Benefits and Costs of shared, modular automated Vehicles for Freight and Passenger Transport: The Case of U-Shift

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Benefits and Costs of shared, modular automated Vehicles for Freight and Passenger Transport: The Case of U-Shift

This study analyses the costs and benefits of fully automated vehicles, operated as part of a ride-sharing system and it compares two alternative technological solutions. For the first solution, automated driving is enabled by hardware and software fully incorporated in the vehicle. For the second solution, automated driving of vehicles is supported by 'smart roads' and vehicle movements are coordinated by a central traffic management centre. The study conducts a cost-benefit analysis of these options and a Base Case. The results demonstrate the economic viability of both technological alternatives and show that benefits from improvements in road safety, air pollution and CO_2 emissions outweigh costs. The results further demonstrate that the infrastructure-based automation approach is a more cost-efficient way to enable full automation of driving, compared to the current industry-driven approach which is based on vehicles where automated driving tasks are not supported by the road infrastructure.

Keywords: automated vehicles, on-demand mobility, smart roads, road safety, CO_2 emissions, cost-benefit analysis, U-Shift

1 Introduction

To enable automated driving of vehicles, the German Aerospace Center (DLR) is researching a solution where the vehicles' automation tasks are supported by 'smart roads'. In this case, most sensor technologies and software are embedded in the road infrastructure, rather than the vehicles themselves. In addition to cost efficiencies, this allows to optimize traffic flows through centralized trip scheduling and route planning. This approach is referred to as "Managed Automated Driving" (MAD) in the remainder of this study. In contrast, the industry's approach is to develop 'autonomous vehicles' in the literal sense, operating independently of the conditions of the road infrastructure and environment ("Automated Driving", AD). While the focus of previous studies was mainly on the latter (see for example Andersson and Ivehammar 2019; Infrastructure Victoria 2018; BITRE 2017), this study undertakes a cost-benefit analysis (CBA) of both technological solutions and compares them to a Base Case, reflecting a moderate progress of vehicle technology.

DLR researches the two technological options MAD and AD as part of the vehicle concept *U-Shift*, a modular, automated vehicle for goods and passenger mobility. This CBA is conducted for a future implementation scenario 'Vision 2040' under which *U-Shift* vehicles are rolled-out large-scale in the urban area of Stuttgart (Germany) as part of an on-demand sharing system to provide goods and passenger mobility.

2 Technological Features of *U-Shift* and Managed Automated Driving (MAD)

The vehicle concept *U-Shift*, developed at DLR (Friedrich, Ulrich, and Schmid 2019; Ulrich et al., "Technologies for a modular vehicle concept," 2019), is a modular vehicle at driving automation level 4 as defined by SAE (2018)[1]. The vehicle is modular as it consists of a ‘self-driving’, electrically powered rolling chassis (‘Driveboard’) and an interchangeable vehicle body. The modularity allows to separate the Driveboard from the vehicle body; quickly and without an external device. For example, *U-Shift* can be equipped with a people-mover body (see Figure 1) to provide ride-sharing service, offering seats for nine passengers and including a wheelchair area. For freight tasks, cargo bodies with up to 1.6 tonne payload can be mounted.

Figure 1 *U-Shift Driveboard*, cargo and people-mover bodies. Source: DLR-FK, CC-BY 3.0

The Driveboard (chassis) is designed to be durable. It is equipped with sensors and software for automated driving, therefore expensive. It can operate 24/7 as part of a Driveboard-sharing system, picking up vehicle bodies from customers as needed. The

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[1] This study uses taxonomy defined by the Society of Automobile Engineers (SAE 2018). Following SAE (2018) definition of level 4 automation, the human is not required under any condition to drive the vehicle or to take over driving, while the Automated driving feature is conducting the driving task. These, however, are not operating under all conditions (e.g. only within a geographically-defined area).

modularity of *U-Shift* allows sharing, even among passenger and freight sector agents, and therefore it is a cost-efficient solution. An additional advantage of the modular approach is that it ensures maximum flexibility with regards to the design of vehicle bodies. It can be designed low-cost (as no automation technology is needed), but tailored to a variety of user requirements. For example, a simple, cheap metal construction may be sufficient for non-perishable goods, while a reefer configuration may be needed for hauling temperature-sensitive goods.

U-Shift is similar to vehicle concepts researched by the automotive industry (such as Schaeffler Mover from Schaeffler, Vision Urbanetic from Mercedes-Benz or NXT Concept from Scania), but presents some major differences. For example, while *metroSNAP* from Rinspeed also offers a modular solution, it requires an external device for swapping the vehicle bodies. Toyota’s *e-Palette* is designed for different use cases similar to *U-Shift*, but is not a modular vehicle.

To enable automated driving of *U-Shift*, two technological options are investigated at DLR. Firstly, Managed Automated Driving (MAD), which requires sensors and software embedded in the road infrastructure, while the vehicle contains a minimum level of automation components. This is our preferred approach for *U-Shift* deployment. Secondly, Automated Driving (AD), in which *U-Shift* is fully equipped with sensors and software. AD is comparable to the approach pursued by industry, such as Waymo’s Automated Driving System. The components required as part of MAD and AD respectively are illustrated in Table 11.

Table 1 *U-Shift* driving automation technology: list of hardware and software

Item	Managed Automated Driving – MAD	Automated Driving – AD
Vehicle	2 on-board unit GPS Odometry- and steering angle sensor	V2X on-board unit DGPS + inertial measurement unit Odometry- and steering angle sensors 3 cameras 4 lidars 6 radars
Road	2 stereo cameras (depth camera) Backend, software, Wifi / 5G antenna/ fibre optic	

Source: own analysis

MAD is based on a connected and automated vehicle (CAV) system, where road vehicles are able to communicate with each other and with road-side infrastructure (EC 2019). This connectivity allows sharing of sensor data among vehicles and infrastructure, which, in combination, enable the automated driving task. The advantage of this approach is that sensor occlusion caused by other traffic participants is mitigated and that the vehicle has access to a larger field of view, compared to the more commonly used in-vehicle perception systems. By having full sensing access before entering a traffic scene, the automated vehicle can behave less restrictive and conservative compared to in-vehicle based automation. It also collects temporal and spatial data on planned trips and real-time traffic information. With a central traffic management centre in place, this information can be used to optimize signalling and to plan the movements of vehicles, e.g. through determining their routes and speeds.

The computational complexity of MAD is high, especially for object and environment sensing (which enables the automated driving task) and, to a lesser extent, for traffic management tasks. Initial solutions for infrastructure-based sensing exist and have been tested (e.g. Fleck et al. 2018, 2020), but need to be improved in terms of cost, quality, standardization, latency, robustness and power consumption, to be widely applicable. A major point of criticism of the concept MAD is the need for direct radio signalling between infrastructure and automated vehicles which is of major interest regarding safety and availability considerations.[2]

3 CBA Scenarios

To ensure cost-efficient operation and sustainable transport outcomes of *U-Shift* deployment, DLR identified and assessed a range of suitable use cases (see e.g. Ulrich et al., “New Operating Strategies,” 2019), among these *Vision 2040*. This scenario was developed to reflect large-scale implementation in 2040 in Stuttgart (Germany) as part of a feasibility study undertaken in 2020 (Grünhäuser et al. 2020). Under this vision, all urban truck and van movements will be replaced by *U-Shift*. During peak hours, *U-Shift* provides ride-sharing services for passengers. This service is designed to disincentivise car usage and to improve the attractiveness of existing public transport services, for example through the provision of feeder services.

The two distinct technological options MAD and AD are assessed as part of Vision 2040 and compared to a Base Case as summarised in Table 2.

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[2] However, this problem is not unique to MAD. High precision GNSS/GPS positioning systems to enable AD can be blocked by a scammer device, camera sensors might be blinded by a malicious attacker or interferences in radar and lidar data may be provoked by using retroreflective materials. These circumstances may be addressed partially by introducing regulations as currently seen in the GNSS/GPS case, where scamming devices are forbidden by law and high implementation and testing standards in line with critical infrastructure.

Table 2 Description of CBA scenarios

	Vision 2040 – MAD	**Vision 2040 – AD**	**Base Case**
Transport tasks of *U-Shift*	Movement of goods are undertaken by *U-Shift*. During peak hours, *U-Shift* is used for ride-sharing services.	As Vision 2040 – MAD.	*U-Shift* vehicles are not implemented.
Trip planning and traffic management	*U-Shift* trip scheduling, routing and driving are centrally coordinated by a Traffic Management Centre to optimize transport system outcomes.	No change compared to *status quo.*	No change compared to *status quo.*
Technology features	Automated driving of vehicles is enabled by sensor technology and software predominantly incorporated in the road infrastructure.	Automated driving is enabled by sensor technology embedded in *U-Shift* vehicles.	Electrified powertrains gradually replace combustion engines and vehicles will increasingly feature driver assistance and safety systems.
Geographic scope	Stuttgart	Stuttgart	Stuttgart

In line with common practice, the Base Case reflects a ‘without-case’ where no implementation of the technology is assumed. This scenario is characterized by the main features of the current transport system, but reflects plausible technological advances by 2040 (see Table 2).

For the purpose of this CBA, *Vision 2040* scenarios are applied to the setting and conditions in Stuttgart, the Capital city of Baden-Württemberg in Germany’s South West (Figure 22) with 604,000 inhabitants (Statistisches Amt der Landeshauptstadt Stuttgart 2021) and a strong automotive and mechanical industry.

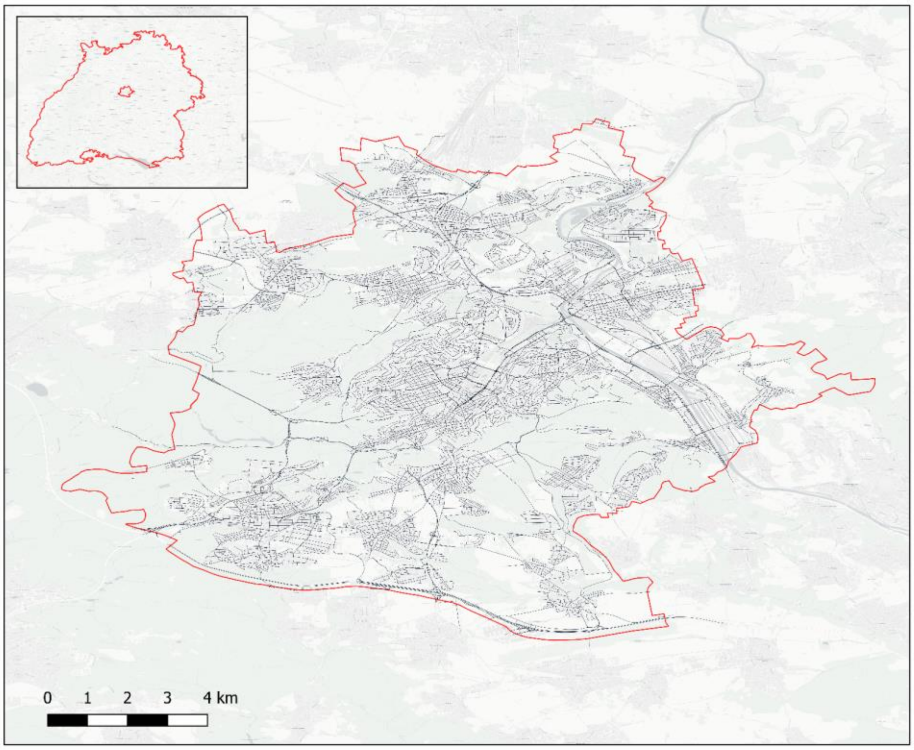

Figure 2 Case study city: Stuttgart (main image); Baden-Württemberg (top left). Source: own elaboration

The mobility system in Stuttgart is typical of a German city, with an overall dominance of private vehicle use (for people and goods transport) and a comprehensive heavy and light rail and bus network. However, the mode share of cycling (in terms of trips) is lower (7%) compared to all other German cities with a population of 500,000 or more (which averages 16%, including Stuttgart) (Nobis 2019).

4 Method

The impacts of the implementation of *U-Shift* as part of a vehicle sharing and ride-pooling system is analysed via a cost-benefit analysis (CBA). The CBA quantifies the capital expenditures (CAPEX) and operational expenses (OPEX) of *Vision 2040 – MAD*, *Vison 2040 – AD* and the Base Case. Benefits assessed include improvements in road safety and reductions in CO_2 emissions and air pollution.

The CBA approach adopted in this study follows Assing et al. (2006), which develops and applies a simplified CBA to assess intelligent vehicle safety systems. It focuses on the calculation of costs and benefits of a target year, as opposed to the analysis of costs and benefit streams over the entire project life cycle. The latter approach is commonly applied around the globe to inform transport infrastructure investment decisions of the public sector (see for example TfNSW 2019).

The approach chosen for this CBA is a shortcut compared to the cash flow approach. However, it provides a clear indication of the economic viability of the scenarios assessed and provides insights into the main contributors of *U-Shift* implementation that achieve desired benefits.

Following the selected approach, CAPEX are apportioned to the target year (2040), i.e., dividing its total value by the expected asset life. OPEX and benefits are calculated for the target year. The study identified 2040 as a plausible target year for introduction of *U-Shift,* as a number of technological and regulatory barriers for automated vehicles in general still persist, preventing wide-spread implementation for some years to come. All costs and benefits are expressed in €2019 prices. The base year is 2040.

5 Analysis

5.1 Energy Consumption

Energy consumption of *U-Shift* is a major driver for fuel costs, CO_2 emissions and air pollution. The CBA captures energy required for propulsion of vehicles as well as operation of the Automated Driving System and auxiliaries (such as heating and cooling). Simulations of energy consumption were undertaken with Dymola, a programming environment of the object-oriented modelling language Modelica. To simulate energy consumption of vehicles with Dymola, DLR has developed the 'AlternativeVehicles' library for electric drivetrains (Hülsebusch et al. 2009). Using this library, a model of a battery electric drivetrain was used with *U-Shift* parameters.

We used Class 1 of the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) (Liebl et al. 2014) to represent the speed-time profiles of freight movements. For ride-pooling services, we simulated energy consumption for the Standardised On-Road Test Cycles 2 (SORT2) (UITP 2014). The main characteristics of the two driving cycles are presented in Table 11 of the Appendix. In general, energy consumption depends on the vehicle's characteristics such as the size of the frontal area, vehicle mass and typical drivetrain efficiencies and these were used as input parameters to the simulation. Table 12 and Table 13 of the Appendix illustrate these parameters, reflecting the state of development of *U-Shift* in May 2020.

The results of the simulations are illustrated in Table 3 and show that energy consumption under the WLTC1 (goods movement) is generally lower compared to SORT2 (people movement) because the former includes less and shorter acceleration phases.

Table 3 Energy consumption (propulsion): ***U-Shift***

***U-Shift* configuration**	**Load**	**Standardised driving cycle**	**Energy consumption**
			kWh/100km
Driveboard	Not applicable	WLTC1	8.43
		SORT2	10.75
Driveboard + freight body	Empty	WLTC1	15.30
	Full	WLTC1	19.67
Driveboard + people mover body	Empty	SORT2	17.99
	Full	SORT2	24.75

Source: DLR analysis based on Dymola simulations

The required power of auxiliaries such as heating and cooling are estimated at 0.5 kW by experts involved in the *U-Shift* development. However, this would not allow for reefer systems. With respect to the energy required for operation of the Automated Driving System, we assume an average energy consumption of 3.5 kWh/100 km, informed by Gawron (2018). Under *Vision 2040 – MAD*, where most of the automation hardware and software is embedded in the infrastructure rather than the vehicle itself, we assume 50% of this energy consumption. Under this option, additional energy is required to operate the infrastructure-based automation system. Based on expert guesses from suppliers of components for *U-Shift*, we assume an annual electricity consumption of 680 kWh per *digital package*. This excludes the computational power to enable the optimization of centralized trip scheduling and route planning.[3]

Table 4 illustrates average energy consumption for *U-Shift* Driveboard and a freight body. Energy consumption of a people mover configuration is slightly higher: 25.7 kWh/100km and 26.3 kWh/100km for MAD and AD respectively.

Table 4 Energy consumption rate, *U-Shift* Driveboard + freight body

Item	**Vision 2040 – MAD**	**Vision 2040 –AD**
	kWh/100km	kWh/100km
Propulsion[1]	18.6	18.4
Auxiliaries[2]	2.5	2.5
Driving automation technology (vehicle)[3]	2.6	3.5
Total average energy consumption	**23.7**	**24.4**

Sources: [1] Dymola simulation; [2] project experts' guess; [3] own calculation based on Gawron et al. (2018)

5.2 Road Transport Outcomes

The implementation of *U-Shift* under *Vision 2040* is expected to have a substantial impact on Stuttgart's future mobility system as it enables shared mobility for passengers and goods.

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[3] However, it is argued that the (substantial) installed computational power to enable the automated driving task is sufficient to allow for the traffic management task. This will be investigated in future studies.

A number of assumptions were adopted to derive transport indicators, in particular vehicle km travelled (vkm). Across all scenarios we assume an increase in road transport demand. Based on projections prepared by the German Environment Agency, which is the basis for German's National Energy and Climate Plan (BMWi 2020), from today to 2030 we assume annual average growth rates of 0.2% for passenger road transport, and 1.3% for road freight. Demand between 2030 to 2040 is assumed to grow at the same rates. Under the scenario definition of *Vision 2040,* all movements by trucks and vans (light commercial vehicles, LCVs) are replaced by *U-Shift.* For passenger transport, it is assumed that ride-pooling services during peak hours replace some car trips. Table 5 presents resulting vkm in 2040 for the three options considered and, for comparison, historic values for 2017.

Table 5 Indicators of road transport

Vehicle	**2017**	**Base Case**	**Vision 2040 – MAD**	**Vision 2040 – AD**
	mio. vkm	mio. vkm	mio. vkm	mio. vkm
Cars	3,609	3,707	2,868	2,936
LCVs	341	461	0	0
Trucks	39	53	0	0
U-Shift Passenger	0	0	328	352
U-Shift Freight	0	0	1,094	1,172

Sources: 2017 data provided by Statistisches Landesamt Baden-Württemberg; other values: own analysis

To calculate the number of *U-Shift* Driveboards and bodies required to fully replace commercial vehicles in 2040, we assume that *U-Shift* carries on average 1.2 t per trip under *Vision 2040 – MAD* and 1.1 t under *Vision 2040 – AD,* respectively. The difference is based on different assumptions regarding the average load factor. A load factor of 75% is assumed under the former scenario, enabled by the central coordination of transport tasks, compared to an average load factor of 70% for the latter. Secondly, we expect that Driveboards for freight deliveries are used on average 15 hours per day. Assuming an average speed of 20 km/h, approximately 12.000 Driveboards are required under *Vision 2040 – MAD* and 13,000 Driveboards under *Vision 2040 – AD*. This includes an additional 5% spare Driveboards to address downtime due to vehicle maintenance and inspection works. During AM and PM peak hours, all *U-Shift* Driveboards are used for ride-pooling services, each of them connected with a people mover body, meaning that the number of people mover bodies required are equal to the numbers of Driveboards calculated above.

The number of vehicle bodies required for freight are expected to be larger compared to the number of Driveboards as these not only serve as transport units but also as mobile parcel stations or storage spaces. However, limited available public space in Stuttgart, and urban areas in general, limit the desired number of *U-Shift* bodies. As a result, for this study we assume 1.5 bodies for each available Driveboard.

The estimation of effects of *U-Shift* on road passenger transport outcomes are based on ISV (2016), which modelled nine scenarios of fully automated people movers in Stuttgart. As these scenarios include a range of use cases (e.g. for private use, as part of vehicle and ride-sharing systems), we were able to identify a use case similar to *U-Shift Vision 2040*. Based on ISV (2016), we assume that ride pooling adds on average 100 meters to the average trip length to account for detours to collect passengers and an additional 5% of trips due to empty-running of *U-Shift*. The capacity of *U-Shift* in its current configuration is nine people. According to an ISV (2016) simulation for a scenario similar to *U-Shift* vision, occupation rate of ride pooling services in Stuttgart averages three passengers, an assumption we adopt for *Vision 2040 – AD*. Under *Vision 2040 – MAD* we assume a slightly higher factor of 3.5, enabled by centralized trip planning. Table 141414 of the Appendix provides details on the road transport outcomes calculated for the purpose of this CBA.

5.3 Costs

The CBA quantifies costs for purchasing and operating the road vehicles and automation technology required under *Vision 2040 – MAD*, *Vision 2040 – AD* and the Base Case. As noted earlier, CAPEX are not included as total amounts, but rather apportioned to 2040, taking into account expected asset lives.

5.3.1 Vehicle Acquisition Costs

All scenarios considered require substantial investments in vehicles. To determine the total costs, current average prices of cars, LCVs and trucks were established. On average, Germans spent €29,303 (excluding GST[4]) for new cars in 2019 based on an analysis by the CAR Centre Automotive Research (TZ 2020). Combining information on LCV 2018 stock data (KBA 2018) with list prices taken from ADAC Autorechner (ADAC 2020), we derive an average price of €26,800 for LCVs. Finally, we estimate an average cost of €107,000 per truck based on stock data registered on 1st January 2019 in Stuttgart (KBA 2019) and vehicle cost data taken from Kleiner (2020).

Taken today's vehicle costs as start point, we project vehicle prices for 2040. We expect an increasing share of vehicles with electrified drivetrains over the coming decades, as a result of strict EU CO_2 emission standards for new cars, LCVs and trucks. Based on the DLR Vehicle Technology Scenario Model (VECTOR21) (Ariadne 2021), we assume that this will not lead to an increase in vehicle prices in real terms in 2040 (compared to today) as electrified drivetrains will eventually reach cost parity with vehicles with combustion engines. Furthermore, we assume that road vehicles will include SAE level 3 driving technology in 2040. Following Brost et al. (2019), this

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[4] Note that values presented in this chapter (and used in the CBA) are net of the Goods and Services Tax (GST), which was 19% at the time of this study.

could cost an additional €5,000 per vehicle, which is taken into account as part of this CBA to estimate future vehicle costs (as can be seen in Table 6).

Table 6 Vehicles, 2040 unit cost rates (excl. GST) (rounded), €2019

Vehicle segment	Value
	€
Cars[1]	34,000
LCVs[2]	32,000
Trucks[3]	110,000

Sources: [1] Brost et al. (2019); TZ (2020); [2] Brost et al. (2019); KBA (2018); ADAC (2020); [3] Brost et al. (2019); KBA, 2019; Kleiner, 2020

Cost estimates for *U-Shift* vehicles are preliminary, given the early stage of development of the vehicle. The initial estimates taken for this CBA are based on expert guesses on behalf of the development team as well as projections of costs of key components such as the battery. Due to the high uncertainty of future costs, we allow for sufficient contingency. For example, we assume battery pack cost to reach 100€/kWh by 2040. This is conservative as average costs have decreased on average by 18% per year over the past decade and averaged €120/kWh in 2020 according to a market survey by Bloomberg (2020). For the vehicle-based automation approach under *Vision 2040 – AD* we assume automated driving technology costs amounting to €11,000. Table 77 shows that *U-Shift* Driveboards under *Vision 2040 – MAD* are substantially cheaper because driving automation technology is largely included in the road infrastructure (see Table 11).

Table 7 *U-Shift,* 2040 unit cost rates (excl. GST), €2019

Configuration	Vision 2040 – MAD	Vision 2040 – AD
	€	€
U-Shift Driveboard	50,000	85,000
***U-Shift* body for freight delivery**	11,000	15,000
***U-Shift* body for passenger transport**	29,000	38,000

Source: DLR

Under the Base Case, only conventional vehicles are required. Table 141414 (Appendix) contains estimates of the respective fleet sizes.

5.3.2 Digital Road-side Equipment Costs

The infrastructure-based automation solution under *Vision 2040 – MAD* incurs substantial expenses for road-side driving automation technology. As described in Chapter 2, stereo cameras, together with communication technology are bundled and distributed across the road network (where available, at existing lightning poles).

To estimate the number and locations of road-side driving automation technology packages (*digital packages*) needed to equip Stuttgart's road network, a GIS-Analysis using Quantum GIS 3.10 and ArcMap 10.1 has been conducted to inform this CBA. This analysis was conducted assuming that sensors cover a road length of 70 meters. For crossings and roundabouts, it was assumed that one package is needed per arm. The geographic scope is the area of the municipality of Stuttgart. The analysis excludes components that may be required to equip private roads or loading/unloading facilities (e.g. in factories or supermarkets).[5]

Firstly, we identified crossings and roundabouts, as well as roads in Stuttgart based on the Open Street Map (OSM) data model, combined with analysis using geospatial lookup-chains and the topology of road segments. Secondly, we allocated digital equipment packages to roads, crossings and roundabouts (see Figure 3). The result of this analysis identified a need for around 38,000 digital units to cover the area of Stuttgart under *Vision 2040 – MAD.*

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[5] This would require a detailed analysis and in some circumstances existing infrastructure (such as cameras or fibre optic) may already be available. In any case, we expect that the additional investment required is negligible compared to the equipment of Stuttgart's public road system considered in this study.

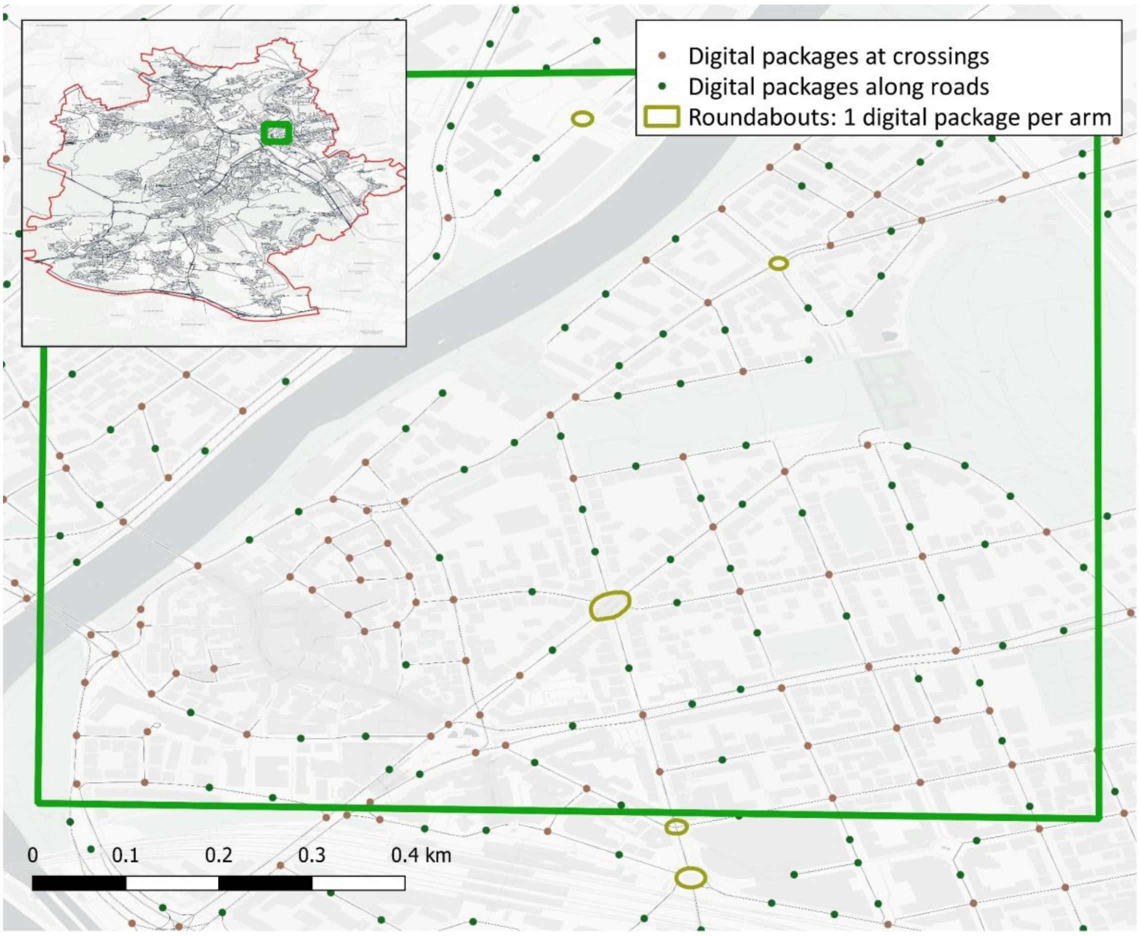

Figure 3 GIS-allocated locations of digital equipment. Source: own elaboration

The project team, with input from industry, estimate a unit cost rate per *digital package* of €15,000, reflecting costs for hardware and a portion of overall costs for software, backend and fibre optic. As the future costs of digital equipment are highly uncertain due to fast technological advances, we conducted a sensitivity analysis on CAPEX in Chapter 6.

5.3.3 OPEX

OPEX include costs for fuel/electricity, assurance, maintenance of vehicles and staff and electricity expenses for operating the digital road-side infrastructure.

To quantify fuel costs, we take the product of total mileage travelled (see Table 5), fuel consumption per km and fuel prices. Assumptions on fuel consumption are described in Chapter 5.1. We assume that real prices for fuels and electricity (excl. taxes) in 2040 are similar to 2019 values in real terms (see Table 8). To calculate electricity costs for vehicle owners, we added 0.08 €/vkm on top of electricity to capture costs for charging infrastructure.

Table 8 Electricity and fuel, 2040 unit cost rates (excl. taxes), €2019

Energy carrier	Unit	Value
Electricity[1]	€/kWh	0.23
Petrol[2]	€/l	0.55
Diesel[2]	€/l	0.59
Compressed Natural Gas (CNG)[3]	€/kg	0.76
Liquified Natural Gas (LNG)[4]	€/kg	0.48
Liquefied Petroleum Gas (LPG)[5]	€/l	0.45

Sources: [1] Bundesnetzagentur, Bundeskartellamt (2019); own assumption; [2] MWV (2020); [3] own calculation based on CNG.info (2020); [4] own calculation based on Baywa (2020) [5] own calculation based on ADAC (2020)

To quantify maintenance and assurance cost of vehicles we use values from the literature. Bösch et al. (2018) developed a model for calculating operational cost of autonomous vehicles for different deployment scenarios. Based on their assumptions, we adopted an average cost rate of 0.22 €/vkm for *U-Shift* operations. For conventional cars, we adopt maintenance cost rates of 0.06-0.08 €/vkm depending on the drivetrain based on the DLR vehicle scenario model (Ariadne 2021).

Operation of digital road-side infrastructure incurs electricity cost (based on energy consumption rates derived in Section 5.1) and expenses for staff. For this CBA we assume 50 full-time staff required to operate the traffic management centre with an average hourly rate of €37.40 and 100 full-time staff for maintenance works of the digital road-side infrastructure with an average hourly rate of €25.15 (based on 2019 actual hourly rates in Germany).

5.4 Benefits

Automated driving is expected to enable substantial improvements in road safety. In addition, it can facilitate the transformation of a mobility system characterised by individual motorised transport to shared mobility, resulting in CO_2 emission reductions and improvements in air pollution.

5.4.1 Road Safety

Road safety benefits are derived by comparing crash costs under *Vision 2040 – MAD* and *Vision 2040 – AD* against the Base Case. The study portrays road safety benefits for all road users (road vehicles, pedestrians and cyclists) due to a reduction in accidents caused by road vehicles. We value crash costs using the inclusive Willingness-to-pay (WTP) approach, consisting of the individuals' WTP to avoid death or injury as well as cost to society due to the crash, such as emergency costs. Unit cost rates for the former are taken from Bickel *et al.* (2005), while BASt (2019) provides German specific values for the latter. These are summarized in Table 15 of the Appendix.

U-Shift is expected to improve road safety because automated vehicles completely eliminate accidents caused by human error, which are responsible of around 90% of crashes (Official Journal of the European Union 2019). To explore this hypothesis further, Mueller, Cicchino, and Zuby (2020), analysed 5,471 serious crashes in the United States occurring between 2005 and 2007 and stored in the National Motor Vehicle Crash Causation Survey (NMVCCS) database. Of these, 94% crashes were caused by human error. The study allocated crashes to five categories of driver-related contributing factors: (1) sensing/perceiving; (2) predicting; (3) planning/deciding; (4) execution/performance and (5) incapacitation. The study concluded that, assuming automated vehicles would have superior perception and be incapable of incapacitation, 34% of crashes could be eliminated.

We identified additional crash causes that could be eliminated by automated driving technology, building on Mueller, Cicchino, and Zuby (2020). The results of this qualitative assessment are illustrated in Table 16 (Appendix). We argue that most (3) planning/deciding and some of the (4) execution/performance crashes could be avoided (such as crashes caused by panic/freezing). In contrast to Mueller, Cicchino, and Zuby (2020), we argue that some of the (1) sensing/perceiving accidents related to view obstruction could still prevail. Based on our analysis, we adopt the conservative assumption that *Vision 2040 – MAD* leads to a reduction of 73% of accidents (compared to today), and 68% under *Vision 2040 – AD*. Under *Vision 2040 – MAD* more crashes can be prevented as the visual area is larger (due to the distribution of sensor technology along roads) compared to *Vision 2040 – AD.*

For the conventional fleet we assume that road safety will improve gradually over the period from now until 2040. This is in line with the historic trend, government strategic goals and an increase in drivers' safety systems in new vehicles. To project road safety for 2040, firstly, we establish today's road safety situation in Stuttgart and secondly, examine historic trends. Today (i.e., for the calculation of road safety we referred to 2017 data as this represents the most recent year where data was available for crashes and vkm at the time of this study), car drivers caused 23,128 accidents in Stuttgart, of which 4 fatal crashes, 110 major injuries crashes and 1,358 minor injuries crashes. Trucks and vans caused 1,472 crashes, of which no fatal crashes, 9 major injuries crashes and 116 minor injuries crashes (data provided by Statistisches Landesamt Baden-Württemberg for the purpose of this study). Between 1995 and 2017, the average crash rate (number of crashes per million vkm) of accidents with fatalities and injuries decreased by 0.8% per year (p.a.), while '(substantial) property damage only' crashes declined by 1.5% p.a. (Statistisches Landesamt Baden-Württemberg 2020). For the purpose of this appraisal, we assume a continuation of these trends until 2040.

5.4.2 Reduction in CO_2 Emissions

In the past few years, decarbonising German's economy has become the first priority of national politics and policies. Germany is set to reduce CO_2 emissions by 65% from 1990 to 2030 and to achieve climate neutrality by 2045 (BMUV 2021). An important climate policy measure pursued by EU regulations and German policies is the electrification of road vehicles. This is in line with *U-Shift* technology, which consists of a fully electric drivetrain. In addition, *U-Shift* ride pooling services will replace some car trips, leading to a reduction in vkm (see Table 5) with a positive effect on CO_2 emissions.

To estimate benefits from CO_2 reductions, we quantify total well-to-wheel emissions and apply a unit cost rate for CO_2. The unit cost rate for CO_2 generally reflects (global) economic damages from climate change impacts, which result from the emission of CO_2 into the atmosphere. The difficulty to scientifically estimate a quantitative value is obvious given the complexity of the task at hand. For the purpose of this study, we adopt a unit cost rate of €232 (2019) per tonne CO_2 for 2040, following guidance from the German Environment Agency (UBA 2019). This value was estimated using a social discount rate of 1%.

CO_2 emissions under *Vision 2040 – MAD* and *Vision 2040 – AD* are caused by private cars and *U-Shift*. To account for *U-Shift* movements, we used Dymola to model energy consumption, as described in Section 5.1, and applied the expected CO_2-intensity of electricity in Germany in 2040 of 71 gCO_2/kWh based on scenario forecasts by Ffe (2019). Moreover, under *Vision 2040* scenarios, *U-Shift* provides ride-pooling services, resulting in a decrease of total vkm for passenger transport compared to the Base Case. While an average of 3.5 passengers are transported by *U-Shift*, the car occupancy road is assumed to be only 1.3 (based on real-world data). An opposite effect is observed for goods transport. The replacement of trucks and vans with *U-Shift* leads to more vkm, therefore counteracting CO_2 reductions.

For estimating emissions under the Base Case, we use projections of average CO_2 emissions of the 2040 fleet provided in the *Handbook emission factors for road transport* (HBEFA) v4.1 (Infras 2019) and our own assumptions on vkm (see Table 5).

5.4.3 Air Pollution

Reducing air pollution results in improvement in humans' health and damage to materials. The former includes not only benefits in terms of a reduction in health costs borne by society, but also a WTP value of individuals to avoid pain and grief. Parameter values are based on guidance by the German Environment Agency (UBA 2019), differentiating among the five main pollutants of road transport (PM2.5, PM10, NOx, SO2 and NH3). Of these pollutants, PM2.5 has by far the largest social unit cost rate with €254.000 per tonne emitted.

Like in the case of CO_2 calculations, we sourced emissions factors differentiated by vehicle category from Infras (2019) and applied them to respective annual mileages (see Table 5). *U-Shift* will not cause exhaust emissions from burning fuel, however, we consider non-exhaust emissions – which is a major source of PM2.5 emissions. For *U-Shift*, we refer to Infras (2019) emission factors for electric light commercial vehicle due to its comparable size.

6 Results

Table 9 illustrates the results of the rapid CBA, detailing standalone costs and benefits of *Vision 2040 – MAD, Vision 2040 – AD* and the Base Case as well as incremental values. Values are expressed in 2019 prices and 2040 is used as base year. The main indicators to evaluate the economic viability of an intervention are generally the Net Present Value (NPV) and Benefit-Cost Ratio (BCR)[6]. These are also presented in the table.

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[6] The BCRs were calculated using the 'incremental' approach. The denominator consists of the incremental costs of the project case compared to the Base Case and the nominator of the incremental benefits, respectively.

Table 9 CBA core results, €2019

Item	**Base Case**	**Vision 2040 - MAD**	**Vision 2040 - AD**	**Vision 2040 - MAD**	**Vision 2040 - AD**
	Standalone mio. €	Standalone mio. €	Standalone mio. €	Incremental mio. €	Incremental mio. €
CAPEX					
U-Shift	0	107	171	107	171
MAD smart roads	0	58	0	58	0
Cars	870	673	689	-197	-181
LCV	49	0	0	-49	-49
Trucks	40	0	0	-40	-40
Total CAPEX	**958**	**837**	**860**	**-121**	**-98**
OPEX					
U-Shift	0	385	414	385	414
MAD staff	0	46	0	46	0
MAD electricity	0	4	0	4	0
Cars	635	491	503	-144	-132
LCV	59	0	0	-59	-59
Trucks	27	0	0	-27	-27
Total OPEX	**721**	**926**	**917**	**205**	**196**
Total costs	**1,680**	**1,763**	**1,778**	**83**	**98**
Benefits					
Road safety	-398	-317	-332	81	66
CO_2 emissions	-153	-107	-110	46	43
Air pollution	-96	-73	-75	24	21
Total benefits	**-647**	**-497**	**-517**	**151**	**131**
NPV				67	33
BCR				**1.80**	**1.34**

The results show that deployment of *U-Shift* is economically viable as it leads to a BCR of 1.8 and a NPV of €67 million for *Vision 2040 – MAD* and 1.3 and €33 million for *Vision 2040 – AD*, respectively. Road safety improvements represent the largest benefit as *U-Shift* is expected to be considerably safer than conventional vehicles. Most benefits accrue due to a reduction in ‘minor vehicle damage only’ crashes, followed by damages due to crash-related major and minor injuries. There are few fatal crashes caused by road vehicles in Stuttgart today[7], so there is no noticeable effect on fatal crashes from the use of *U-Shift*. Another driver for road safety improvements is that *U-Shift* leads to a reduction in vkm as it bundles passenger trips. This effect is countervailed by an increase in vkm in the freight sector (as payload of *U-Shift* is substantially lower compared to conventional trucks).

Under *Vision 2040 – MAD*, road transport emissions are reduced by 30% compared to the Base Case, leading to an annual saving of €46 million in climate damages. Similar to improvements in air pollution, the magnitude could be increased by extending ride-pooling services to off-peak hours, resulting in a further decline in vkm of private cars.

The largest driver for costs to deploy *U-Shift* (under both scenarios) are OPEX. Under our preferred approach, *Vision 2040 – MAD*, we estimate annual costs of €385 million. The majority of these costs (i.e., 80%) constitute maintenance and assurance costs.

There is substantial uncertainty on future costs and benefits. These include especially costs and energy consumption of automation components, as well as safety benefits. We therefore conduct sensitivity tests, analysing the robustness of results against a 20% increase and decrease of costs and benefits, respectively. The results in Table 10 show that *Vision 2040 – MAD*, the infrastructure-based automation approach, is more robust against pessimistic estimates compared to *Vision 2040 – AD*. It can be further seen that the results are sensitive to relatively minor changes in costs and benefits.

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[7] There was 1 fatality caused by motor vehicles in 2018 and 4 in 2017 (Statistisches Landesamt Baden-Württemberg, 2020).

Table 10 CBA sensitivity analysis results, €2019

Sensitivity test	Vision 2040 - MAD		Vision 2040 - AD	
	NPV € mio.	BCR	NPV € mio.	BCR
CAPEX +20%	34	1.3	-1	1.0
CAPEX -20%	100	3.0	67	2.1
Benefits +20%	166	3.0	136	2.4
Benefits -20%	-32	0.6	-71	0.3

7 Discussion

The cost-efficiency of the infrastructure-based approach is higher than the approach currently pursued by industry if (and only if) there exists a sufficient number of vehicles that can connect to the ‘smart roads’. While this solution requires substantial initial investment for road-side digital technology, costs can be shared across users. This study showed a glimpse of this potential, as the break-even point was already achieved with a relatively small number of vehicles using the smart road system, i.e. 11,579 *U-Shift* vehicles. Higher benefits could therefore be achieved in a scenario where other road vehicles could connect to the smart road system.

The results demonstrate that an extension of ride-pooling services may provide additional benefits from *U-Shift* deployment. In contrast, the CBA results show that the full potential for replacing trucks can only be realised if the payload of *U-Shift* is increased.

A limitation of this CBA is that there are some missing cost and benefit categories. This includes congestion benefits from improved traffic management under *Vision 2040 – MAD* and accessibility benefits for people living in areas that are not sufficiently served by public transport and have no access to private transport. We have also neglected economic costs from parking *U-Shift* and other road vehicles and this should be included in future studies. In addition, the CBA does not consider (substantial) CO_2 emissions caused by the production of vehicles. Lifecycle emissions of *U-Shift* are subject to ongoing research at the German Aerospace Centre, but not available at the time this CBA was conducted (see Bieber, 2020 for preliminary results). On the other hand, it was a conscious decision to exclude potential benefits from travel time savings as the economic rationale is missing. *U-Shift* does not reduce travel times, nor will it reduce the time cost component of travelling (people switch from car to a people mover service, with comparable features of a today's small bus).

We underestimate road safety benefits as we captured a reduction in crashes caused by vehicles, but omit potential improvements from reducing crashes caused by cyclists and pedestrians. This is a strong assumption as automated vehicles will be more forgiving to pedestrians' and cyclists' errors compared to human drivers as machines have generally shorter reaction times and greater visual areas. The magnitude of the effect depends on the specific crash scenario (some may be unavoidable even by machines) and the level of road safety desired, which has to be weighed against driving performance (e.g. the maximum allowed speed of automated vehicles).

8 Conclusions

The results of this CBA show that the automated vehicle *U-Shift*, implemented as part of a 2040 roll-out scenario in Stuttgart, would lead to positive net effects. It generates a reduction of road sector's CO_2 emissions by 30% and an improvement in air quality and road safety. The key to realise these benefits is that *U-Shift* is being deployed as part of a ride-sharing system, therefore reducing total fleet mileage. Moreover, benefits from *U-Shift* are driven by its superiority compared to today's vehicles in terms of crash avoidance systems and its electric drivetrain – two aspects of *U-Shift* common to driving automation technology in general.

In this study, we compared two different technological solutions to achieve vehicle driving automation, an infrastructure-based approach ('smart roads'), MAD, and a vehicle-based approach, AD. The results show that the economic viability of MAD, our preferred approach, is higher compared to AD. MAD enables central orchestration of traffic flows and therefore optimises system performance.

The results of the sensitivity test show that results are sensitive to relatively minor changes of inputs, highlighting the importance of future research into quantifying impacts of automation technology. This includes, but is not limited to the potentially high energy consumption of automation technologies itself. It also highlights the importance of policy-makers’ role in providing an adequate framework to deploy the technology, for example, ensuring the technology is fit-for-purpose to deliver expected road safety benefits and a reduction in total mileage of road transport.

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Declaration of interest statement

None

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Appendix

Table 11 Description of WLTC1 und SORT

Item	WLTC1	SORT
Average speed	25.5 km/h	18 km/h
% of stops	21.0 %	33.4 %
Maximum acceleration	0.81 m/s²	0.62 m/s²
Maximum speed	64.4 km/h	50.0 km/h
Duration	1,611 s	183 s
Distance	11,428 m	920 m

Source: own analysis based on Liebl et al. (2014) and Union Internationale des Transports Publics (2014)

Table 12 Input parameters for Dymola simulation: *U-Shift* vehicle characteristics

Item	Value
Weight, chassis only	2 t
Weight, *U-Shift* (loaded)	4.2 t
Weight, *U-Shift* (unloaded)	2.7 t
Front surface, chassis only	1.98 m²
Front surface, *U-Shift*	6.02 m²
Drag coefficient (cW), chassis only	0.4
Drag coefficient (cW), *U-Shift*	0.45
Rolling resistance coefficient	0.008
Dynamic radius wheel	36.5 cm
Rotational inertia mass factor	1.04
Rotational mass	152 kg
Inertia of shaft	10.66 kgm²

Source: DLR

Table 13 Input parameters for Dymola simulation: other assumptions of *U-Shift*

Item	Value
Battery type	LI-NMC Battery (Akasol)
Auxilary power	0 W
Electric motor	Generic electric motor at 100 kW power (UQM Power Phase 100, including power electronic), central motor architecture
Gear ratio	3
Environmental conditions	20°C, dry road, p=1,013 bar

Source: DLR

Table 14 Transport indicators

Indicator	**2017**	**Base Case**	**Vision 2040 - MAD**	**Vision 2040 - AD**
Vkm				
Cars, mio. vkm	3,609	3,707	2,868	2,936
LCVs, mio. vkm	341	461	0	0
Trucks, mio. vkm	39	53	0	0
***U-Shift* passenger, mio. vkm**	0	0	328	352
***U-Shift* freight, mio. vkm**	0	0	1,094	1,172
Passenger-kilometres (pkm) / ton-kilometres (tkm)				
Cars, mio. pkm	4,692	4,820	3,728	3,817
LCVs, mio. tkm	597	807	0	0
Trucks, mio. tkm	299	404	0	0
***U-Shift*, mio. pkm**	n.a.	n.a.	1.091	1.002
***U-Shift*, mio. tkm**	n.a.	n.a.	1.211	1.211
Load factor				
Cars (passenger/vehicle)	1.3	1.3	1.3	1.3
LCVs (t/vehicle)	1.8	1.8	n.a.	n.a.
Trucks (t/vehicle)	7.6	7.6	n.a.	n.a.
***U-Shift* passenger (passenger/vehicle)**	n.a.	n.a.	3.5	3.0
***U-Shift* freight (t/vehicle)**	n.a.	n.a.	1.2	1.1
Number of vehicles				
Cars	304,632	304,632	235,643	241,275
LCVs	13,599	18,359	n.a.	n.a.
Trucks	2,818	3,804	n.a.	n.a.
***U-Shift* bodies (people mover)**	n.a.	n.a.	12,158	13,026
***U-Shift* bodies (cargo)**	n.a.	n.a.	18,237	19,540
***U-Shift* Driveboards**	n.a.	n.a.	12,158	13,026

Source: 2017 data provided by Statistisches Landesamt Baden-Württemberg; other values: own analysis

Table 15 Road safety, unit cost rates, €2019

Damage category	Resource cost[1]	Individuals' WTP[2]
Damage to a person		
Fatality	1,168,123 €	1,854,513 €
Major injury	118,144 €	240,718 €
Minor injury	5,218 €	18,545 €
Property damage		
Fatal crash	52,120 €	n.a.
Major injury crash	24,367 €	n.a.
Minor injury crash	15,645 €	n.a.
Major property damage crash	23,194 €	n.a.
Other property damage crash	6,273 €	n.a.

Sources: [1] BASt (2019); [2] Bickel et al. (2005)

Table 16 Assessment of performance of *U-Shift* vehicles compared to today's vehicles based on Mueller, Cicchino, and Zuby (2020) crash data

Type of crash factor	Subcategory of crash factor	Performance of *U-Shift* compared to today's vehicles	
		MAD	AD
Sensing and perceiving	Inattention	Elimination of risk	Elimination of risk
	Internal distraction	Elimination of risk	Elimination of risk
	External distraction	Elimination of risk	Elimination of risk
	Inadequate surveillance (e.g., failed to look or looked but did not see)	Elimination of risk	Elimination of risk
	Other recognition error	Elimination of risk	Elimination of risk
	Unknown recognition error	Elimination of risk	Elimination of risk
	Turned with obstructed view	Elimination of risk	Elimination of risk
	Lights failed	Elimination of risk	Elimination of risk
	Vehicle-related vision obstructions	Elimination of risk	Moderate improvement
	Signs/signals inadequate	Elimination of risk	Moderate improvement
	View obstructed by roadway design/furniture	Elimination of risk	Moderate improvement
	View obstructed by other vehicles	Elimination of risk	Moderate improvement
	Fog	Elimination of risk	Eliminated
	Glare	Elimination of risk	Elimination of risk
	Blowing debris	Elimination of risk	Elimination of risk

	Driver inattention	Elimination of risk	Elimination of risk
	Inadequate surveillance	Elimination of risk	Elimination of risk
	Other driver recognition factors	Elimination of risk	Elimination of risk
	Other nondriving activities	Elimination of risk	Elimination of risk
	Driver conversing	Elimination of risk	Elimination of risk
	Other driver decision factors (crossed with obstructed view and turned with obstructed view)	Elimination of risk	Elimination of risk
	View obstruction: Related to load	Elimination of risk	Elimination of risk
	View obstruction: Related to vehicle design	Elimination of risk	Moderate improvement
	View obstruction: Related to other	Elimination of risk	Moderate improvement
	Roadway view obstructions	Elimination of risk	Moderate improvement
	View obstructed by other vehicle	Elimination of risk	Moderate improvement
	Sun glare	Elimination of risk	Elimination of risk
	Headlight glare	Elimination of risk	Elimination of risk
	Looking for street address	Elimination of risk	Elimination of risk
	Looking at building	Elimination of risk	Elimination of risk
	Unspecified outside focus	Elimination of risk	Elimination of risk
Planning and deciding	Too fast for conditions	Elimination of risk	Elimination of risk
	Too fast to be able to respond to unexpected actions of others	Moderate improvement	Moderate improvement
	Too fast for curve/turn	Elimination of risk	Elimination of risk
	Too slow for traffic stream	Elimination of risk	Elimination of risk
	Following too closely to respond to unexpected actions	Elimination of risk	Elimination of risk
	Illegal maneuver	Elimination of risk	Elimination of risk
	Aggressive driving behavior	Elimination of risk	Elimination of risk
	Maintenance problems (potholes, etc.)	Moderate improvement	Moderate improvement
	Slick roads	Elimination of risk	Elimination of risk
	Rain, snow	Elimination of risk	Elimination of risk

	Precrash event of loss of control because too fast for conditions	Elimination of risk	Elimination of risk
	Following too closely	Elimination of risk	Elimination of risk
	Illegal maneuvers	Elimination of risk	Elimination of risk
	Other driver decision factors (stopped when not required, proceeded with insufficient clearance, and turned without signaling)	Elimination of risk	Elimination of risk
	Aggressive driving act: Speeding	Elimination of risk	Elimination of risk
	Aggressive driving act: Tailgating	Elimination of risk	Elimination of risk
	Aggressive driving act: Rapid/frequent lane changes/weaving	Elimination of risk	Elimination of risk
	Aggressive driving act: Ignoring traffic control devices	Elimination of risk	Elimination of risk
	Aggressive driving act: Accelerating rapidly from stop	Elimination of risk	Elimination of risk
	Aggressive driving act: Stopping suddenly	Elimination of risk	Elimination of risk
	Aggressive driving act: Obstructing the path of others	Elimination of risk	Elimination of risk
Execution and performance	Inadequate evasive action (e.g. braking only, not braking and steering)	Moderate improvement (uncertain)	Moderate improvement (uncertain)
	Incorrect evasive action	Moderate improvement (uncertain)	Moderate improvement (uncertain)
	Panic/freezing	Elimination of risk	Elimination of risk
	Overcompensation	Elimination of risk	Elimination of risk
	Poor directional control (e.g., failing to control the vehicle with skill ordinarily expected)	Moderate improvement (uncertain)	Moderate improvement (uncertain)
	Other performance error	Elimination of risk	Elimination of risk
	Unknown performance error	Elimination of risk	Elimination of risk

	Incorrect/inadequate evasive action	Moderate improvement (uncertain)	Moderate improvement (uncertain)
	Driver performance error	Elimination of risk	Elimination of risk
Predicting	Misjudgment of gap or other's speed	Elimination of risk	Elimination of risk
	False assumption of other’s actions	Moderate improvement	Moderate improvement
	Misjudgment of distance or speed of other vehicle	Elimination of risk	Elimination of risk
	False assumption of other’s actions	Moderate improvement	Moderate improvement
Incapacitation	Sleeping, that is, actually asleep	Elimination of risk	Elimination of risk
	Heart attack or other physical impairment of the ability to act	Elimination of risk	Elimination of risk
	Other critical nonperformance	Elimination of risk	Elimination of risk
	Unknown critical nonperformance	Elimination of risk	Elimination of risk
	Blood alcohol concentration	Elimination of risk	Elimination of risk
Unavoidable by driver	Brakes failed	No improvement	No improvement
	Degraded braking capability	No improvement	No improvement
	Tires/wheels failed	No improvement	No improvement
	Other tire degradation	No improvement	No improvement
	Steering failed	No improvement	No improvement
	Suspension failed	No improvement	No improvement
	Transmission/engine failure	No improvement	No improvement
	Cargo shifted	No improvement	No improvement
	Trailer attachment failed	No improvement	No improvement
	Jackknifed	No improvement	No improvement
	Other vehicle failure	No improvement	No improvement
	Unknown vehicle failures	No improvement	No improvement
	Signs/signals missing	No improvement	No improvement
	Road design: Roadway geometry (e.g., ramp curvature)	No improvement	No improvement
	Road design: Sight distance	No improvement	No improvement

Source: columns1+2: Mueller, Cicchino, and Zuby (2020). Columns 3+4: own assessment

Table 17 Air pollutants, unit cost rates, €2019

Pollutant	**Value**
	€/t
PM2.5	254,082
PM10	29,861
Nox	19,384
SO2	16,345
NH3	34,890

Source: UBA (2019)