D3.4 General impacts and design recommendations

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0.1	2020-03-04	Fredrik Johansson	Added introduction, overview of modelling and assessment approach and copied in conclusion bullets from ppt for each use case
0.2	2020-03-10	Chengxi Liu	Revised introduction and drafted “use case design recommendations” from results in D4.3.
0.3	2020-04-21	Johan Olstam	Added safety results for use case 1
0.4	2020-04-28	Johan Olstam	Added safety results for all use cases and in the conclusion section
0.5	2020-04-29	Fredrik Johansson	Final minor revision, mostly formatting and some formulations.

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Table of contents

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The CoEXist assessment approach

The aim of the CoEXist project is to enable local road authorities and other urban mobility stakeholders to assess the impact of the introduction of connected and automated vehicles (CAVs). To achieve this, the PTV traffic modelling software Visum and Vissim are extended to handle traffic with various mixes of different types of CAVs. Also, a structured assessment approach is developed to analyse modelling results from Visum and Vissim which can be used by road authorities to assess the traffic impact of automation for a given road design, traffic control, regulations, etc.. This model-based assessment approach is tested and demonstrated by applying it to eight use cases in four European cities on both macro and micro levels. The conclusions of these assessments are briefly summarized in this deliverable and design recommendations for the studied infrastructures are provided.

Since the uncertainty regarding future CAV behaviour is large, the assessment approach describes a range of likely behaviours to obtain an interval within which it is likely that the impact of automated vehicles will be. The behaviours of the automated vehicles are specified by driving logics which are functionally defined, that is, they are specified in terms of how and where they can operate safely, disregarding the specifics of the enabling technologies. The driving logics represents a range of behaviours spanning from the very cautious *Rail-safe* driving logic, to the superhuman *All-knowing* driving logic. Since CAVs are likely to vary their behaviour depending on the complexity of the driving context and the road environment, the driving logics are combined into three AV classes: *Basic*, *Intermediate*, and *Advanced*, by specifying which driving logic a vehicle of an AV class will use on each road type.

A key goal of CoEXist is to assess the impact of automated vehicles during the whole era of coexistence of conventional and automated vehicles, from the first introduction of automated vehicles to full automation of the transportation system. This is facilitated by discretizing the era of coexistence into three stages and assessing the impact of automated vehicles separately for each stage: the *Introductory stage,* when the majority of vehicles still are conventional cars; the *Established stage*, when automated driving has been established as an important mode; and the *Prevalent stage*, when automated driving is the norm.

To gauge the uncertainty of the predicted impact of automated vehicles at each stage, the traffic performance is assessed multiple times for each stage under varying assumptions. The varied parameters are among others: penetration rates of various AV classes, traffic volumes, and behavioural adaptation of non-automated modes of transport. The result is presented as an interval of likely impacts of automated vehicles for each stage of coexistence.

In addition to the traffic modelling-based approach to assess impacts on traffic performance, two different safety assessment approaches are developed to enable first estimates on effects on safety. The first approach provide qualitative indications on how different automation functions (as ACC, Traffic chauffeur, or Highway pilot) might effect safety for different types of accidents in four different types of road environments, hence it gives a rough estimate on potential safety gains. The second approach is based on site specific safety inspections in combination with assessment on how the different driving logics might affect the accident risk for the identified safety risks.

Both to test and demonstrate the assessment approach, and to gain insights into concrete challenges of road authorities trying to prepare for the arrival of automated vehicles, it is applied to eight use cases in

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four European cities. Based on the results from the eight use cases, design recommendations on how the infrastructure can be adjusted in order to better handle the introduction of AVs are provided in this deliverable.

For a detailed description of the developed traffic modelling tools, see CoEXist deliverable D2.11 (Sukennik, 2020) and D2.8 (Sonnleitner and Friedrich, 2020), and for the assessment approach see D3.1 (Olstam, 2018), D3.2 (Olstam et al., 2019) and D3.3 (Pereira et al., 2020). The detailed description of the applications to eight use cases can be found in D3.1 (Olstam, 2018), D4.1 (Liu and Olstam, 2018), D4.2 (Olstam et al., 2020a) and D4.3 (Olstam et al., 2020b).

The following sections provide summaries of findings from each use case and their use case specific design recommendations followed by general conclusions and recommendations in the final sections.

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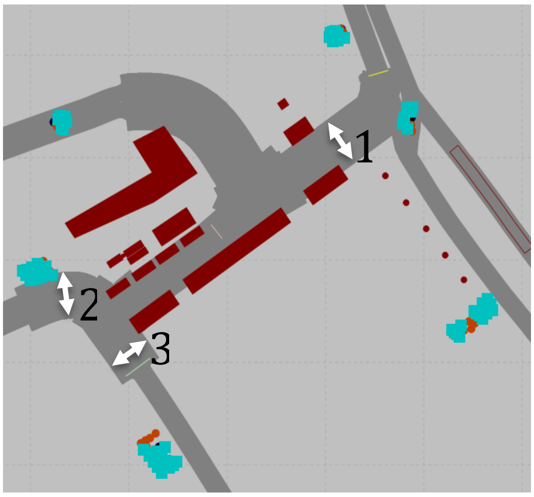
Use case 1: Shared space

A microscopic Vissim model of a shared space with large pedestrian volumes in the city centre of Gothenburg is used to investigate the traffic effects of introducing an automated last mile service. The service consists of automated minibuses. These pass through the shared space and do not have any stops for boarding or alighting within the study area. As a possible measure to improve traffic performance for the motorized traffic without delaying pedestrians, channelization of pedestrian flows using pedestrian crossings is evaluated, as presented in the figure.



Vehicle travel time increases through the shared space area.

The simulations indicate a negative impact on traffic performance for all three stages. However, since this is partly due to full speed limit compliance of CAVs this may be positive for safety. Delay for cars and minibuses increases substantially when automated vehicles are introduced since the first CAVs are very cautious when interacting with pedestrians. When the CAVs get more advanced their negative impact on traffic performance is reduced. Twice the average walking speed is often seen as a minimum for a last mile service to be attractive. The simulations indicate that the minibuses will have an average speed lower than this threshold through the shared space due to delays resulting from interactions with pedestrians. However, minibus trips will not only go through shared space areas which will result in an average trip speed above twice the walking speed.

Traffic performance for pedestrians is unaffected by the introduction of automated vehicles

Both automated and conventional vehicles give way to pedestrians and the additional safety distance kept by automated vehicles does not affect the pedestrian traffic; the pedestrians were already mostly unaffected by the vehicle traffic since they always claim their right of way.

Channelizing pedestrian flows leads to breakdown of vehicle traffic

The investigated measure to channelize pedestrian flows using pedestrian crossings fails dramatically. Long queues of vehicles are formed behind automated vehicles waiting at the pedestrian crossings unable to get past the continuous flow of pedestrians formed by the channelization; vehicle traffic breaks down completely.

Potential safety effects

The analysis indicates a positive impact on the safety both for pedestrians and vehicles (excluding potential technology failures). A large part of the risk reduction is due to that AVs are assumed to make less (or no) “driving errors”, compared to human drivers.. Furthermore, automated vehicles can be expected to be more effective in reacting to unforeseen situations (e.g. a pedestrian that suddenly cross the road), due to their improved reaction times. However, there might be an increased risk of rear-end collisions due to preceding cautious automated vehicles driving at a very slow speed, and a high possibility of sudden braking As a consequence the following car could be led to keep smaller distances with the vehicles in front and, therefore, jeopardise safety.

Design recommendations

The findings described above suggest that the current design works well from a pedestrian perspective but not so well from a vehicle traffic performance perspective when automated vehicles are introduced. Channelization do not solve the problem. Rather, the results indicate that it may be beneficial for vehicle traffic performance to spread out pedestrian flows crossing the road over a larger area rather than channelizing the flows to pedestrian crossings.

The current design also works quite well from a safety point of view, but some minor changes are suggested as increased visibility of some signs and removal of some obstacles, which to a large extent also could increase safety in the current situation. But there are also recommendations that focuses mainly on automated vehicles as increasing the space between the vehicle carriageway and the no traffic area which can help automated vehicles to better identify pedestrians that are going to make some risky movement (e.g. crossing the street) and, if the space is clearly highlighted (e.g. by the use of different pavement heights, textures or colours), pedestrians will probably be more careful while crossing the road and give more possibilities to the vehicles to move on and don’t stop.

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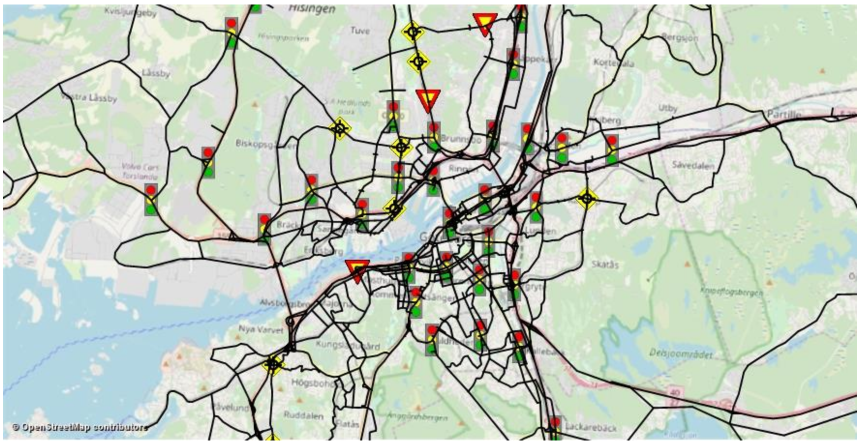
Use case 2: Accessibility during long-term construction works

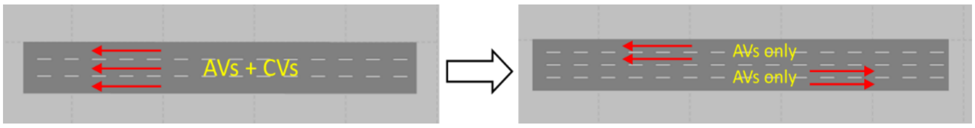
A Visum model over the Greater Gothenburg area was used to investigate how accessibility during long-term construction works is affected by the introduction of automated vehicles. The study area includes the metropolitan area of Gothenburg and its surrounding suburban and rural areas. The figure on the right shows an overview of the coded network and the centre of the study area.



Transition from negative to positive impacts of AVs during the Established stage

The modelling results show a minor increase in car travel times and slightly larger increase in car delays during the Introductory stage. This negative impact on traffic performance switches to positive (decrease in car travel time and delay) in the Established stage. In the Prevalent stage, a rather substantial positive impact on car travel times and delays are observed. At the meanwhile, large variations in travel time and delay are estimated in the Established stage which can be attributed to transition from mainly cautious to more advanced AVs and with a large uncertainty regarding the mixture of AV types. Important to note is that the model results do not include increases in travel time due to increased speed compliance of CAVs which is considered in some of the microscopic use cases, but this is probably of minor importance since the network in general is highly congested.

Positive impact in Established and Prevalent stages from redesigning from a one-way three lane tunnel tube into a two-way AV-only tunnel tube (measure 1)



The long-term construction imply closing of a tunnel tube in one direction. A redesign as shown by the figures leads to a marginal increase in car travel times and delays in the Introductory stage but a slight decrease in travel time and delay in the Established stage and somewhat larger effects in the Prevalent stage. CVs have a shorter travel time and delays compared to the case without this measure. in the Established and Prevalent stages. This is due to route shift of AVs from alternative routes to the tunnel, which free capacity on alternative routes.

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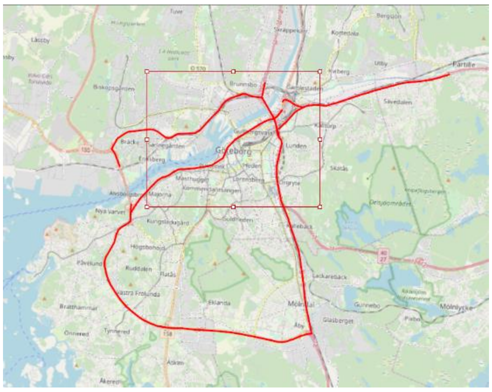
No positive impacts in any of the three stages from reserving a bus and AV lane on the motorway network (measure 2)

This measure leads to a marginal increase in car travel times and delays in the Introductory stage but no increase or decrease in the Established and Prevalent stages. Travel times on bus lanes decrease in Introductory stage but increase in Established and Prevalent stages and gains of reserving a lane for buses and AVs disappear. ,



Potential safety effects

The macroscopic transport model used in this use case does not provide data or sufficient information for assessing impacts of AVs on safety, but it is possible to analyse effects on vehicle kilometres. An increase in kilometers driven imply more accidents if the accident probability per vehicle kilometers stay the same. The vehicle kilometers on motorways seems to decrease in the Introductory stage and increase in the Established and Prevalent stages, while total vehicle kilometers on urban streets exhibit an opposite trend. This indicates potentially an increased risk (if assuming no change in risk per km of the AV introduction) on motorways in the Established and Prevalent stages due to higher volumes.

Design recommendations

The findings described above suggest that a slight increase in delays and congestion levels on the urban core networks in the Introductory stage, especially on motorways. In the Established and Prevalent stages, delays and congestion levels have a moderate decrease. Reserving a bottleneck link (in this case a tunnel) that increases the capacity for AVs has in general a positive impact on traffic performance in the Established and Prevalent stages when AV share is high. However, only reserving a lane on the major motorway network that does not increase overall capacity but just redistributes capacity to AVs does not lead to any positive impacts on traffic performance. In the Introductory stage, buses gain from a shorter travel times and delays while cars lose from such a measure. In the Established and Prevalent stages, there is no gain or loss for either buses or cars.

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Use case 3: Signalised intersection including pedestrians and cyclists

A microscopic Vissim model was used to investigate the traffic performance impact of the introduction of automated vehicles on the traffic at a signalised intersection with an advanced control algorithm at one of the main arterials in Helmond.

Increased travel time, especially for CAVs

Due to the full speed limit compliance of the automated vehicles, these experience significantly increased travel times. The speed compliant CAVs also reduce the possibility of speeding for the conventional vehicles, increasing their average travel time. This effect increases with the penetration rate of CAVs but is partly counteracted by decreased delay at the intersection as the CAVs get more advanced.

The advanced adaptive traffic signal control adapts to the partly automated traffic, redistributing green time between motorized traffic and active modes

The saturation flow is lowered by the presence of cautious AVs and increased by the presence of advanced AVs since the former claim more safety margins and the later less. The advanced traffic signal control algorithm reacts to the changes in saturation flow (or some effect of them), by redistributing green time from and to the active modes, respectively. That is, in the introductory stage the green time share is increased for vehicles and reduced for bicycles and pedestrians to keep the vehicle flow up, while it is opposite in the Prevalent stage. This adaption leads to increased delay and travel time for active modes in the Introductory stage, while decreased delay and travel time in the Prevalent stage.

Potential safety effects

The analysis indicates a potential reduction of road traffic crash risk and that the benefits increase with increased penetration rate of automated vehicles. A large part of the risk reduction is due to that AVs are assumed to make less (or no) “driving errors”, compared to human drivers. Most of the remaining risk is due to situations where the automated vehicle could be involved in a crash due to a traffic condition caused by a conventional vehicle. The more conservative driving logics may lead to more frequent sudden brakes which might cause problems from a human driver perspective.

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Design recommendations

When advanced adaptive traffic signal control algorithms are used, care should be taken to ensure that the introduction of automated vehicles does not lead to an unwanted redistribution of green time from active modes, especially in the Introductory stage. However, since this type of intersection is very structured with time separation of all conflicts, the negative impact in the Introductory stage is rather small, so for this stage this type of intersection is preferable.

From a safety perspective it is of interest to find ways to give more time to the AVs to react and understand what happens, e.g. by wider, raised or rumbled lane markings or coloured and raised strips at waiting areas in the intersection.

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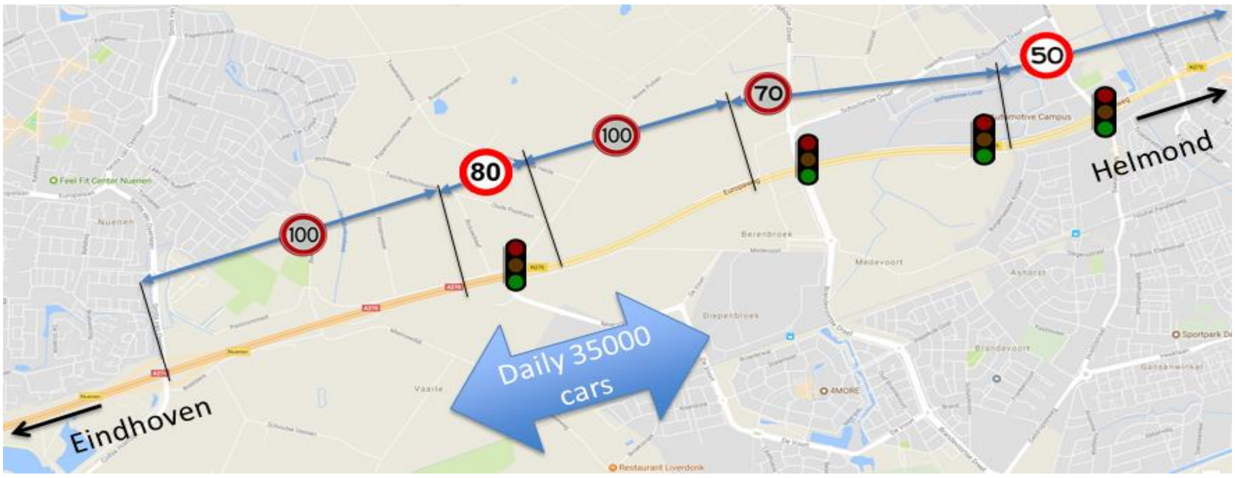
Use case 4: Transition from interurban highway to arterial

A microscopic Vissim model was used to investigate the traffic performance impact of the introduction of automated vehicles at the transition from highway to arterial outside Helmond.



CAV speed compliance leads to increased travel time both for CAVs and CVs

The full speed compliance of automated vehicles reduces speeding among the conventional vehicles and leads to longer travel times for all vehicles except for very high penetration rates of advanced CAVs.

Large discrepancy in delay between automated and conventional vehicles

Since the desired speed of CAVs is close to the speed limit they are hardly delayed at all (except at intersections) while many of the conventional vehicles have desired speeds significantly above the speed limit and are thus delayed significantly by slow-moving CAVs.

Platooning leads to a slight improvement overall for motorized traffic and significant improvement for active modes

Allowing CAVs to form ad-hoc platoons, either in any lane or only in the rightmost lane, slightly improves travel time and delay for motorized traffic. Platooning leads to increased saturation flow at intersections and thereby less need for green time, which enables redistribution of green times to the active modes who receives the benefits of the increased intersection capacity. The difference between allowing platooning in any lane or only in the rightmost is small.

Potential safety effects

The analysis indicates a potential reduction of road traffic crash risk and that the benefits increase with increased penetration rate of automated vehicles. A large part of the risk reduction is due to that AVs are assumed to make less (or no) "driving errors", compared to human drivers. Most of the remaining risk is due to situations where the automated vehicle could be involved in a crash due to a traffic condition caused by a conventional vehicle. The risk reduction increase with increasing penetration rate of AVs but the change is not that large since higher penetration rates also imply more "aggressive" AVs using the All-

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knowing driving logic which aggressiveness might lead to unexpected behaviour compared to the two more conservative driving logics, so new crashes could occur.

Design recommendations

Facilitating platoon formation at intersections can be a way of improving the conditions for active modes without reducing the throughput of motorized traffic. The recommendations from a safety point of view consist to a large degree of measures that also improve safety for the current situation with conventional vehicles, e.g. installation of safety barriers and barrier terminals, replace street lamps by breakable poles, removing obstacles, reducing speed limits, etc. This is natural since most of the residual risk is due to the traffic situations caused by conventional vehicles which will be present in the future scenarios

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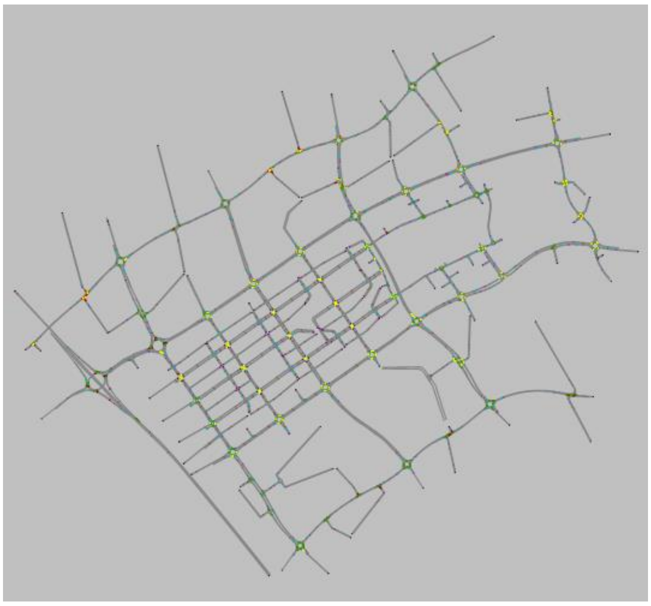
Use case 5: Waiting and drop-off areas for passengers

A large microscopic model of The Central Milton Keynes area and its immediate surroundings was implemented in Vissim to investigate the effects of restricting access to the city centre for cars and instead provide vehicle intercept areas at the perimeter of the city centre for transfer to other modes.



Introduction of CAVs first significantly worsen and then significantly improve traffic performance

On the one hand, the cautious AVs in the Introductory stage cause significant delay, likely at the many roundabouts of the city. On the other hand, in the Prevalent stage advanced AVs significantly improve the traffic performance and decrease travel time even though they comply fully to the speed limits.

Introduction of pickup and drop-off areas reduce in-car travel time significantly

The introduction of high capacity pickup and drop-off areas at the perimeter of the city centre significantly reduces in-car travel time. However, part of the reduced travel time is replaced by travel between the origin/destination in the city centre and pickup and drop-of areas, which is not included in the model.

Car parks at the city perimeter increase in-car travel time due to their limited inflow capacity

If the pickup and drop-off areas are replaced by car parks the result is instead an increase in travel time and delay due to queue formation from the car park entrances. However, if it is possible to add a third lane on the links towards the car parks there are even larger positive effects than from the pickup and drop-off areas.

Potential safety effects

The analysis indicates that introduction of AVs would impact the city safety positively. As expected, due to better lane control, better surrounding awareness, etc. there would be less accidents on both arterials and urban streets. In addition, restricting the access to the city centre will remove human error accidents in this area. As there is grade separation between motorized vehicles and active modes within Milton Keynes a lot of accidents with pedestrians and accidents with parked vehicles are already avoided regardless of AVs and the main gain would be related to single vehicle crashes or vehicle collisions.

Design recommendations

Vehicle intercept locations at the city centre perimeter can lead to significant traffic performance improvement, provided that their capacity is sufficient to handle the incoming traffic and that there exists a well-functioning transit system within the city centre.

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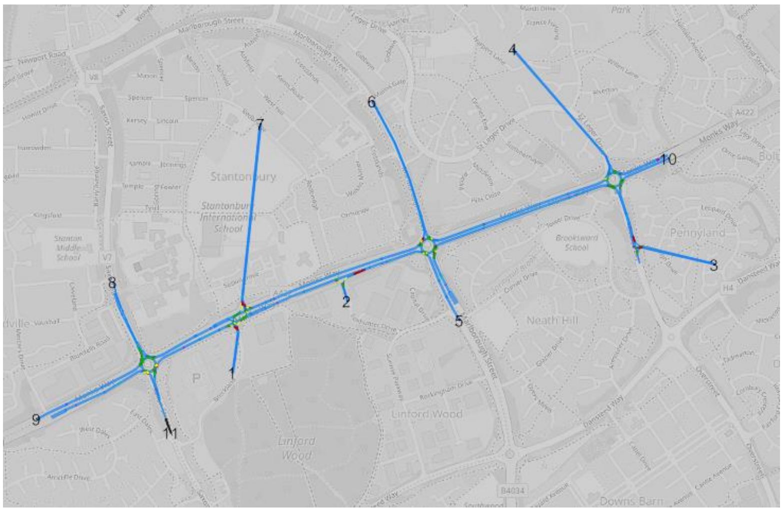
Use case 6: Roundabouts

A microscopic Vissim model of the H3 Monks Way outside of the Milton Keynes city centre was used to investigate the traffic performance impact of automated vehicles on an arterial with roundabouts.



Large increase in travel time and delay for the Introductory stage

The cautious CAVs in the Introductory stage have trouble entering roundabouts due to their large required gaps, leading to queue build-up behind them and large delays for both automated and conventional vehicles. For a future demand of 120% of todays the system seems to be close to breakdown in the Introductory stage with very large delays. However, the traffic condition improves as soon as the Basic AVs are replaced by Intermediate AVs and there are large improvements as most of the traffic is advanced AVs.

Adding traffic control based on V2V communication at roundabouts amplify the effects

Implementing a specific V2V based control system for CAVs at roundabouts increases the effects; the traffic conditions deteriorate even more in the introductory stage with several hundred percent increase in delay, and the benefits in the Established and Prevalent stages are also amplified.

Adding a third lane would dramatically improve traffic performance if possible

If CAVs are able to drive much more precise than human drivers, it could be possible to reduce the lane width to two thirds of the present width and thus include three lanes in each direction. The simulations indicate that this would dramatically increase traffic performance, but it would require a fully automated vehicle fleet.

Potential safety effects

The analysis indicates that introduction of AVs would impact the safety positively. As expected, due to better lane control and better surrounding awareness there would be less accidents. As there is grade separation between motorized vehicles and active modes along the arterial and in the roundabouts a lot of accident with pedestrians and accidents with parked vehicles are already avoided regardless of AVs.

Design recommendations

The evaluated V2V-based control system should not be implemented until the CAVs present in the system is sufficiently advanced, corresponding to the Established stage used in the evaluation. The city should continue to investigate further solutions to improve the capacity at roundabouts for cautious CAVs to be prepared if the CAV development and deployment result in a scenario similar to the introductory stage investigated in CoEXist.

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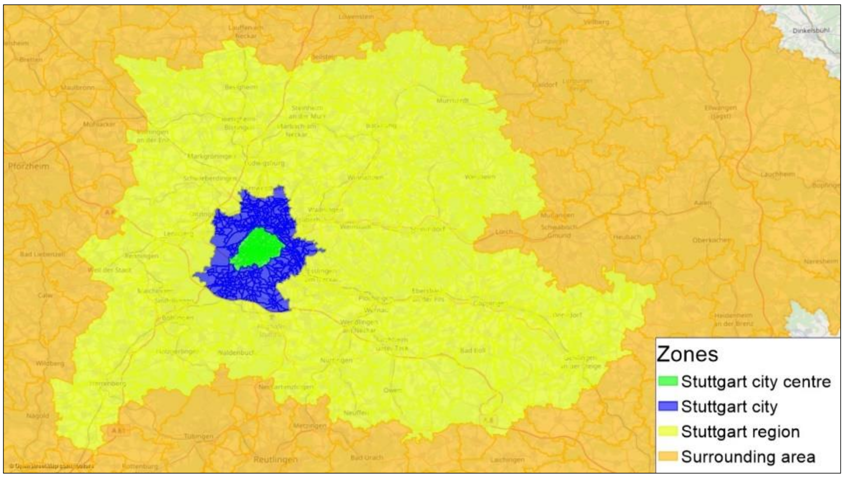
Use case 7: Impacts of CAV on travel time and mode choice on a network level

A macroscopic multimodal Visum model for the Stuttgart Region was used to investigate the impact of automated vehicles on road capacity, route choice and mode choice. The model includes detailed car and public transport networks. Travel modes for passenger transport that are considered in the mode choice are walking, cycling, public transport (bus and rail), car driver and car passenger. The figure on the right shows an overview of the study area.



Cautious CAVs lead to lower traffic performance/capacity while more advanced AVs improve traffic performance

The modelling results show a modal shift from car modes (car driver and passenger) to other modes in the Introductory stage with cautious CAVs (which decrease road capacity). In the Established and Prevalent stages, more advanced CAVs that imply increased road capacity lead to a modal shift from other modes to car modes.

Travel time assumed to be perceived as a shorter period amplifies the modal shift towards car transport to an even greater extent than traffic performance/capacity impacts

On the one hand, an introduction of CAVs means that travel time can be perceived as a shorter period due to the possibility to do other things than driving. On the other hand, an introduction of CAVs leads to a decrease/increase in road capacity. The impact from travel time perception amplifies the modal shift towards car to an even greater extent than road capacity impacts.

Advanced CAVs also lead to a different destination choice

The possibility to do other things than driving makes traveling by car more comfortable, which consequently will cause people to conduct longer trips on average and therefore total distance travelled and total time spent increases for car traffic.

More roads included in the operational design domain (ODD) of CAV amplify the impacts

If CAVs' can and are allowed to operate in automated driving mode on all main roads compared to if they only can and are allowed to operate in automated mode on motorways amplifies the impacts on traffic performance. A bigger magnitude of a decrease in traffic performance metrics can be found in the Introductory stage with cautious CAVs while that of an increase are found in the Established and Prevalent stages with more advanced CAVs.

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Potential safety effects

The macroscopic travel demand model used in this use case does not provide data or sufficient information for assessing impacts of AVs on safety, but it is possible to analyse effects on vehicle kilometres. An increase in kilometers driven imply more accidents if the accident probability per vehicle kilometers stay the same. The more advanced AVs imply an increase in the vehicle kilometers travelled by car and the effect is enlarged if the travel time perception decrease. Hence, there might be a risk of decreased safety (if assuming no change in risk per km of the AV introduction) due to more car kilometers when AVs are introduced.

Design recommendations

Until fully automated vehicles and related services are available, there will be a long period with highly automated vehicles. This use case shows a probable development in cities and regions. The findings described above suggest a general trend of decreased traffic performance/capacity with cautious CAVs while more advanced CAVs which may only be available at a later stage lead to increased traffic performance/capacity. Perception of travel time plays a very important role as it represents benefits in travel comfort for car trips and the related impact on mode choice and destination choice is larger than traffic performance/capacity impacts.

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Use case 8: Impact of driverless car- and ridesharing services

The Stuttgart Region travel demand model was used to provide a better understanding of the impacts of driverless mobility services on travel behaviour. The examined scenarios differ in terms of the available transport modes, the price levels and the willingness to share a car or a ride. The investigated mobility services include a carsharing service, ridesharing not integrated into public transport and ridesharing fully integrated into public transport.

All considered mobility services lead to modal shifts to this new service

In all scenarios tested, driverless carsharing, direct ridesharing services and ridesharing not integrated in public transport have a non-neglectable share, suggesting that all considered mobility services lead to modal shifts. This also leads to increase of vehicle mileage in the study area and its impact is larger in the city compared to the region. The direct ridesharing services of public transport get large modal shares compared to driverless carsharing and ridesharing not integrated in public transport.

Substantial substitution rates between the considered services and privately owned vehicles

For the same number of trips, driverless carsharing service needs roughly twice as many vehicles as driverless ridesharing service. If bus services are removed completely the public transport integrated ridesharing service can replace the bus service (with direct trips and feeder service to rail transport), but vehicle mileage will increase, especially in the city. One ridesharing vehicle is able to replace approximately seven privately owned vehicles.

The considered variation in mobility service prices only had small effects

The price reduction for direct ridesharing services by 20% leads to only neglectable increase in modal shift and trip distance in the city (less than 1%). However, only a limited set of price variations is tested.

Design recommendations

There is a big difference in terms of the results if the mobility service is integrated into public transport or not. If the driverless ridesharing service is integrated into public transport , the public transport operator decides on which trips are suitable or allowed for direct service (door-to-door) and which trips will only be supplemented by a feeder service (with CAV) to line-based public transport. In this use case, direct ridesharing service is included in the public transport ticket while costs for direct ridesharing service correspond to average public transport costs depending on trip distance. However, the cost is assumed lower than costs for ridesharing not integrated into public transport or carsharing. The results heavily rely on assumptions and are consequently very speculative. The decisive assumptions mainly concern the characteristics of the automated mobility services and how travellers with or without car availability perceive and evaluate these services.

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General single infrastructure level effects and recommendations

The traffic performance effects of automation are investigated through microsimulation in use case 1 and 3-6. All these except use case 5 focuses on small areas with one type of infrastructure in focus, while use case 5 models a whole city centre with its immediate surroundings. The results of all five microscopic use cases indicate a decreased traffic performance in the Introductory stage due to the cautious CAVs. However, the magnitude of the decrease varies substantially between the investigated sites, with large decrease in traffic performance for less structured traffic environments like roundabouts and shared space, and smaller decrease for highly structured traffic environments like highways, arterials and signal-controlled intersections. The negative effects are reduced as the CAVs get more advanced, and in most cases the conditions improve above the baseline in the Prevalent stage, and in some cases dramatically so. The Established stage can in most use cases bring either improved or worsened traffic performance, depending on how quickly the early cautious CAVs are phased out and replaced by more advanced CAVs.

The simulation results indicate that in the Prevalent stage, when a large part of the vehicle fleet consists of advanced CAVs, there are several ways to amplify the positive traffic performance effects of the CAVs, such as redistributing green time in intersections to active modes or introducing V2V based control in roundabouts. However, it seems harder to reduce the negative effects during the Introductory stage, when CAVs are very cautious; it rather seems that such attempts may backfire, reducing the traffic performance even more, which highlights the prompt need to plan for the introduction of CAVs and for careful modelling of proposed measures. It may be the case that for some performance critical infrastructure it is most beneficial to avoid the introduction of Basic CAVs altogether, and only allow automated vehicles when they safely can operate with safety margins comparable to those of human drivers. This may be especially relevant if the investigated traffic environment is less structured, such as roundabouts.

General network level effects and recommendations

The network level effects of CAVs are investigated in use case 2, 7 and 8. Use case 2 focuses on the impacts of CAVs on road capacity and route choice and use case 7 additionally focuses on the impacts on modal shift. Use case 8 focuses on the impacts of introducing driverless car sharing systems on road capacity, route choice and modal shift. The results show that a decreased traffic performance is observed in the Introductory stage with cautious CAVs while an improved traffic performance can be found in the Established and Prevalent stages with more advanced CAVs. Change in travel time perception due to the possibility to do other things than driving plays an important role which consequently leads to modal shift to car and longer travel distance and time per trip. Driverless car- and ridesharing services have a potential large impact in reducing privately owned vehicles. Among all three types of sharing services, direct ridesharing services achieve the highest modal share.

The findings suggest that the transition period of CAVs will very possibly start from an increased congestion in the urban areas when there is a low market share of CAVs with mainly cautious driving logic.

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Measures that prioritize CAVs such as road or lane reservations for CAVs are not recommended during this Introductory stage. It is, however, recommended to open only part of the network, e.g. motorway, for CAVs and thereby reduce the negative impact of CAVs on the network level. When it comes to the Established and Prevalent stages where more advanced CAVs have a considerable market share, measures that prioritize CAVs can be considered effective since more advanced CAVs can better make use of the existing capacities. However, measures that only redistribute capacities such as reserving a lane for CAVs are not recommended but measures that increase CAV capacity, such as redesigning a 2-lane motorway to a 3-lane motorway for CAVs can be considered. Although delay minutes are expected to be improved in the Established and Prevalent stages, travel time and vehicle kilometre travelled will increase due to change in travel time perception, which suggests a potential negative environmental impact.

The results also suggest that driverless car- and ridesharing services, especially the direct ridesharing service, may be considered an attractive solution from a passenger perspective. However, total vehicle mileage will still increase, especially in the city. It is therefore recommended that direct driverless ridesharing services as a complement to the existing public transport system is considered to improve mobility in the suburban and rural areas. The system, including the fleet size and price settings etc., is recommended to be carefully designed. Qualitative approaches, such as survey studies, and quantitative approaches, such as modelling and simulation, need to be used and integrated.

General conclusions and recommendations

The modelling results of all use cases show that the traffic performance will degrade in an Introductory stage with low penetration rates of Basic AVs, especially in less structured traffic environments. Likewise, the results agree that as the Basic AVs are phased out and replaced by more advanced AVs, the traffic performance will improve, and in a Prevalent stage with high penetration rates of Advanced AVs, the traffic performance will surpass or at least reach levels comparable with that of the baseline. Furthermore, driverless car and ridesharing services may be attractive for users and lead to increased traffic volumes.

In general, the only investigated measure that reduce the negative traffic performance effects in the Introductory stage is to only allow automated driving in highly structured traffic environments like motorways. On the other hand, several of the investigated measures can be implemented to further improve the traffic performance in the Prevalent stage, such as introducing V2V based traffic control in roundabouts or taking advantage of the high precision driving of the AVs by replacing two standard width lanes with three narrow AV exclusive lanes. The results also emphasise the importance of careful modelling of future partly automated traffic when planning infrastructure that are likely to remain through most of the era of coexistence of conventional and automated vehicles.

The conducted safety assessments indicate potential reduction of road traffic crash risk and that the benefits increase with increased penetration rate of automated vehicles and more advanced automation functions. A large part of the risk reduction is due to the fact that AVs are assumed to make less (or no) “driving errors”, compared to human drivers. Most of the remaining risk is due to situations where the automated vehicle could be involved in a crash due to a traffic condition caused by a conventional vehicle. The more conservative driving logics may lead to more frequent sudden brakes which might cause problems from a human driver perspective. While more “aggressive” AVs using the All-knowing

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driving logic might lead to unexpected behaviour compared to the two more conservative driving logics, so new crashes could occur. The results also indicate that different types of automation functions may reduce the risk for some type of accidents and that these gains may arise already at lower level of automation. It is important to note that technical failures are not considered in the safety assessment.

It is noticeable that several of the safety related recommendations apply mainly or also to conventional vehicles. This comes from that most of the residual risk is due to traffic situations caused by conventional vehicles. Hence, a general recommendation is to continue work with increasing the safety of the infrastructure in line with current efforts; conventional vehicles will likely remain on the roads for an extended period, and improving their safety will be beneficial during the whole era of coexistence.

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Partners

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