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TO : Practitioners in the field of automated driving and its impacts on traffic

CC :

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SUBJECT : Next steps in describing possible effects of automated driving on traffic flow

Introduction

Although at times traffic flow can be complicated to understand and predict, our current understanding is nevertheless pretty good and allows predictions of current and future situations to be made. However, this is about to change with the emergence of (partially) automated vehicles[1] on roads. This emergence will change the way people drive (speed and acceleration choices, following behaviour, lane change behaviour) and will change the dynamics present in traffic flow and with that the ability of traffic to move effectively. The first generation of partially automated vehicles is already on the road in the form of Adaptive Cruise Control (ACC) and Lane Keeping Assistance (LKA), as the so-called SAE level 1 vehicle automation (SAE 2014). Practical and technical tests are already widespread on higher levels of automation, with their mass-produced introduction expected in advance of 2020 (Merat et al. 2014). According to Shladover (2016) fully automated (SAE level 5) vehicles will not be here until 2075 at the earliest. At this point, no statement has been made on the point if these changes are going to be positive or negative. The reason for this is that there are too many uncertainties in relation to the effects that automated vehicles will have on traffic. Many enthusiasts have made incredible claims that automated vehicles will solve many of our traffic problems and can have an overwhelming positive effect on mobility, traffic flow and safety. However, these claims are rarely substantiated and are often based on questionable assumptions regarding the future. Furthermore, even if these claims are correct, they are applicable to a situation that lies many decades in the future, i.e. 100% penetration rate, and do not consider the route leading towards this future (the so called transition period). The main consensus within the traffic and mobility community is that traffic flow will initially worsen with the introduction of automated vehicles (Le Vine, Zolfaghari, and Polak 2015, SBD and HERE, 2016). This has a lot to do with conservative settings of automated vehicles, unfamiliarity with automated vehicles from both drivers and other road users, initial teething problems with the technology and a limited ability and penetration for cooperation between vehicles (Shladover, Su, and Lu 2012). Furthermore, there are predictions that traffic volume may eventually increase due to a steep uptake in automated vehicles (Wadud, MacKenzie, and Leiby 2016). However, again there is much uncertainty in relation to these statements, even if they are well substantiated.

In the meantime, road authorities continue to plan for the future of their roads and will often be looking at a time horizon of 10-40 years in the future. They must consider the future state of traffic and therefore also the effect of automated vehicles, and must better understand the uncertainty in the expectations regarding the impact on traffic flow. It is not an option to ignore their effects, as current initial estimations of their effects range from negative to positive. Such impacts and their variability are too large to ignore. However, here lies an immense challenge, as current knowledge on the effects is insufficient to be able to properly consider them. This is the reason why focused and extensive research is required on the effects that automated vehicles will have in the future

[1] In this publication, automated vehicle relates to any vehicle with any level of vehicle automation, and does not exclusively mean fully automated.

throughout their initial deployment in the coming 5 to 10 years up to the point where higher penetration rates are present on roads. Much research is currently on-going on a wide range of issues related to automated driving, however we at TrafficQuest feel that there is an insufficient focus and depth on the transitional phase in which mixed conventional and automated vehicles will be present on the roads and that key components, such as an understanding of vehicle interaction, are missing in current research. We do note that most of the performed research is of high quality and the shortcoming are understandable due to the current constraints of real life data scarcity and the many uncertainties. We propose a substantial effort to alleviate as many of these shortcoming as possible to be able to describe future traffic. Therefore we state an overall goal for research in this area as: **To be able to quantify and describe the effect of automated vehicles in various mixed traffic conditions, primarily in terms of traffic flow, but also in terms of safety, comfort, and environment.** This requires being able to replicate driving behaviour of vehicles in mixed traffic.

In this memo, we describe the challenges in describing traffic with the presence of automated vehicles and look at the uncertainties that exist to be able to estimate and predict the effects on traffic flow and traffic safety. Furthermore, we consider the current state of affairs and the general approach that should be followed to gain greater understanding and make suggestions to what the next steps may be to tackle these challenges, such that road authorities become aware of the possible implications. An outline of this process is given graphically in Figure 1.

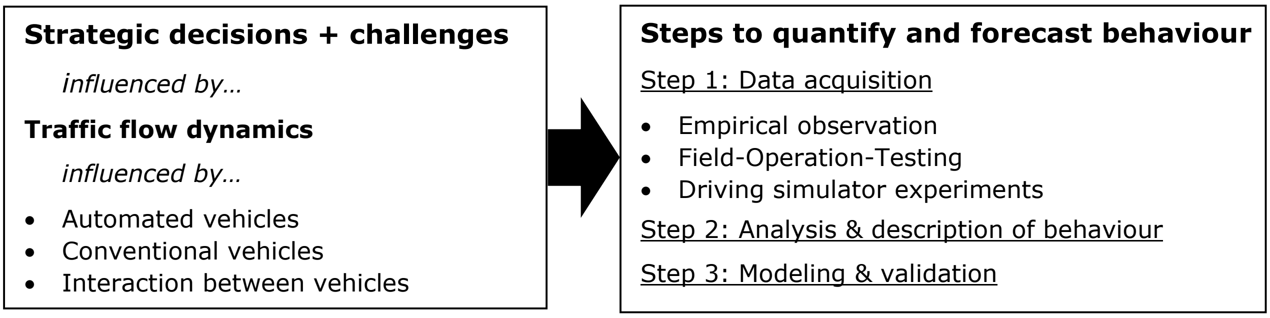

Figure 1: Outline of the solution process to answer strategic challenges for automated vehicles in mixed traffic for an unknown future

The challenge: transition towards mixed traffic

As we brace ourselves for the mass deployment of automated vehicles on roads, planners and road authorities must consider actions to facilitate their introduction. The main challenges here stem from the unknown effects that will occur in mixed conventional and automated traffic in reality. This creates challenges at a strategic level, which stem from the challenges that exist at a traffic flow level and the interactions between vehicles. We will mention a few of the strategic challenges, while the focus here lies with the underlying traffic flow challenges.

Strategic challenges

1. **Strategic planning** demands a knowledge of future traffic states and circumstances. In strategic planning, one often considers a time horizon of 10-40 years in the future. However, the difficulty here is that future traffic states, characterised by traffic throughput, congestion, safety and emissions, are far from certain and are a result of many different scenarios of which the assumptions themselves are immensely uncertain. This begs the question: how can one plan for such a future in which so little is known and in which the introduction of vehicle automation is going to play a major role?

2. A pressing question relates to the initially expected **decrease in traffic performance** due to the introduction of automated vehicles, which may be unable to perform at the same overall level as conventional drivers in many situations[2]. It cannot be expected that road authorities accept such a severe decrease in performance over many years. However, if the drop in performance is over a limited period (years rather than decades), is it reasonable to take action that may cost many millions of euros and may become redundant once automation and cooperative technology reaches the stage that traffic flow improves? This conundrum is one that must be carefully approached and not reactively, but proactively. And again, there remains a great deal of uncertainty in relation to the extent that a decrease or increase in traffic flow performance will occur in mixed traffic as well as an uncertainty in the duration of these periods as technology develops.
3. Another challenge is **traffic safety**. During the transition period, there will be a mix of conventional and automated vehicles in close interaction. We currently lack an understanding of drivers' behavioural adaptation (of the manually controlled vehicles) when they interact with automated vehicles, and consequently the impact on traffic safety.

These strategic challenges are just three of a number of challenges that exist. They are all directly linked to the ability to describe and predict traffic flow in mixed conventional and automated vehicle conditions. This memo will not address the above challenges any further, but will rather focus on the underlying challenges of addressing uncertainties in the description and prediction of future mixed traffic flows.

Traffic flow challenges

This section presents the main challenges of modelling drivers' behaviour in mixed traffic:

1. The foremost challenges relate to accurate **real-life descriptions of the microscopic behaviour of automated vehicles**. These descriptions need to be detailed and accurate. Knowledge is required of the intricate algorithms that govern the automated parts of driving in automated vehicles and how these differ between manufacturers. At the same time, a theoretical implementation of automated vehicles will not optimally reflect how these vehicles perform in practice. Interaction with infrastructure and real life conditions always influences the performance of a system compared to the performance found under theoretical or ideal testing conditions. Therefore, ground-truths are required on how automated vehicles of different levels of automation will perform in reality. However, the majority of these vehicles do not exist yet or are not yet suitable for public use and certainly not at sufficient penetration rates. And here lies the heart of much of this challenge.
   The required behaviour to be captured and be reproduced for automated vehicles can be split into three general dimensions:
   - Longitudinal movement
     This is a description of the car-following and in-lane forward movement of a vehicle and is typically the movement that systems such as ACC control. These systems are currently in use on roads, however there is limited translation of the real world performance of various ACC systems towards simulation, other than presumed and theoretical implementations of performance.
   - Lateral movement (incl. lane-changes)
     This involves all lateral, or sideways, movements of a vehicle, both within a lane or when changing lanes (such as in overtaking behaviour or changing lanes to exit the motorway). Currently Lane Keeping Technology is present in some vehicles, however the lane changing technology soon expected in production vehicles, is the main reason to focus on these movements in more detail. Currently, there is little evidence on how these systems will perform and what this will mean for the surrounding traffic flow.

[2] It is recognized that vehicle cooperation will alleviate some of these problems, however this is not initially expected to be widely available in the initial deployment of vehicle automation.

- Interaction with other vehicles
  Arguably the most important area in which a deficiency in knowledge exists and that is of greatest influence on traffic flow and traffic safety, is the interaction between automated vehicles and conventional vehicles. By definition, traffic flow performance is the result of drivers' behaviour, in which the interaction between vehicles is one of the main aspects. For these reasons, interactions between vehicles is one that certainly requires the greatest degree of attention, while it cannot be considered independently, as it also depends on the previous two areas.

2. Being able to accurately **describe and model conventional vehicles** gains additional importance when we need to consider interactions with automated vehicles. Traffic flow theory and simulation has a long research history that facilitated the possibility to represent individual vehicle movements in a simulation modelling environment. There are many differences between approaches used in simulation models and the quality of the modelled behaviour in relation to real life (Calvert et al. 2015). In many cases the deficiencies of these models is acceptable for the purposes they are used for. A main reason for this is that the simulated vehicles will show similar, or even identical, behaviour and can be calibrated as part of the entire traffic system. However, when it comes to modelling the interaction between automated vehicles and conventional vehicles, it is not possible to assume the same behaviour as when two conventional vehicles interact. Moreover, these differences, both obvious and subtle, lie at the heart of what influences traffic flow and cannot, by any means, be discarded. Any inaccuracies in modelling the behaviour of one or the other will result in very different outcomes of a model and make the results redundant for the most part. Furthermore, the ability to correct errors through calibration when simulating conventional vehicles is not an option when it comes to a mixed conventional and automated vehicle system, as no accurate ground truths to what the results should be exist. Therefore, it is immensely important that the quality of simulation of conventional vehicles is high, so as to allow a fair representation of their behaviour in relation to automated vehicles. If conventional vehicles do not behave as they should in simulation, there is no point placing automated vehicles in the same system, as the interaction between the two types of vehicles will not be modelled correctly, which will be further touched upon in the next area. A final note when it comes to the simulation of conventional vehicles, is that in general longitudinal behaviour is sufficiently accurate. The main deficiencies come in the combination of lateral behaviour, especially lane-changing movements and decisions, and the aspects of stochasticity (Daamen, Loot, and Hoogendoorn 2010). Starting with the latter, traffic is full of stochastic elements, which stem from human behaviour and also external factors (Calvert et al. 2012). These aspects are important in traffic flow and are only partially considered in simulation models. Furthermore, they form one of the main differences between automated vehicles and conventional vehicles, as automated vehicles are presumed to show much less stochastic behaviour. Lateral movement of conventional vehicles has a lot do to with decision making by the human drivers, but also driving styles and experience when it comes to performance of manoeuvres (Farah et al. 2009). There is a large diversity in these aspects, which is rarely considered in traffic models. This is probably the area of micro simulation in which the greatest advances can still be made.

3. The microscopic behaviour of drivers in **conventional vehicles in the vicinity of automated vehicles** is also a research area of which little is known. As previously mentioned, vehicle interaction is probably the most important aspect that will influence traffic flow in mixed traffic. At the same time, it is also an aspect of which very little is known. This has to do in part with the first area that was mentioned: that the performance of automated vehicles of varying levels is yet unknown. However, it also has a lot to do with the cognitive and intuitive reactions of drivers to a new type of driving. Car drivers use experience and taught ability to drive and are pretty good at anticipating and recognising the behaviour of other drivers in conventional vehicles. With the introduction of automated vehicles, a new level of ability and behaviour from these automated vehicles is introduced into the traffic system. This will demand that drivers will have to adapt their driving behaviour to cater for these vehicles. In some cases it may be that a

driver will not be able to satisfactorily react to the behaviour of automated vehicles. In other cases, there may be a relatively large deviation in how automated vehicles behave depending on the manufacturer or physical circumstances. This also forms a challenge for how drivers may react, which may even be overly cautious. Analysis of these aspects and others are required to be able to gain insight into the efficiency of conventional vehicles in mixed traffic. It may be that this is less positive than it is in regular traffic flow, which in turn may lead to a further degradation of traffic flow in mixed traffic conditions. These aspects also form a feedback loop to the second area of describing conventional vehicles in traffic simulation.

Research areas and questions

In the previous section, some of the main challenges of automated driving in mixed traffic conditions were discussed, especially in relation to forecasting their effects. In this section, uncertainties and potential research required to address these issues are summarised, primarily following the same categorisation of the challenges. One should keep in mind that for each question, the addressed issue applies for all the different levels of automation and often also between the levels of automation. For example, the behaviour of an SAE level 1 vehicle (i.e. with ACC) can be measured against the behaviour of an SAE level 4 vehicle (i.e. fully automated on designated infrastructure) as well as against a conventional vehicle.

Behaviour of automated vehicles in practice

What is the **longitudinal** (following) behaviour of automated vehicles in practice? How does this compare to the programmed behaviour from the applied algorithm in the vehicle? How much do automated driving algorithms from different manufacturers differ?

What is the expected **lateral** (lane-changing) behaviour of automated vehicles in practice? Under which conditions does an automated vehicle change lanes (which triggers), and how does this differ from conventional vehicles? Is it more efficient and sufficiently safe? What are the physical trajectories involved with lane changes by automated vehicles (i.e. the smoothness, speed of movement, etc.)? Are automated vehicles able to effectively change lanes in all traffic states and speeds? How much does lane changing differ with automated driving from different manufacturers?

How do automated vehicles **interact** with conventional vehicles? How well can automated vehicles anticipate the behaviour of conventional vehicles? Does this require more space and longer times compared to conventional vehicles? How well will automated vehicles be able to recognise behaviour of conventional and other automated vehicles? How well can automated vehicles take the needs of conventional vehicles into account, i.e. the need to change lane, to merge, etc., and how will this differ under different traffic conditions? Will automated vehicles give more consideration to conventional vehicles compared to other automated vehicles? Will automated vehicles be strictly and inflexibly programmed to deal with different traffic situations? How will automated vehicles deal with 'soft' road regulations (i.e. where drivers in practice act differently from the described regulations, such as at on-ramps)?

Description of conventional vehicles (theoretical and simulated)

What are the main deficiencies in the (lateral) simulation of conventional vehicles? Is there sufficient understanding of these behavioural dynamics and can they be captured in new (lateral) models? Which experiments or analyses are required to capture and describe these behavioural dynamics better? What is the extent of variation between different drivers and can this be included in traffic simulation of conventional vehicles?

Behaviour of conventional vehicles in mixed traffic

Will drivers of conventional vehicles react differently to automated vehicles compared to conventional vehicles? What might the difference in the reaction to automated vehicles be? Are these differences in reaction problematic for traffic flow, but also for safety and emissions, and require additional attention? Is the intention of an automated vehicle known and visible for drivers of conventional vehicles? Is it necessary that this should be conveyed and how?

Strategic policy challenges in relation to automated vehicles

To what extent is dedicated infrastructure required for automated vehicles? At which locations might dedicated infrastructure yield the greatest gains? Is dedicated infrastructural financially and economically feasible? How much and what type of intervention is required from road authorities to deal with automated vehicles on roads?

General research approach

The current state of affairs in relation to forecasting future traffic, in which both automated and conventional vehicles are present, is shrouded in a large amount of uncertainty due to the vast amount of unknowns in the development, deployment and practical consequences of automated driving. The last aspect is the most important for estimating the effect of automated driving in traffic and has been discussed in the previous sections. From each of the previously described uncertainties, a common denominator is the lack of ground truths on the real effects of various aspects of automated driving. These ground truths relate to tangible information about what can be expected in practice. Much effort can be applied to theoretically estimate the effects, however if there is no to little information of these effects from reality, then the design, calibration, validation and verification of any developments really has little value. To solve this issue, effort is required to gain a greater degree of ground truths, which can be used to assist the understanding and description of the effects of automated vehicles in mixed traffic. For a general approach to evaluating C-ITS and automated driving, see Taale, Van Lint and Wilmink (2016).

In general, there are three main approaches that can be followed to gain a greater degree of ground truths. These are **empirical analysis** of current automated vehicle fleets, **Field-Operational-Tests** (FOT), and the use of **driving simulators**. The level of importance and usefulness is reflected in the order these are mentioned in, however real limitations mean that empirical observations and sometimes FOT's are not always possible. The approaches are further concisely described here.

Empirical analysis refers to analysis of systems and situations that already exist and are in use in reality and can therefore be observed. Empirical analysis is by far one of the most preferred ways to gain insights into the effects that automated driving has on traffic flow. The main difficulty is that there are far too few (partially) automated vehicles on roads to observe their overall influence. At the moment a limited number of vehicles has SAE level 1 technology. Their penetration rate does not readily allow much information extraction. Furthermore, higher SAE level vehicles are not yet present and therefore nothing can be derived in that respect from empirical analysis.

Field-Operational-Tests (FOT) are generally seen as the next best thing to empirical analysis. FOT's are tests of automated systems that are performed in real-life, sometimes on off-road test-sites, sometimes on dedicated infrastructure and sometimes in a real life environment, sometimes with extra safety measures in place. An advantage of FOT's is that the derived data is collected from direct observations in practice and therefore resembles the type of data that may be captured during empirical analysis. It is therefore the closest we can get to empirical observations in (partly) controlled settings. FOT's, however, do have some downsides. There are limits to what can actually be tested with a limited number of vehicles and especially in relation to interaction with other vehicles. There are also limitations on the available infrastructure and duration of experiments. FOT's can also be relatively expensive to carry out due to the necessity to fit-out and observe the individual vehicles and to put safety procedures into effect, and also provisions for the used infrastructure. These costs are generally much higher when a larger number of vehicles are involved, which tends to be the situations that are often required when considering the influence on complete traffic flow.

Driving simulators may be seen as a last resort as part of this list, but are nevertheless a very important option, as they allow situations and technologies that cannot be analysed in practice to be considered. Moreover, they allow a great degree of flexibility compared to real life testing and will generally come at a much lower cost and can be applied without needing to acquire a large list of permits. The main challenge is something of a chicken-egg problem. Driving simulators need to be able to simulate the other (automated) vehicles that surround the test vehicle in the simulation environment. However, deriving behaviour for these vehicles can often be the goal of the tests, as well as deriving the behaviour of automated vehicles. Therefore a certain amount of realism in the behaviour of other vehicles is lost. Also, the fact that a driving simulator is an artificial environment influences the ability of test persons to properly react to the situations they are placed in.

Next steps

The questions relating to the current challenges and uncertainties, as previously posed, require purposeful action to be sufficiently answered. The general approaches from the previous section are all required to aid this process. Furthermore, different questions relating to different levels of vehicles automation will require different steps to be answered. In this section, we give an overview of the required steps that need to be applied to allow the posed research questions on the challenges and uncertainties to be answered. The procedure is described generically, but can be applied to most of the questions from the 'uncertainty' section. The general procedure can also be seen in Figure 1.

Step 1: Obtaining ground-truths

The first step is a crucial one, that may require a substantial amount of resources and time, and relates to obtaining ground truths on vehicle behaviour for the considered situation, level of automation, degree of interaction and quantity of vehicles. This is also the only step in which a distinction is made between the level of automation.

SAE Level 0 & 1 vehicles already exist on roads. For this reason, it is possible to obtain ground truths from empirical observations in practice, which is almost always preferred as it reduces the amount of conversion from observations to real behaviour. It is, however, difficult to distinguish between level 0 and level 1 vehicles.
Action: Set-up empirical experiments to capture real-life movement and behaviour of SAE level 1 vehicles and other surrounding vehicles (level 0).

SAE Level 1-5 and mixed level traffic do not yet exist on roads or are not common, and therefore require an alternative approach to gain ground truths. Note that SAE level 1 is also included here, as some situations and questions will require a higher penetration rate of automated vehicles at this level than what is current in practice.
Action: Firstly, it is required to gain some theoretical understanding of how the considered automated vehicles drive. For this, a description or estimate of their behaviour is required, either directly from the applied algorithms of the vehicles themselves, or from expert judgement. Secondly, set-up Field-Operational-Tests or driving simulator experiments to capture realistic behaviour of drivers in relation to the automated vehicles and surrounding conventional vehicles. This may require an iterative loop if the original behaviour of surrounding vehicles is initially not realistic enough.

Step 2: Analyse and describing behaviour
The obtained ground truths from the first step give valuable insights into behaviour and perception of vehicles and drivers for a considered case. The data collected during the first stages need to be translated into useable information for simulation.
Action: Analyse the experiment data and derive behavioural dynamics. Describe the behavioural dynamics in the form of algorithms, such that they can be applied in a simulation model.

Step 3: Implement and validate in a (simulation) model
Once tangible specifications have been derived, it then becomes possible to implement these in (existing) simulation models, which will allow a flexible forecasting of varied situations to be estimated and their effects on traffic flow and safety to be quantified. It is also important to make sure that the model correctly replicates the desired behaviour, therefore validation and verification of the model is required to make sure that the output is reliable.
Action: Implement algorithms in a simulation model and validate the simulated outcomes.

Step 4: Consider findings of microscopic modelling in strategic models
Findings from simulations of automated driving obtained with microscopic models are valuable input for strategic models (mostly macroscopic models). To do this efficiently, relevant indicators can be determined directly in the microscopic simulations (e.g. the indicator 'change in road capacity').
Action: Define how input parameters for macroscopic models can be derived from microscopic simulation output.

Conclusions

To be able to accurately make quantitative predictions about the future state of traffic flow, requires insights into the expected changes of the future vehicle population. In the coming years and decades extensive changes to the vehicle population are expected due to the increased introduction of vehicle automation. Having (partially) automated vehicles on roads will change traffic flow dynamics and how drivers of conventional vehicles will behave, however there is still very little known in relation to what this really means for traffic flow in reality.

In this memo, we have tried to describe this problem and why it is important. The main challenges and uncertainties are posed as pressing research questions, while a general approach and required steps to tackle these questions are given. This is performed as a starting point and to give perspective to decision makers and policymakers on how they may go about solving some of the many issues that exist when trying to predict future traffic flows and all the related questions for planning, investments and other strategic decisions. Being able to forecast future situations is essential and the use of models is imperative, as the complexity of traffic dynamics does not allow estimates to be made of the cuff.

The main challenges relating to the influence of automated vehicles involves gaining greater insights on the behaviour of automated vehicles in practice, the influence they will have on conventional vehicle drivers, the interaction between the different types of automated vehicles and conventional vehicles, and the off spinning strategic challenges. An important omission is currently the lack of ground truths for the influence of automated vehicles. In general, three approaches can be applied to gain greater understanding of ground truths: empirical analysis, Field-Operational-Testing and driving simulator experiments. These should be applied as part of a purposeful course of obtaining ground truths through experiments, describing the derived data from the experiments, and implementing these in simulation environments. This will require (international) collaboration between knowledge partners road authorities. Several projects already underway may contribute, other studies complementing on-going research can be set up in the coming period.

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