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Translating the SAMEN scientific findings to practical applications and implications

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The SAMEN project aimed to investigate different aspects of the interactions between human road users and automated vehicles in mixed traffic during the currently upcoming transitional period, specifically in terms of driving behaviour. The findings of this research have been published in scientific journals. In these scientific publications, the focus was on the direct (academic) research results which look at the deeper and fundamental understanding of the subject matter, rather than the potential usability in the shorter and longer term for road authorities, vehicle approval agencies, or the education of human drivers.

This publication is meant to do just that. Based on the practical knowledge, provided by CROW, RDW, and Rijkswaterstaat, as well as some private parties, we seek to assess what the scientific findings mean to practitioners in the field. To do this, we need to explore the possibilities in a systematic way. We will do this along two pathways.

This publication adheres to the process guidelines for asset management. Government organisations have the task to provide society with a mobility system that contributes to health, safety, the living environment, and accessibility (Snellen, 't Hoen, & Bastiaanssen, 2021). For this, CROW promotes the iAMPro asset management model (CROW, 2023), which covers the steps from (government) policy, through design, and from realisation to the maintenance stage of capital goods such as roads and objects in public spaces, using lines of sight for functionalities that should or could be provided by these capital goods.

This document will focus on the potential line of sight for safe automated driving in mixed traffic. For ADAS applications, a preliminary line of sight was already developed. This will be used as a basis, where some parts can be now further elaborated on, based on the research results, and other insights might give reason to add aspects to the preliminary line of sight.

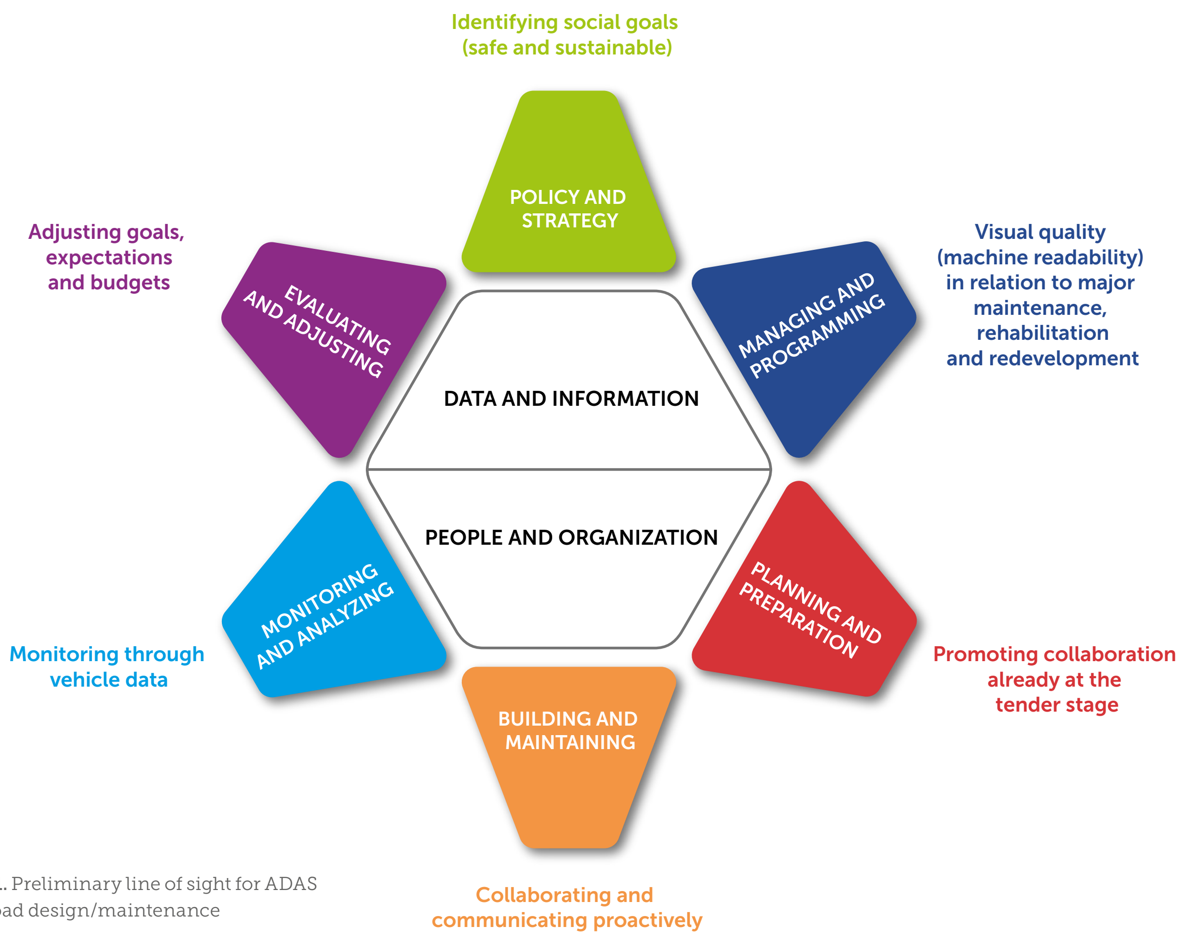


Figure 1. Preliminary line of sight for ADAS and road design/maintenance

Policy and strategy determine the ambitions

Governments can profit from developments in smart mobility technology along the levels on the so-called ladder of smart mobility (CROW, 2022). This ladder is created to help road authorities to assess their ambitions on the implementation of smart mobility policies and measures. The first level is that of basic compliance to current standards and regulations, which already facilitate the safe introduction of smart mobility innovations. Especially the ownership and public availability of high-quality data on the infrastructure is an important issue here. The second level is about a proactive attitude towards current and near-future developments: how can e.g. municipalities use readily available technology to actively contribute to the four dimensions in which policy objectives are formulated (or reversely: how can potential risks and drawbacks of a certain technology be mitigated through proactive policy measures?). The third level is that of the innovators. Some road authorities might want to actively experiment with novel technologies, e.g. by providing stretches of road for living lab experiments or demonstrations.

Programming and execution determine the performance

In the Netherlands, the design, realisation and maintenance processes of policy measures, specifically related to dimensions, materialisation and quality assurance, is regulated and guided through publications of CROW and other parties; the implications of the scientific findings will be compared to some of the current guidelines. This will, more often than not, probably lead to the conclusion that current guidelines are already sufficient to deal with AV technology – which is logical because car manufacturers try to develop their products to comply with what is available on a worldwide scale in terms of infrastructure quality.

How to read this publication

We will systematically go along each scientific finding and then summarise how these relate to practical implications. For brevity, very theoretical and very long-term implications will not be elaborated on. Although level 1 and 2 of the ladder of smart mobility are most relevant for current practitioners, we also look forward to level 3 potential.

1 Human drivers' behaviour and modelling in mixed traffic (i.e. from human drivers' point of view)

Scientific findings

In general, the research shows that the presence of automated vehicles influences human drivers' behaviour, leading to interactions that influence the way traffic flows, especially at intersections. The main influential factors are (1) the recognisability of the automated vehicle (AV), and (2) the 'driving style' of the AV (more defensive vs. less defensive, response times, braking behaviour when approaching a queue or a stop line, etc.), (Reddy et al., 2022).

Simulations have revealed that humans adapt their gap acceptance for merging in a stream of AVs, especially when these are recognisable and when they are programmed to have a less defensive driving style.

Analysis from an open dataset from Waymo has shown that the approach of a signalised intersection of an AV is significantly different from human behaviour (Wang et al., 2023). Deceleration is smoother and starts earlier. Furthermore, the response time of an AV is significantly higher (1.0s vs 0.7s for HDVs), which can be attributed to humans being able to 'read' the traffic flows at the intersection and anticipating the moment they get a green light. Also, the behaviour of humans waiting behind an AV in a traffic light queue is different from waiting behind an HDV, showing smaller gaps and less response time when accelerating from a green signal.

Policy and strategy

The interactions between AVs and HDVs at intersections have a potential impact on traffic safety and accessibility (capacity changes). Especially from a traffic safety point of view, it is necessary to assess which combinations of recognisability and driving style provide an improvement from the present situation. This could be translated into testing standards for vehicle approval institutions, as well into guidelines for driving education.

Programming and execution

From a public asset management point of view, it is desirable to assess whether current design guidelines are still appropriate and whether deviating from these guidelines should be more restricted or not. For some situations, natural driving behaviour by AVs can be improved through external assistance (V2X), requiring data standardisation. This standardisation is largely already available through the iTLC standards by CROW. For such systems to work reliably, it is required that road authorities keep working on data availability and quality. The revised ITS directive by the European Commission provides the legal framework for this.

Summary: interaction HDV-AV		
Finding	Potential consequence	Actions to be taken
Human drivers accept larger gaps when merging in front of recognizable AVs when these are programmed to have a less defensive driving style.	With homogeneous headways and driving speeds, and higher degrees of AV penetration rates, merging by HDVs can become problematic, leading to larger queues and unpredictable merging behaviour by human drivers. More defensive AVs can have an adverse effect on road capacity, due to larger headways, which are at the same time not enough large to facilitate a human driver to merge leading to increasing delays.	Level 1 adhere to current guidelines to create uniform and predictable road situations. Level 2 re-evaluate criteria for intersection design (at what intensities should prioritisation and/or signalisation be applied?). Level 3 Use V2X technology to force larger natural-looking gaps when AV traffic is approaching an intersection to facilitate other traffic e.g. HDVs to merge. Level 3 Human drivers: training to cope safely with the estimation of AV headways and gaps. Level 3 actively research other types of road situations and technologies, volunteering for scientific experimentation.
The approach of a signalised intersection takes longer and is smoother for an AV.	The approaching time for a traffic light determines the duration of the extended green phase (in Dutch standards).	Level 2 Evaluate whether this different behaviour falls within the current parameters of the guideline for inter-green intervals. Level 3 Use V2X technology to inform the AV on approaching speeds, based on time-to-red calculations.
Response time when traffic light changes to green is significantly longer.	The inter-green intervals are based on an assumption for the response times of human drivers. This could influence the capacity of the signal phasing configuration. Longer response times for an AV being the first vehicle can lead to unexpected behaviour by following HDVs, potentially resulting in minor crashes at green light.	Level 2 Evaluate whether this different behaviour falls within the current parameters of the guideline for inter-green intervals. Level 3 Use V2X technology to inform the AV on time-to-green calculations, giving it a lower response time.
Behavioural models of the described observations are publicly available.	It is possible for researchers, software developers, and policymaking professionals to use these models to improve their tools for designing and evaluating the infrastructure.	Level 2 Evaluate whether these models have implications for current design standards. Level 3 Volunteer to perform experiments to test these models more thoroughly in living lab situations.
Ignoring behavioural adaptation of human drivers results in an underestimation of delays in traffic.	This will affect the capacity of the intersection and level of service for the minor road.	Level 2 Evaluate whether this have implications for current design standards. Level 3 Use V2X technology to inform AVs to adjust their time headways to facilitate traffic merging from the minor road.

2 AV Operational Design Domain (ODD)

Scientific findings

The reliability of systems that control an automated vehicle is heavily dependent on how the autonomous vehicle can interpret information about the road and its surroundings. The quality of sensing and perception is often based on vision, and pertains to the recognition of lane markings, road edges, anomalies, etc. The better a vehicle is able to 'understand' what it is seeing, the more diverse types of situations can be handled while driving automatically. Within the SAMEN project, both the technology for detecting lane markings and anomalies, as well as the current state of marking detection performance in different ADAS systems were studied.

The recognition of markings was studied through designing a hybrid spatial-temporal deep neural network model, that was trained to recognise lane markings in different circumstances (Dong et al., 2023). This is an advanced type of deep neural network model which utilizes the spatial and temporal correlations between several consecutive images to detect the lane marking in the very last image. Furthermore, a self-supervised pre-training method based on masked sequential autoencoders was proposed to further enhance the detection accuracy and speed up the model training (Li and Dong, 2023). It turned out that by using these advanced models together with the pre-training method, the system became much better at interpreting the markings, also in difficult circumstances. However, some combinations of factors (badly maintained markings, darkness, etc.) remain difficult for machine sensing and perception.

Similarly, using a semi-supervised Hierarchical Extreme Learning Machines (HELM) model combined with surrogate safety measures as input features, it was possible to detect abnormal driving behaviour from real-world data (Zhang et al., 2023). This could be applied to filter out abnormal behaviours when trying to train automated driving systems with imitation through historical human driving data to achieve more 'human-like' driving behaviour.

A field test was performed to see how well different types of lane markings were detected by existing ADAS systems that are available in current car models (den Otter, 2023). This showed that newer types of markings have better performance than normal paint, and that challenging road circumstances (artificial lights, rain) have a significant impact on the recognisability of markings by ADAS systems, especially when normal paint is applied.

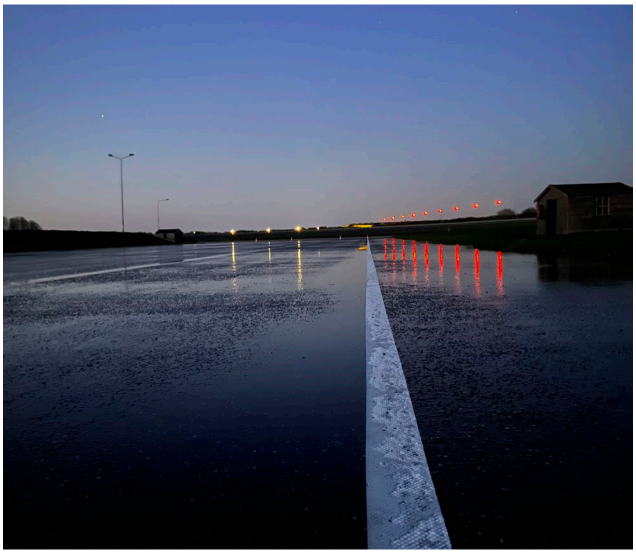
To enhance the capabilities of the AV to interact with surrounding vehicles in challenging situations (e.g. roundabouts) a social-aware planning and control model based on driving risk field and model predictive contouring control was developed (Zhang et al., 2024). The combination of the driving risk field, social-value orientation, and model predictive control allows the consideration of the accuracy of controls, the perceived danger of other vehicles, and balancing the benefits of ego AV versus those of surrounding vehicles.

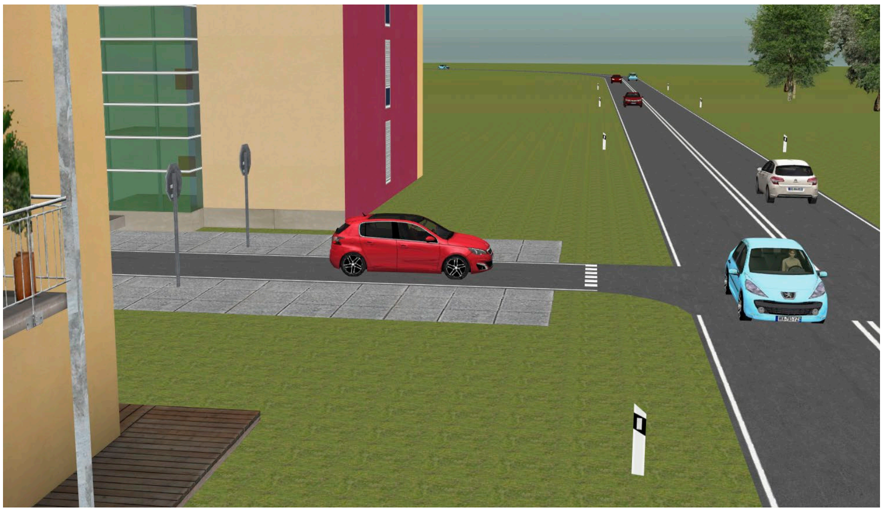
Policy and strategy

If governments have the ambition to enlarge the ODD for AVs, a minimal level of service should be available. This would enable car manufacturers to comply with a minimum standard for road markings that should be detected by a vehicle. For road authorities and contractors, such a standard can be used to determine whether a road is fit for automated driving, potentially avoiding liability issues. For the short term, it is unclear whether current guidelines for markings are sufficient to provide satisfactory visibility for automated systems. Especially if machine readability aspects are not yet described in the current guidelines, adding this could improve the overall procurement process.

Programming and execution

Using the state-of-the-art machine learning model presented, road authorities could automatically make an inventory of their road network to determine which areas are subpar for AV driving. This can help in prioritizing refurbishment and redesign activities for asset managers. Knowing which types of markings are better recognised by automated vehicles, road authorities can actively require that such technologies or equivalents are being procured.





Summary: AV behaviour and control		
Finding	Potential consequence	Actions to be taken
A machine learning model is able to improve the interpretation of vision images for the detection of lane markings. Still, this model is not always able to recognise markings in difficult situations.	Since most commercially available lane detection systems are 'black box' technology, there is no standard to which current and new lane detection systems can be benchmarked against. The now publicly available model could be seen as a yardstick to which the performance of commercial systems can be compared with. This can be relevant for vehicle testing and admission. Having a publicly available method to perceive lane markings, this can also be applied to assess the quality of markings in different circumstances. Video footage of roads can be fed into it to assess whether this 'baseline' system can successfully recognise the markings and identify potential problems. The more structural problems in terms of road design of marking configurations could be tracked back to design standards. These could be identified by combining the readability data into one national database.	Level 1 Adhere to road design standards and standards for the quality of markings for both humans and AVs. Level 2 Perform a quality check using an open-source benchmark system to assess the machine readability of markings, feeding into the maintenance cycle. Level 3 Identify structural machine readability issues in lane marking configurations that can be solved by modifying road design standards. Level 3 Volunteer as a road authority to further improve the methods and technology, by co-operating in field experiments. Level 3 Establish a living database of machine readability of markings of the road network and automatize the maintenance process.
Anomaly and peculiarity detection using a semi-supervised Hierarchical Extreme Learning Machines model (HELM) model can identify abnormal driving behaviour in a data set of driving behaviours.	Being able to pick out abnormal driving behaviours can be used to make traffic enforcement more efficient. Also, these abnormal driving data can be ignored when using human behaviour to train AVs to drive closer to human naturalistic behaviour. Furthermore, it could be used by the testing and admission authority to see whether a new vehicle is performing well enough in terms of driving behaviour.	These are not relevant for road authorities. For law enforcement, insurance compamies, as well as vehicle admission, this can be relevant.
Different types of markings have different performance levels in different circumstances. Especially in challenging conditions, modern types of markings outperform regular paint.	The findings of this test give insight into the performance of new marking types. The machine readability performance is not completely described by the current testing standards.	Level 1 Adhere to standards for road markings. Level 2 Do a regular assessment of machine readability of road markings in challenging circumstances and 'fix' the problematic locations. Level 3 Improve the set of testing criteria to include the performance indicators that determine machine readability.
Social-aware planning and control models can improve the driving behaviour of an AV in challenging interactions such as on a roundabout.	Further insight into the controlling of an AV can contribute to more systematic and objective assessments of driving behaviour models in new vehicle types. This is relevant for testing and admission. Apart from the AV application, the type of modelling can also be used to improve microscopic traffic models that rely on naturalistic driving behaviour.	Level 1 Adhere to current guidelines to create uniform and predictable road situations. Level 2 Proactively set criteria for admitting new AVs on the road considering the level to which an AV is socially aware. Level 3 Improve the set of testing criteria to include the performance indicators that determine socially aware driving.

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References

CROW. (2022). Ladder van Smart Mobility. Retrieved from https://www.crow.nl/kennis/bibliotheek-verkeer-en-vervoer/kennisdocumenten/infographic-de-ladder-van-smart-mobility

CROW. (2023). Het iAMPro model voor Assetmanagement. Retrieved from https://essit.nl/over-assetmanagement/wat-is-het-iampro-model-voor-assetmanagement

CROW. (2023). Landelijke iVRI standaarden. Retrieved from https://www.crow.nl/thema-s/smart-mobility/landelijke-ivri-standaarden

den Otter, M. (2023). Impact of improved lane marking properties on the performance of Lane Keeping Assistance systems in varying circumstances. Master thesis, Delft University of Technology.

Dong, Y., Patil, S., Van Arem, B., & Farah, H. (2023). A hybrid spatial–temporal deep learning architecture for lane detection. Computer-Aided Civil and Infrastructure Engineering, 38(1), 67-86.

Li, R. and Dong, Y., Robust lane detection through self pre-training with masked sequential autoencoders and fine-tuning with customized PolyLoss. IEEE Transactions on Intelligent Transportation Systems, vol. 24, no. 12, pp. 14121-14132.

Reddy, N., Hoogendoorn, S. P., & Farah, H. (2022). How do the recognizability and driving styles of automated vehicles affect human drivers' gap acceptance at T-Intersections?. *Transportation research part F: traffic psychology and behaviour*, *90*, 451-465.

Snellen, D., 't Hoen, M., & Bastiaanssen, J. (2021). *Brede welvaart en mobiliteit*. Retrieved from https://www.pbl.nl/publicaties/brede-welvaart-en-mobiliteit

Wang, Y., Farah, H., Yu, R., Qiu, S., & van Arem, B. (2023). Characterizing behavioral differences of autonomous vehicles and human-driven vehicles at signalized intersections based on Waymo Open Dataset. Transportation research record, 2677(11), 324-337.

Zhang, L., Dong, Y., Farah, H., Zgonnikov, A., & van Arem, B. (2023). Data-driven Semi-supervised Machine Learning with Surrogate Safety Measures for Abnormal Driving Behavior Detection. arXiv preprint arXiv:2312.04610.

Zhang, L., Dong, Y., Farah, H., & van Arem, B. (2023, October). Social-Aware Planning and Control for Automated Vehicles Based on Driving Risk Field and Model Predictive Contouring Control: Driving Through Roundabouts as a Case Study. In 2023 IEEE International Conference on Systems, Man, and Cybernetics (SMC) (pp. 3297-3304). IEEE.

Colophon

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