platooning, fuel savings could reach almost 10% (National Renewable Energy Laboratory, 2015), an important figure as fuel costs account for more than 30% of total road freight costs (Fender & Pierce, 2012). Trucking companies can be expected to be especially responsive to these potential cost savings and are particularly able to realise these savings as they can organise their own platooning.

3.3.1 Assisted highway trucking

As is true for AV technology in general, it remains uncertain when fully autonomous trucks will be commercially available. With its Future Truck 2025 project, Mercedes-Benz committed itself to bringing an autonomous truck to the market by 2025 (Anon., 2014), and other producers made similar commitments. In the meantime several autonomous support systems are already present in today's trucks. Think for example of systems informing and alerting the driver to safe driving distances and activity in the vehicle's blind spots, emergency braking, lane keeping, etc.

Based on these automation features, DHL (2014) describes some assisted highway trucking scenarios that could impact the operations of road freight operators. In first instance DHL (2014) expects an assisted highway trucking system capable of autonomously safely driving a truck within its lane. The driver would be required to take over at any time to merge into traffic, overtake other vehicles and enter or leave the highway. In this first step the driver is only marginally relieved of their driving duties and can barely perform other actions. In a second more advanced scenario the assisted highway trucking system is capable of controlling the truck during most of the journey on the highway. The driver would thus be able to perform other tasks or relax. In a third assisted highway trucking scenario no driver is required to be present during the highway journey. A driver could thus bring the truck to the entrance of the highway and then leave the truck. The truck could drive non-stop on the highway until it has to leave the highway, where another driver waits to bring the truck to its final destination.

3.3.2 Platooning

The real revolution in long-haul trucking facilitated by vehicle automation technology, however, will most likely come in the form of platooning. Consequently, and as already mentioned, most research and test projects concerning automated highway trucking have focused on platooning.

Vehicle automation technology and V2V communication allow vehicles in platoons to travel much closer together than would be possible with human drivers. Essentially all vehicles in the platoon have to communicate constantly with each other so they can immediately mimic the actions of the previous vehicle in the platoon, whilst the first vehicle can adapt its actions and speed to the situation of the following vehicles. Bergenhem et al. (2012) provide a comprehensive review of different platooning systems and the existing platooning research.

In the first instance, platooning would allow the drivers of follower vehicles in a platoon to perform other tasks than driving or to relax (Bergenhem, et al., 2012). The driver in the first vehicle would have to be ready to take control of the vehicle at all times. Along the way different trucks could take the lead so there is no need to stop in order to let the drivers rest. In later stages no drivers would need to be present in the follower vehicles and possibly also not in the first vehicle.

Janssen et al. (2015) describe different ways to form platoons. In the first instance, when the penetration rate of platooning technology amongst trucks is rather low, platoons will have to be scheduled. Transport planners of road freight companies will have to plan the journeys of their trucks so that multiple trucks can travel together in a platoon. In addition, there is of course the potential of cooperating across company borders when scheduling platoons. In a later stage when platoon technology is more common, platoons could be formed ‘on-the-fly’. This means that trucks on the road could dynamically connect to form platoons when encountering each other on highways. Janssen et al. (2015) also foresee an opportunity for platoon service providers to come into existence. These would act as intermediaries between various transport companies so as to establish platoons. They would essentially function as control towers for platoon formation, guaranteeing the safety of trucks entering platoons.

3.3.3 Impact on logistics operations

Janssen et al. (2015) look into the potential impact of platooning on the supply chain operations and processes of road freight transporters. These effects are also partly induced by assisted highway trucking. First of all, carriers will have to take platoon formation into account when scheduling and routing the trips of their trucks, thus further complicating the optimal vehicle schedules and routes. Furthermore, in order, to fully benefit from platooning, it might be necessary to cooperate across company borders when scheduling and routing. Secondly, when drivers can perform other tasks when riding on highways, carriers could alter their operations so that the labour time of drivers sitting in their truck on highways is utilised. Drivers could, for example, engage in working on shipping documents, preparing their arrival, planning their next trip, etc., thus decentralising part of the administrative and planning work of carriers. Third, when trucks ride driverless on highways, but need to be dropped off and picked up by drivers at the beginning and the end of the highway, this will have a severe impact on the organisation of carriers who have to ensure the presence of drivers when and wherever required.

3.4 Autonomous vehicle solutions to bridge the last mile

The last part, the so-called ‘last mile’, of a supply chain or distribution network that needs to be traversed to reach local stores and customers is often the least efficient and most difficult part. This is because it often consists of smaller roads or urban environments where transport is slower, and because flows become more fractioned and loads thus smaller. Consequently, the last mile problem is a well-known topic in logistics research and a true challenge for logistics professionals.

This section takes the final step in bringing AVs out into everyday traffic, by looking at their potential to provide new solutions for bridging the last mile. In order to do so AVs of automation Level 4 are required, ones that are fully capable of driving themselves in the uncertain and complex world of urban traffic. This goes beyond the capabilities of the technology that is currently tested, and vehicle automation technology will thus have to mature further before the scenarios described in this section become possible. Consequently, this section is the most hypothetical, but it remains within the boundaries of what is expected to be technically feasible by the end of the next decade.

One of the often predicted effects of the introduction of Level 4 AVs is a significant change in car ownership structures through the introduction of advanced car sharing and mobility-on-demand systems in which passengers do not own a car, but rather summon one when needed. As already mentioned the implementation of such a system would bring additional efficiency gains as cars are typically parked during 95% of their lifetime (Shoup, 2005) and in the US less than 12% of privately owned cars are on the road during peak time (Silberg & Wallace, 2012). Consequently, the little research and simulations that exist concerning new urban transport models enabled by Level 4 AVs, focus on this new car ownership model. The International Transport Forum (2015), for example, estimates that in a mid-sized European city the same mobility can be achieved with 10% of today's cars when using an AV based car-sharing system.

Whilst some early publications look at this new car ownership model, literature about the new solutions for the last mile problem in logistics facilitated by AVs has yet to appear. However, some first conceptual ideas for bridging the last mile in logistics with AVs have been introduced. All of these would have a significant impact on the business model, operations and processes of retailers, e-commerce businesses and package delivery companies. In the remainder of this section these conceptual solutions are briefly presented.

Autonomous grocery shopping: A first model described by Sand (2015) relies on the aforementioned new car ownership model facilitating a system of mobility on demand. Sand (2015) portrays a system in which a customer places an online order for a supermarket or other retailer and orders an autonomous car to drive by the retailer to pick up the order. Meanwhile the retailer prepares the order so it can be loaded into the autonomous car as soon as it arrives. For traditional retailers this implies that many fewer customers will physically visit their store and thus the floor layout could be redesigned, creating a store adapted to serving autonomous vehicles picking up orders, much like a warehouse of an e-commerce retailer. Sand (2015) suggest that as a consequence traditional retailers such as supermarkets will grow in size and move to the outskirts of cities, essentially enhancing the direct competition with e-commerce retailers.

Home delivery logistics network: Also Kay (2013) predicts the end of all non-recreational shopping. He describes a home delivery logistics network in which goods are delivered to customers in reusable containers by driverless delivery vehicles, being small cargo-only AVs. The network consists of many small distribution centres (DC) such that an order can be sent from a store to the nearest DC after which it moves through the network of DC's again, to the DC that is closest to the customer, from which the order is delivered to the customer. The idea is that several orders can be combined when being transported by a driverless delivery vehicle through the network of DC's. As the empty containers would be shipped back from the customer to the nearest DC, they could also be used to ship items such as waste from the customer’s home to the DC. In order to be economically feasible, the small DC’s would need to be fully automated.

Autonomous parcels: DHL (2014) outlines an even more futuristic solution for the fully autonomous delivery of goods. In this scenario an autonomous truck could drop a group of parcel-sized autonomous vehicles off close to their destination. These small vehicles swarm out to nearby destinations and then, after delivering their orders, the vehicles can gather again in the autonomous truck to return to a DC.

Pack station based solutions: DHL (2014) further proposes two solutions based on pack stations that seem to be more feasible in the near future. The first solution is based on the belief that machine-to-pack handovers of packages is technically feasible today. Currently human delivery agents serve a network of pack stations at which customers can pick up or drop off their packages. In the future AVs equipped to load and unload pack stations could perform this task. The second pack station-based solution takes automation one step further as it entails self-driving repositories. In this case customers would not have to go to a pack station, but the pack station could come to the customer. This solution appears as the most feasible one in order to completely automate mobile deliveries.

Support vehicles for letter and parcel deliveries: the last AV-based solution for the last mile problem proposed by DHL (2014) will most likely be the first one to be implemented. The solution starts from the observation that a serious inefficiency in today’s letter and parcel delivery consists of long-distance walking occurring when the driver cannot find a parking spot close to the destination. This inefficiency could be resolved by AVs following the delivery agent during the delivery of several parcels in a single area. When the walking distance to the next destination becomes too great, the delivery agent will get into the vehicle and drive to the next destination, after which the AV follows the agent whilst delivering parcels within a walkable distance. When the AV is nearly empty, the agent can instruct another AV to join him with a new load of letters and parcels, while the first AV returns to the DC. This system could significantly increase the productivity of delivery agents in urban areas.

4. Reflection on autonomous vehicles and related logistics research

Based on the previous sections, this section reflects on the state-of-the-art of autonomous vehicles and related logistics research. Conclusions of special importance to scholars and logistics professionals are highlighted and suggestions for further logistics research concerning AVs are made.

Despite the scepticism evolving around the feasibility of the introduction of AVs in everyday traffic, most industry watchers and references consulted seem to agree that the question is not whether AVs will be available for mass consumption, but rather when they will be available. The technology necessary for introducing highly automated vehicles in everyday traffic already largely exists today, and the potential gains for both businesses and the society at large incentivise businesses and governments to compete for pole position amongst the early developers and adopters of AVs despite their drawbacks. With nearly all large automobile manufactures and other powerful companies as Google working on their AV and governments investing in research projects, it is unlikely that the development of AVs will come to an end. As a matter of fact, many vehicle automation features are already present in automobiles entering the market today and it can be expected that vehicles of automation Level 4 will be readily available by the end of the next decade.

However, in the race to develop a functional and commercially available AV of automation Level 3 and 4, it is vital not to neglect some serious threats to the development of AVs such as the safety and security risk, the privacy and ethics issue, and the human factors and liability challenges described in Section 2. This is important not only because failing to do so could cause a setback in the adoption of AVs, delaying the possibility of enjoying their benefits, but more importantly also because neglecting these issues could result in serious negative externalities of AVs for users and society at large. Given the urge for AV developers to take the lead in introducing AVs, it can be expected that they will not pay sufficient attention to the aforementioned threats. It will thus be up to legislators to ensure that the risks that come with AVs are sufficiently mitigated. Besides, users of vehicle automation technology, such as logistics professionals, have to be aware of these risks so as to be able to take them into account when adopting AVs.

As has been argued before, AVs are of special relevance for the logistics industry. Not only because logistics often provides ideal circumstances for becoming an early adopter of vehicle automation technologies, but also because the smart usage of AVs is likely to create a competitive advantage over competitors. This is both because the usage of AVs could result in significant cost reductions and efficiency gains, and also because they it result in new business models enhancing the customer experience. What is more, to make the most of AVs, businesses will in part have to revise their operations and possibly re-evaluate their entire supply chain.

Given the significant impact the adoption of AVs can be expected to have on best practices in the logistics industry, it is surprising to find how little logistics-related research exists concerning AVs that goes beyond the dispatching, scheduling and routing of AVs in secure indoor and outdoor environments. The limited work that has been done so far to analyse and test the potential impact and best usage of AVs in logistics is performed by practitioners and business analysts, and is largely unavailable in the public domain. Given the literature concerning AVs in logistics that is currently available, one can conclude that rigorous findings from scientifically sound research, R&D efforts and field studies are needed, as opposed to publications intended at commercial promotion, to optimally prepare the logistics industry for the adoption of AVs and to reduce the level of ignorance of the potential of AVs in logistics.

As mentioned before, the most common applications of AVs today can be found in indoor and secure outdoor logistics settings. Consequently, the existing logistics research regarding AVs concentrates on these settings. In particular, the focus is on the dispatching, scheduling and routing of AVs applied in these situations. Nevertheless more research would be beneficial. In particular, studies looking at different aspects of AV traffic management would be helpful, taking in such matters as dispatching, scheduling, routing, avoiding deadlocks and congestion, automated vehicle recharging and the required number of vehicles. Also research investigating new site layouts adapted to AVs and newly enabled warehouse designs would be beneficial in order to harvest the potential benefits of AVs in these secure logistics settings.

When it comes to the usage of automated trucks in long-haul trucking, most existing research focuses on platooning. However, the focus is rather on the platoon itself rather than on how platoons can be scheduled and what the effects of platooning would be on the scheduling and route planning of businesses. Additional questions arise about the impact of platooning on the overall supply chain of businesses. For example, as the costs of trucking reduce, it is not unreasonable to expect that the optimal amount of vehicles and the number of warehouses change. Besides, when drivers can perform other tasks while driving on highways or when trucks can ride driverless on highways, the operations of businesses involved in trucking might be affected further. Also the increased connectivity of automated trucks could impact planning processes and enable businesses to make their supply chain leaner. Academic research looking into these effects would not only be interesting, but could also greatly contribute to the effective adoption of AVs for long-haul trucking.

As noted in the previous section, the adoption of AVs could lead to the development of an array of new models to solve the last mile problem. So far several ideas for new solutions have been presented, but for virtually none of these are there publicly available detailed descriptions or simulations of their effects. Hence there is an overwhelming potential for researchers to develop these models further and to perform simulations and field tests. Here too questions arise on the impact of these models bridging the last mile on the overall operations and supply chains of businesses.

5. Conclusion

This paper presents the researcher and the logistics professional with a broad introduction to autonomous vehicles by evaluating the state-of-the art of autonomous vehicles and their potential consequences for the logistics industry. The aim is to provide clarity as to where the development of AVs and related research stands and what further research is needed to allow for the efficient adoption of the technology in the logistics industry. The baseline idea of this paper is that vehicle automation technology is rapidly developing and will be available soon, and that businesses in the logistics industry can develop a competitive advantage when effectively adopting this new technology.

The first part of this paper presents the general background knowledge of AVs needed to fully understand the state-of-the art of AVs and their potential for the logistics industry. To that end popular research topics regarding AVs that should be of special interest to scholars and logistics practitioners are represented. These research areas are vehicle automation technology, liability and legislative challenges, and the ethics and human factors challenges. Along with these topics, the following additional background is provided in the appendices: a definition of the different levels of automation and a timeline for the development of AVs, the expected benefits of AVs (increasing safety, efficiency and the comfort and productivity of drivers), and the drawbacks of AVs (increased total vehicle miles travelled, the threat to existing industries, safety and security risks and privacy issues).

The second part of this paper then focuses on the usage and potential consequences of AVs for the logistics industry. AVs are already commonly used in indoor and secure outdoor logistics settings and thus the applications of AVs in these environments are discussed first. When bringing AVs into everyday traffic the most obvious application in the logistics industry is long-haul freight transport and thus the next section discusses this application. Lastly, the potential solutions for the last mile problem facilitated by vehicle automation technology are looked at.

The third part of the paper highlights the conclusions of this paper that are of special importance to logistics scholars and professionals and it presents future research avenues that can contribute to the effective adoption of vehicle automation technologies by the logistics industry. The recent technological advancements in vehicle automation are bringing about the next big revolution in mobility and the transportation sector. The adoption of AVs holds the promise of completely innovating the way in which mobility and transportation logistics are dealt with. Despite the array of opportunities for the logistics industry to benefit from this new technology and for businesses to build logistics-based competitive advantages, little attention has been given to the potential consequences of AVs for the logistics industry. Many research opportunities can thus be explored to contribute to the effective adoption of autonomous vehicles in logistics.

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Appendix A: Levels of automation

The NHTSA defined five levels of vehicle automation in order to allow for clarity in discussing AVs. The definitions are based on the balance between vehicle and human control. The explanation of the definitions below is a shortened version of the definitions as provided by the NHTSA (2013). This study focuses on the potential impact of the introduction of automation Level 3 and 4. The levels are:

- *Level 0 – No automation:* The driver is in complete and sole control of the primary vehicle controls (brake, steering, throttle, and motive power) at all times, and is solely responsible for monitoring the motorway and for safe operations of all vehicle controls.
- *Level 1 – Function-specific automation:* Automation involves one or more specific control functions; if multiple functions are automated, they operate independently from each other. The driver has overall control, and is solely responsible for safe operation. The vehicle may have multiple capabilities combining individual driver support and crash avoidance technologies, but does not replace driver vigilance and does not assume driving responsibility from the driver.
- *Level 2 – Combined vehicle automation:* This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. Vehicles at this level of automation can utilize shared authority when the driver cedes active primary control in certain limited driving situations. The driver is still responsible for monitoring the roadway and safe operation and is expected to be available for control at all times and at short notice.
- *Level 3 – Limited self-driving automation:* Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time.
- *Level 4 – Full self-driving automation:* The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates

that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.

Appendix B: A timeline of autonomous vehicle development

AVs might seem to be a new development, but the idea has been around for decades. Already in 1939 General Motors presented some sort of AV at the New York World Fair in the form of automobile guidance with electrical conductors inserted in the road (Vanderbilt, 2012). Ever since universities, businesses and governments have invested in AV projects. In 1977 for example the first autonomous vehicle able to process images of the road ahead was displayed by S. Tsugawa at Japan's Tsukuba Mechanical Engineering Laboratory, and from 1987 until 1995 the European Commission funded the EUREKA Prometheus Project on autonomous vehicles (Shanker, et al., 2013). These are two examples of what Anderson et al. (2014) identified as the first phase in the development of AVs, lasting from approximately 1980 until 2003. During this foundational research phase researchers tried on the one hand to develop automated highway systems in which vehicles relied heavily on infrastructure and on the other hand worked on truly autonomous vehicles independent of infrastructure.

The turning point in the development of AV technology, leading to the recent breakthrough, was the Grand Challenges organised by the US Defense Department's Defense Advanced Research Project Agency (DARPA), identified by Anderson et al. (2014) as the second phase ranging from 2003 until 2007. In 2004 and 2005 participating autonomous vehicles needed to complete a 150-mile off road race. The progress made between both challenges was enormous, as the best participant in the 2004 challenge drove not even eight miles whilst in 2005 five teams made it to the finish (Urmson, et al., 2004; Urmson, et al., 2006). In 2007 the "Urban Course" completed the series of DARPA AV challenges by asking participating teams to design an AV capable of completing a 60-mile urban track obeying traffic laws and navigating between other vehicles. Six teams completed this course (Buehler, et al., 2008). The DARPA challenges initially intended to boost the development of AV technology for military purposes, but civilian applications followed swiftly. The Grand Challenges got many players in today's AV market interested in the technology, and many members of participating teams are today involved in the AV development of these players (Shanker, et al., 2013).

The third, and for now, last phase in the development of AVs identified by Anderson et al. (2014) is commercial development. The beginning of this phase is marked by the start of Google's driverless car project. What is arguably the most well-known AV project started with Google hiring the head of the team winning the second DARPA challenge (Markoff, 2010). Ever since companies, among them many that are traditionally not active in the automobile industry, such as Google, Cisco and IBM, but also Baidu and possibly Apple, have been announcing AV projects. The entrance of these new players threatens to disrupt the automobile industry and traditional manufacturers have not hesitated to respond.

Almost all big automobile manufacturers have declared themselves to be working on an AV, among them Audi, VW, Mercedes-Benz, BMW, Ford, GM, Nissan, Toyota, Volvo, Renault, Daimler and Tesla. Interesting from a logistics point of view is the fact that, amongst others, Volvo and Mercedes-Benz are not only working on autonomous cars, but also on autonomous trucks. The race to present the first fully operative AV ready for mass consumption has clearly begun.

Several countries have joined the competition for heading the development of AVs, on the one hand by sponsoring research and test projects and on the other hand by adopting legislation aimed at creating an environment in which the development of AVs can thrive. As early as 2012, Shladover (2012a; 2012b) provided an overview of activities in Europe and Asia with regards to cooperative vehicle–highway automation systems, and made a comparison with activities in the US. More recently Trimble et al. (2014) have made a partial update of this review by looking at AV projects in Europe and Asia. These reviews discuss projects supported by the European Commission and the governments of the United Kingdom, the Netherlands, France, Germany, Italy, Japan and South Korea. In the US the DARPA challenges are an obvious example and more recently several states have passed legislation to allow for AV testing (Anderson, et al., 2014). Besides, several governments have explicitly expressed their ambition to be at the forefront of the development and adoption of AVs. The UK, for example, has published a report evaluating the UK's legislative framework for AV testing as compared to other European and Asian countries and the US (Department for Transport, 2015). Furthermore, Godsmark et al. (2015) assess the potential impact of AVs for Canada and propose action for Canada to catch up and prepare for the introduction of AVs. Also the Belgian government has expressed its willingness to allow AV tests (Haeck, 2014; Moens, 2014) after recognising the risk of lagging behind relative to surrounding countries such as the Netherlands (Anon., 2014).

Looking towards the future, several timelines for adoption have been published. Shanker et al. (2013) present four phases (not to be confused with the aforementioned levels of automation) of which the first, Passive Autonomous Driving 2012 – 2016, is mostly completed. In this phase autonomous capacity is meant to correct rather than control. Technology needed for this phase (adaptive cruise control, crash sensing, lane departure warning, etc.) is present in many models currently on the market. The second phase, Limited Driver Substitution 2015 – 2019, still assumes the driver as the primary operator, but the vehicle can take over some tasks, for example parking. Increasingly features needed for this phase are installed in vehicles entering the market today. In the Complete Autonomous Capability 2018 – 2022 phase, the vehicle is able to drive itself, but a person is assumed to be present in the driving seat to react in the event of an emergency. These are the vehicles being tested and developed today. The last phase, identified by Shanker et al. (2013), is more speculative and assumes 100% penetration of AV technology after 2030. Trimble et al. (2014) discuss several other timelines that have been published, all of which follow more or less the same pattern with vehicles of automation Level 3 and 4 being available for consumption between 2017 and 2025, and a penetration rate shortly after 2030 that allows capitalizing on most AV benefits.

Appendix C: Expected benefits of autonomous vehicles

Many companies and governments are only investing in developing AVs because the stakes are so high. The potential gains stemming from the introduction of AVs largely result from the potential to reduce the impact of many of the adverse effects of today's automobiles. Shanker et al. (2013) made a rough estimate predicting that the full adoption of AVs could save the US economy $1.3 trillion per year. This amounts to $5.6 trillion savings per year globally when assuming the same savings over GDP ratio, which is an oversimplifying assumption of course. It must be noted that this estimation only includes cost savings and does not take value created by e.g. manufactures into account. On the other hand offsetting losses and the cost of AVs are not accounted for. However, the cost drivers resulting in this estimate are similar to the benefits of AVs that are often cited, and are briefly listed below. A more detailed discussion of several of these effects is given by Anderson et al. (2014), by Eugensson, et al. (2013) and in the compilation edited by Meyer & Beiker (2014).

Where **safety** is concerned, according to the World Health Organization (2013) 1.24 million road traffic deaths occur annually, with traffic fatalities being the number one cause of death for those aged between 15 and 29, and many more are injured. On its website the European Commission's Directorate General Mobility and Transport reports more than 30,000 deaths on the EU's roads in 2011. The number of permanently disabling injuries, serious injuries and minor injuries are respectively four, eight and 50 times higher. The total cost of road accidents is estimated to reach on average 2.5% of a country's GNP (Elvik, 2000). What is more, according to Maddox (2012) 93% of crashes can be attributed to human error, whether or not caused by driving under the influence (of drink or drugs). Recognition errors would account for 41% of crashes (inattention, internal and external distractions, inadequate surveillance, etc.), 34% are decision errors (driving aggressively, speeding, etc.) and 10% are performance errors (National Highway Traffic Safety Administration , 2008). It is mostly accepted that AVs would eliminate most of today's causes for accidents and largely reduce the number of road crashes, especially as the adoption rate increases and humans take less control of their AV. Designing a system that is safe in nearly every situation is, of course, a very complex challenge (Campbell, et al., 2010), but the end goal of virtually crash-less cars is deemed feasible (Maddox, 2012; Silberg & Wallace, 2012; Underwood, 2014). There is already proof of the safety effect of automation features present in today's cars and full automation is the next step in eliminating road fatalities (Dang, 2007). Hayes (2011) predicts that road fatality rates will approach those seen in rail and aviation, i.e. 1% of today's rate.

The full adoption of AVs would result in **efficiency gain**s in many different ways. The safety effects described above could eventually result in the redundancy of many of the safety features included in the design of today’s cars (Silberg & Wallace, 2012). For example air bags, roll cages and weighty amounts of steel might no longer be needed. Also services resulting from today’s accidents could become redundant. Think for example of the large market for car insurance, traffic police, vehicle repair shops and medical care for crash victims. The reduction in traffic accidents could also significantly reduce congestion as it is estimated that 25% of congestion is caused by travel incidents, approximately half of which are crashes (Federal Highway Administration, 2005). AVs could lead to further congestion reductions because of increased vehicle throughput caused by their optimised driving compared to human driving, as explained by Anderson et al. (2014). Not only are AVs able to react faster, they can also match their behaviour more effectively to their environment when equipped with Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication systems, leading to synchronised braking and accelerating as well as smarter routing. This enables them to drive safely at higher speed and with reduced space between vehicles (Tientrakool, et al., 2011). According to Fernandez & Nunes (2012) platooning could increase lane capacity by up to 500%. Platoons are often referred to as road trains. They essentially are convoys of vehicles cooperatively driving together at very small distances from each other. The first vehicle takes the lead and the others just have to follow. In congested circumstances AVs could avoid inefficient start and stop conditions (Sorensen, et al., 2008) thus avoiding traffic-destabilizing shockwave propagation (Fagnant & Kockelman, 2013). The degree of these efficiency gains very much depends on the AV adoption rate of course. Shladover et al. (2012), for example, estimate that a 10%, 50% and 90% penetration rate of cooperative adaptive cruise control would induce a lane capacity increase by around 1%, 21% and 80% respectively. AVs would also allow for smarter traffic management, reducing for example waiting time at intersections and optimizing the speed with which intersections are approached (Li, et al., 2013). Another factor influencing the effect on congestion is the impact of AVs on vehicle miles travelled. The net effect of this is uncertain as there are positive and negative effects as discussed by Anderson et al (2014). Besides, reduced congestion, optimized driving, lighter vehicles and smart traffic management are all factors that imply increased energy efficiency. Platooning would allow for up to 15% fuel savings (Bullis, 2011). For aggressive drivers optimized driving could potentially save 20% - 30 % fuel (Gonder, et al., 2012), whilst this saving goes up to 15% for nonaggressive drivers (Brown, et al., 2014). Also according to Brown et al. (2014) lighter vehicles and the optimized design allowed by AV technology could allow for as much as 50% energy savings. As these examples show, the introduction of AVs will imply significant energy efficiency gains. However, the net effect on fuel usage is uncertain as, for example, faster driving and an increase in vehicle usage will increase consumption of fuel. Another efficiency effect of increased lane capacity and improved driving relates to infrastructure. As noted by Silberg & Wallace (2012) today’s roads are designed for human drivers and their imperfections. Extra-wide lanes, guardrails, stop signs, wide shoulders, rumble strips and other safety infrastructure could become redundant. AVs could also have surprising effects with regards to parking space. Shoup (2005) found that as much as one third of land in many major city centers is devoted to parking. Level 4 AVs would be able to drop their passengers off in the center then to drive to a more remote parking lot, thus allowing reallocating significant amounts of land in city centers. It is often recognized that Level 4 AVs could significantly change car ownership structures through the introduction of advanced car sharing and mobility on demand systems in which passengers do not own a car, but rather summon one when needed. Much like taxis now, but with the advantage of not having to pay for a human driver. The implementation of such a system would bring additional efficiency gains as cars are typically parked during 95% of their lifetime (Shoup, 2005) and in the US less than 12% of privately owned cars are on the road during peak time (Silberg & Wallace, 2012). The International Transport Forum (2015) estimates that in a mid-sized European city the same mobility can be derived with 10% of today's cars when using an AV based car-sharing system.

The full adoption of AVs will also result in more **comfort and productivity for passengers**. On average approximately 80% of the US work force spends 50 minutes in an automobile commuting per workday (2012). The total time spent in automobiles is of course much larger; Americans spend on average 75 billion hours per year on the road (Shanker, et al., 2013). With the introduction of Level 4 AVs this time could be used more productively. Be it to work, relax, eat, sleep, converse or however people choose to use their time, the potential time gain is enormous - especially considering how stressful the daily driving experience is for many people (Eden, 2002). In freight transport additional productivity could be gained as AVs do not need to rest and time limitations placed on driving could be removed. This would allow trucks to travel 24/7 with the potential of achieving cost reductions approximating 40% per kilometre (Bonnet & Fritz, 2000). Besides, Level 4 AVs could greatly impact the mobility of those unable to drive (Anderson, et al., 2014). Be it for children, the elderly, disabled or even the intoxicated, autonomous vehicles could make a big difference in terms of independence and quality of life.

Appendix D: Drawbacks of autonomous vehicles

Despite their benefits AVs come with some serious drawbacks. We list the most important ones.

As noted by Anderson et al. (2014), there is a chance that AVs will **increase the total vehicle miles travelled** which will at least partly reduce the net benefit AVs bring in terms of fuel use and congestion. Especially in the transition period in which many human driven cars are still on the roads, this increase in vehicle miles travelled could even induce a net increase in congestion and fuel use. Besides, by making road travel more comfortable, AVs could lead to increased suburban sprawl as the opportunity cost of commuting would reduce. Similarly public transport would be put at a disadvantage, amongst other things harming those who cannot benefit from the advantages of AVs (Arieff, 2013).

Anderson et al. (2014) also point out that there is another side to the coin where many AV benefits are concerned, as they **threaten industries and the corresponding jobs**. With increased safety automobile insurance could largely become redundant, just like other beneficiaries of the “crash economy” such as vehicle repair shops, doctors and lawyers. Also, as described above, AV car sharing systems could significantly reduce the number of cars needed to serve mobility demand, potentially harming car manufacturers in the long run. Probably more worrying in the eyes of the general public is the fact that every automation exercise directly takes over a function previously performed by humans (Hern, 2014; Kanter, 2015; Rutherford, 2015). In the case of AVs many jobs in the transportation industry could disappear. Taxi, truck and bus drivers might no longer be needed.

Concerning another matter, technology always comes with a general **safety risk** of system failures and design flaws, as regularly illustrated by the bugs being detected in software or the large recalls occurring in the car industry (for a recent example see Ivory & Tabuchi (2015)). One could reasonably assume that this will not be different for AVs. As noted by Cummings & Ryan (2014), it might not even be enough for the fatality rate of AVs to be significantly lower than that of human drivers as even the smallest chance of a machine killing a human will not be easily accepted by the public. An ill-timed fatal accident could thus result in a public rejection of the technology, preventing automation from advancing for years to come. Cummings & Ryan (2014) also point to the risks that come with the shared authority between vehicle and human in Level 2 and 3 of automation. When sitting behind the driving wheel of a highly automated car, human drivers are less attentive, easily distracted, and slower to recognise and react to critical situations (Jamson, et al., 2013; Neubauer, et al., 2012; Rudin-Brown & Parker, 2004; Saxby, et al., 2007; Vollrath, et al., 2011; Young & Stanton, 2007). Besides, when drivers perceive the automation technology as reliable, they fail to utilise their own skills, resulting in skill degradation and consequently they end up relying even more on technology (Lee & Moray, 1994; Parasuraman, et al., 2000). Then at precisely the moment when the automation might need assistance, the driver is not able to provide it. Cummings & Ryan (2014) stress the importance of taking these issues into account in test settings for as long as Level 4 automation has not been reached.

AVs also come with a **security risk**. The FBI (2014) has released a report in which it states that automation will make a car “more of a potential lethal weapon than it is today”. The security risk goes beyond the direct malicious use one could make of an AV. As AVs will be highly computerised and connected through V2V and V2I communication systems, they are vulnerable to cyberattacks. Malicious hackers could take control of a car, or worse, an entire fleet and transport infrastructure with the intention of disabling the transportation system or causing crashes. In the same way the security of, for example, GPS has been questioned (Humphreys, et al., 2008) and attacks have already occurred on both military and civilian applications (Franceschi-Bicchiera, 2012; Marks, 2012; Waterman, 2012). Fagnant & Kockelman (2013), however, note that nations have generally been able to protect critical national infrastructure systems such as power grids and air traffic control systems from cyberattacks. They further point out that unlike, for example, personal computers, AVs have been developed with incorporated security measures since the initial development phase, making them more robust. In any case cyber security should be a top priority in the development of AVs (Moore-Colyer, 2014).

AVs also create a **privacy issue** (Glancy, 2012), as they will involve the gathering, storing and sharing of usage data. These data can be very useful in streamlining traffic, improving vehicle technology and analysing crashes, but recorded travel patterns could also be used to track individuals for commercial or other purposes. The extent to which data can be used or privacy should be protected is a trade-off that needs to be made by society. Legislators should clearly regulate the storage and usage of these data before the widespread adoption of AVs so as to protect consumers and avoid consequences seen on the Internet today. Even if well regulated, AVs still pose a privacy threat as the aforementioned cyberattacks could also be targeted at stealing data.

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