Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 72 (2023) 1311–1317

Transportation Research Procedia

www.elsevier.com/locate/procedia

Transport Research Arena (TRA) Conference

Connected & Autonomous Vehicles and road infrastructure – state of play and outlook

Hinko van Geelen[a] , Kris Redant[a]*

[a]*Belgian Road Research Centre, Woluwedal 42, 1200, Brussels, Belgium*

Abstract

The developments of connected & autonomous vehicles (CAV) go very fast. Many aspects of CAV are being studied and receive a great deal of attention, but the road infrastructure component seemed underexposed. The Belgian Road Research Centre (BRRC) decided to study on its own expenses the infrastructure component regarding the rollout of connected and autonomous vehicles. The outcome of our research is a comprehensive report that provides insight into the possible consequences for road infrastructure and road authorities. Two scenarios are examined: the co-existence scenario, with different SAE level vehicles using road infrastructure; the full autonomous scenario. For each scenario, special attention was given to the themes 'motorways', 'urban mobility' and 'shuttles'. The report provides insight into "no regret measures" in the field of road infrastructure, and considers the "big picture".

Keywords: Road infrastructure; transport mode; autonomous vehicles; intelligent transport; mobility, forecast.

1. Introduction

The technological developments around self-driving or autonomous vehicles (CAV, connected & autonomous vehicles) go at lightning speed. Are all those involved ready for a successful and safe introduction? How can vehicles with a different degree of autonomy jointly make safe use of the available road infrastructure? As a research institute in the field of road infrastructure, BRRC wished to develop an extensive view on the infrastructure component regarding the rollout of connected and autonomous vehicles.

We initiated a working group with external members that have an interest in the topic (road authorities, public transport organizations, research institutes…). The reason for this research was the insight that many aspects of CAV

* Corresponding author H. van Geelen. Tel.: +32 (0)2 775 82 39; fax: / .
E-mail address: h.vangeelen@brrc.be

10.1016/j.trpro.2023.11.592

are being studied and receive a great deal of attention, but also the feeling that the aspect of 'physical road infrastructure' has so far received only scant attention.

Knowing that the pace of vehicle automation evolution is much higher than road infrastructure upgrades, road asset managers would benefit to know how their actions today do not compromise this advancement. It is essential that road authorities are well armed to take up the challenge and create the conditions that will enable the gradual transition to autonomous vehicles of higher SAE levels (e.g., adapted or easily adaptable infrastructure). At the same time, the data made available by the deployment and use of these vehicles can contribute to the tasks that road authorities have to perform (e.g., road management, road safety and traffic management). The focus of road authorities should continue to be on road infrastructure, but at the same time be extended to digital infrastructure, communication and geolocation. In addition, the use of the road through different modes and for different travel motives has their attention. On the other hand, contractors also need to be prepared for these changes and how this will influence the execution and communication of the road works.

We studied in a span of two years the developments concerning CAV and the role of the infrastructure component. We strived to get answers to unclear issues, like the consequences of CAV on the existing road infrastructure, the opportunities that CAV might offer for the road infrastructure sector, the timeframe within which the road infrastructure should be developed. We explored what is clear and what is still uncertain. From the study of these issues, we have formulated points of attention and recommendations for the road sector.

The outcome of our research is a comprehensive report that provides insight into the possible consequences for road infrastructure and road authorities. Two scenarios are examined: the co-existence scenario, with different SAE level vehicles using road infrastructure; the full autonomous scenario. The realization of this seems far away, but road authorities need to plan long time in advance. For each scenario, special attention was given to the themes 'motorways', 'urban mobility' and 'shuttles'. As a follow-up to the report, BRRC is further exploring the theme of CAV & road safety.

2. Methodology and results

In the working group set up by BRRC, experts from various organizations were able to contribute from their own expertise to the discussions on the research topic. Fascinating knowledge exchanges took place during the meetings of the working group. We screened relevant literature (+215 documents), varying from specific studies to relevant press articles and a few government documents. Together with this screening, expert discussions formed the basis for a report, entitled 'Connected & Autonomous Vehicles and road infrastructure – state op play and outlook', which has been published end of 2020.

The report was written by BRRC experts with input from external members of the working group. It starts with a sound description of the context and the objectives pursued by vehicle automation. Numerous discussions have been held, to assess three themes in particular: (a) infrastructure (design guidelines, road construction and road equipment) for motorways; (2) infrastructure in an urban environment; (3). In anticipation of a distant future, a full autonomous scenario was discussed. More down to earth, the working group elaborates a co-existence scenario of different SAE level vehicles.

The following can serve as an example of the fascinating discussions: the feasibility of society and the pace in which a new technology, which is still in full development, can find its way are estimated differently by the various experts. These discussions sometimes transcend the available knowledge and then are driven by a gut feeling, by personal conviction and by company strategy. As with other emerging technologies, there are some believers and skeptics.

Very typical, for example, was the discussion about the future of individual transport (autonomous cars to replace the current car) versus shared mobility (autonomous robot taxis that could take a large part of privately owned cars off the road). The discussion was about the enforceability and the acceptance of measures. For example, the question was discussed 'how far can you go with restricting access?' Several related aspects came into the discussion:

- the acceptance of access restrictions for certain types of vehicles,
- the access to (personal) AV for categories of users that are unable to drive today, with the potential risk of increase of the number of vehicles on the roads. This can lead to mobility issues. Do we need to regulate this or not?

- Space occupation by AV (robot taxis / 'zombie cars') that drive around without passengers. When should they stop driving around and park? What parking space is needed, and where?

It was also challenging to steer the discussions in the right direction and to focus on the link with the physical road infrastructure. We have consciously broadened the scope of the discussions to mobility in general as a key issue. It also became clear from the discussions that discussions on infrastructure quickly focus on digital infrastructure and tend to underestimate or even neglect the role of the physical component.

BRRC's attention for the link between road infrastructure and CAV continues after the report: the theme of traffic safety is being studied since the end of 2021.

3. Content overview of the report

In a first chapter of the report, we present several contextual topics. This context puts the main challenges for road authorities in the right perspective. A concise description of CAV, ADAS and a driver is followed by a description of the objectives (economic welfare, road safety, mobility, energy efficiency & environment, road capacity...). The SAE-levels of autonomy are presented and linked to the roll-out of CAV. Various obstacles are discussed (p.e. cyber security).

The next chapter deals concretely with the relationship between CAV and infrastructure. The following detected main subjects are part of this chapter:

- Physical infrastructure and digital infrastructure,
- Motorways (design guidelines / road structure / road equipment),
- Roads in urban environment (CAV as a challenge between other challenges / emerging micromobility / sharing systems / greening of transport / speed limit adjustments / digital infrastructure and services / slow mobility and accessibility / diversification of public transport services / delivery goods),
- Shuttles (scope / testing / developments / infrastructure).

In the current article we focus on the conclusions from the closing chapter. These conclusions are likely to apply several years after the publication of the report. Our aim is to provide insight into "no regret measures" in the field of road infrastructure. However, we cannot ignore the "big picture": although road infrastructure is an essential condition for travelling, it obviously has close links with other aspects of society and the travel system (Un) certainty and complexity (outlook and risk management / research for testing) and societal evolutions (policy research and project evaluations /society) precede the conclusions on the road infrastructure issues (signalization / road layout / road structure / road surface).

4. (Un) certainty and complexity

Based on the literature study and discussions, we can say that our journeys in the coming decades will be characterized by a mix of public services and private means of transport, and by a wide variety of connectivity and degrees of autonomy of the vehicles.

A possible final picture - a society with 100% connected journeys (of all types of road users) and autonomous vehicles of only SAE level 5 - remains far away. The necessary changes are so far-reaching that the road to such a society is paved with numerous uncertainties. Weighing the pros and cons, the timing and development of technologies, the rules / roles / responsibilities (for drivers, vehicles, road authorities, policy authorities ...), social acceptance and ethical issues: there are still important aspects in these areas to take steps.

In the coming decades with various levels of autonomy (SAE levels) and connected and non-connected movements, the practical details of the steps to be taken are still unclear. For road authorities, it is important to gain permanent knowledge about progressive insights that remove the uncertainties.

There is a consensus that the gradual introduction of autonomous vehicles is complex. The development of autonomous vehicles is only one of the challenges facing road authorities. In urban context, they must deal with various challenges: the emerging micro-mobility, the subsystems, the greening of transport, the adaptation of speed

limits, the digital infrastructure, the focus on slow mobility and accessibility. Although many questions remain unanswered, all experts agree as well that autonomous vehicles have the potential to bring about major changes and innovations to the entire transport system.

4.1. Future studies and risk management

Due to the uncertainties, road managers should focus more on future studies and risk management when planning the transport system. It is desirable that road authorities think in scenarios, with a long term horizon (10 years and more) on the one hand, and an eye for uncertainties and the overestimation and underestimation of development opportunities on the other hand. It is advisable to act pragmatically afterwards: focus mainly on "no regret" measures for the upcoming lustrum and adjust the actions over time in function of the progressive insight. Next to that, risk management can be a great asset. This is an ongoing process and an essential part of project management.

4.2. Research for testing

The research agenda for the rollout of autonomous vehicles is a full one. Worldwide many tests take place in the field of autonomous shuttles. The current state of affairs is that there is no business case yet. This does not prevent public transport organizations from initiating or continuing tests. The tests usually take place in relatively simple situations, in environments where the confrontation with other road users is limited, and at limited speeds. Gradually, the shuttles are tested in more complex environments, such as on public roads.

Road authorities should play a role in testing with vehicles other than autonomous shuttles, both in preparation and execution. They have excellent information about their road network. They can confront this practical knowledge with ODD (Operational Design Domain) proposed by researchers, the description of the specific operational domains for which an automated function or system is designed to work properly. It is partly up to (local) road authorities to assess how and where the tests can take place in practice.

Participation in the development of the ODD itself is crucial for supralocal road authorities. This can be done by participating in international working groups and research projects, or at least following up on these initiatives. In the further development of the ODD, further attention will have to be paid to transitions between zones or road sections of different ISAD levels (Levels of Infrastructure Support for Automated Driving).

5. Social evolutions / policy

The benefit of autonomous vehicles in a future sustainable mobility policy is a fascinating theme. Some experts see the potential to use autonomous vehicles as a possible solution to current mobility problems (congestion, road safety, environmental pollution). Society may change drastically.

On the one hand, a far-reaching successful introduction of CAV requires continuation of policy research and project evaluations. On the other hand, insight into the social aspects of autonomous vehicles and the associated digitization of society is useful.

5.1. Policy research and evaluation of projects

Research into the cost & benefit of the introduction of autonomous vehicles in the transport system is relevant. Policy documents contain various objectives with advantages and disadvantages. There is often a lack of objective results, and there are contradictions. It is the task of researchers, with the cooperation of road authorities, to perform analyzes, limit uncertainties and apply nuances. The additional research can also provide a more realistic picture of expectations for autonomous vehicles.

Citizen involvement is a crucial aspect in the coordination between road authorities, car manufacturers (vehicle functionalities) and digital service providers in research projects. Acceptance of autonomous vehicles by users and non-users is an essential research area.

Projects with CAV can also be evaluated in the meantime. Those evaluations can lead to project adjustments and can influence future projects. Road authorities can derive concrete actions and options from this. Coordination with policy plans is a point of attention.

5.2. Society

In addition to testing and policy research, a more existential approach is also appropriate. With complex questions such as what kind of society we want to strive for? What kind of cities do we want to live in? With a lot of regulations or a lot of freedom ("state vs. market")? With emphasis on collective or individual transport, or a mix? How to deal with regional differences?

This involves focusing on possible futures for society as a whole. This includes involving relevant stakeholders in determining policy through co-creation. Inclusive thinking around the development of autonomous vehicles can ensure that active (or connected) active road users are duly taken into account. Also, a debate on the use of space by different modes of transport needs to be further pursued. Finally, it can be very helpful to study “best-case” and “worst-case” scenarios in the field of mobility-related aspects.

6. Road infrastructure

Recommendations for the design of traffic infrastructure will have to take the human drivers into account, since most vehicles drivers will still carry out certain actions and corrections for a long time.

Nevertheless, car manufacturers, legislative initiatives, expected evolutions in the vehicle fleet and experience during testing still seem to indicate that road infrastructure will require modifications to facilitate self-driving vehicles. By already considering these expectations in the (re) construction of road infrastructure, subsequent adjustments may become easier. The needs that car manufacturers place most emphasis on today (visibility and harmonization of signage) also make sense for human drivers anyway.

Road authorities traditionally pay attention to physical infrastructure. However, the introduction of self-driving vehicles is introducing new areas for which road authorities should also work on. A digital representation of physical infrastructure ("digital twin") can be used for guidance systems or as an addition or alternative to signage. In case GNSS positioning (GPS, Galileo, ...) is unavailable or insufficiently accurate, balises can make sense to allow (more accurate) positioning. Road infrastructure will need to be complemented by communication infrastructure for the exchange of data.

6.1. Road signaling

It is important that sensors can distinguish and then correctly interpret messages from road signs. Measures that increase the visibility of road signs or road markings, even in less optimal conditions, can certainly contribute to this. Harmonization and simplification of messages will make it easier for vehicle systems to interpret the detected message correctly. European signaling initiatives facilitate the arrival of internationally approved CAV. Road signs and road markings that are not sufficiently recognizable and differ by country or region increase the risk that CAV will not recognize or understand them. In addition to making sense for vehicle systems, human drivers also benefit from uniform and clearly visible messages. Language-related messages should be avoided as much as possible.

If vehicle sensors cannot recognize road signs or road markings correctly, this could be interesting information for road authorities. Connected systems can tell road managers at what locations the signs are insufficiently recognizable. They can use that information as an alternative to visual inspections, and to plan maintenance. The exchange of vehicle data with road authorities can thus contribute to better road infrastructure, both for self-driving vehicles and for human drivers.

Signaling can also be equipped to communicate directly with vehicle systems. Traffic lights and variable traffic signs can already have this option or add it later. Standardized communication protocols are currently being discussed internationally. Today, the choice of the technique used is not yet certain.

6.2. Road layout / road design

It is unlikely that 100% of the vehicles are SAE L5 in the near future. It is currently unclear how incidents will be handled in a traffic system with automated vehicles. Will this be possible in a safe way with the current (or adapted in a distant future) road layout, or will automated vehicles continue to rely on certain infrastructure (e.g., sufficient space for intervention vehicles between vehicles in two adjacent lanes) to handle incidents safely? However, we can assume that fully autonomous vehicles will only be homologated if there are agreements on which infrastructure these vehicles can rely on to handle incidents safely.

It is therefore best to keep all recommendations for road development that apply today. By already considering future adjustments during (re) construction, major works can be limited later. In order to make it possible, for example, to use (later) alternating lanes or dynamic lane layout, physical barriers could be as much as possible avoided (of course always taking into account existing 1 road safety recommendations). The widths of hard shoulder lanes can be adjusted for later conversion into for example a rush-hour lane. At entrances and exits or on weaving strips, space could be provided in order to expand these later for automated traffic and to facilitate weaving movements.

6.3. Road structure

It is yet uncertain whether future vehicles with other drives will be lighter or heavier. Based on the current evolution of the mass of new cars, the expected increase in traffic and the estimate that future vehicle systems may allow the existing road capacity to be used more efficiently, it seems likely that the occupation of a road, both by passenger cars and by freight traffic, will only increase in the future.

This higher occupancy probably has consequences for the load on a road structure. An update of the traffic spectrum (taking into account recent or expected vehicle characteristics) and an estimate of the amount of traffic during the expected lifespan may give rise to other road construction requirements. Due to the higher occupancy, unavailability of a road due to road works or accidents will inevitably also have greater consequences for mobility. Road structures that are more resistant to higher loads, and fast repair techniques seem to be only increasing in importance. In any case, ordinary road users will also benefit from this.

6.4. Road surface

The current generation of vehicle sensors and algorithms can detect and successfully handle defects in the road surface with varying degrees of success. Larger surface defects will remain a problem for the time being and will sometimes lead to a self-driving vehicle (i.e., shuttle) stopping.

In addition, the road surface also plays a role in energy consumption and driving comfort. Both aspects are not exclusively linked to self-driving vehicles, but are becoming more important for electric vehicles (range, consumption) and for the passengers of self-driving vehicles (e.g., shuttles).

It does not seem necessary for the time being to strengthen the existing recommendations for road surfaces. It makes sense though, to ensure that the expected road surface quality is achieved and maintained. Thus, it makes sense to invest in high quality and sustainable repair techniques.

7. Conclusions

Research is still needed in many areas: research for testing and policy research.

Today it is still not very clear which changes to infrastructure are indeed useful for autonomous vehicles. Human drivers continue to play an essential role in driving vehicles for the time being. Based on the literature and discussions, coming decades will be characterized by a mix of public services and private means of transport, and by a wide variety of connectivity and different degrees of vehicle autonomy. Even in a SAE L4 vehicle, a driver must be able to take control at all times. Therefore, it is useful to focus on measures that make sense for autonomous cars AND for human drivers. Such measures are, among others, harmonization of traffic signaling, ensuring good legibility of signaling for vehicle sensors and human drivers, sufficient road surface quality for driving comfort and to avoid false obstacle detections.

Digital maps are indispensable for the safe use of autonomous vehicles and are already deemed necessary for reliable functioning of ISA systems today. An autonomous vehicle that would rely solely on road sign recognition cannot guarantee sufficient safety.

When constructing new infrastructure or major modification works, it is wise to provide space for later adjustments (change of lane width, adjustment of entry and exit lanes, rush-hour lanes).

Considering the increasing load on road structures, with the potential increase in the mass of vehicles (also due to electrification) and an increased risk of rutting caused by autonomous vehicles with no or less wander movement then conventional cars, there may be a need for pavements that are less sensitive to rutting. It also makes sense to keep an eye on the impact on structures.

Acknowledgments

We are thankful for the excellent participation of the members of BRRC's initiated working group. During the expert meetings, we had very interesting discussions that have led to the result, a publication with relevant conclusions for road authorities.

References

Synthesis SE 51 'Belgian Road Research Centre, December 2020. Brussels: BRRC, 2020. 100 p. Legal deposit: D/2020/0690/10. In addition: 215+ documents screened (see list in the publication, available at www.brrc.be).

Dr. Ir. Haneen Farah, Transport & Planning, Delft University of Technology. State of art on infrastructure, 2016.

European Parliament resolution of 15 January 2019 on autonomous driving in European transport (No P8_TA[2019]0005). (2019). Retrieved from https://www.europarl.europa.eu/doceo/document/TA-8-2019-0005_EN.pdf Walker.

The Self-Driving Car Timeline – Predictions from the Top 11 Global Automakers. https://emerj.com/ai-adoption-timelines/self-driving-car-timeline-themselves-top-11-automakers/. 2019

Austroads, Technical Report. Infrastructure changes to support automated vehicles on rural and metropolitan highways and freeways. Audit specification (Module 1), p.9., 2019. Publication no: AP-T347-19 and ISBN: 978-1-925854-46-6

Axhausen, Kay W. What do we want to revolutionize with autonomous vehicles? in 'Route and traffic', Mobility 2050 – transport infrastructure 4.0, VSS, p. 15. January 2019.

Redaction Automobiel Management, March 2019. PSA: no Level 4 and level 5 for private vehicles, March 2019. Automobiel Management (retrieved from www.automobielmanagement.nl) in April 2019.

Marc Green & John Senders, Human Error in Road Accidents, 2013. Retrieved from https://www.visualexpert.com/Resources/roadaccidents.html

Paulsen, J.T. (2018). Physical infrastructure needs for autonomous & connected trucks: An exploratory study (Master thesis, Norwegian University of Science and Technology [NTNU], Trondheim, Norway). Retrieved from https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2562799/19642_FULLTEXT.pdf?sequence=1

Transport Systems Catapult. (2017). Future proofing infrastructure for connected and automated vehicles (Transport Systems Catapult Technical Report, V1.1). Retrieved from https://s3-euwest- 1.amazonaws.com/media.ts.catapult/wp-content/uploads/2017/04/25115313/ATS40-Future-Proofing-Infrastructure-for-CAVs.pdf Virginia Department of Transportation. Connected and automated Vehicle Program Plan, May 2017.

Adams R., Rijkswaterstaat. Brochure Interoperable corridors deploying cooperative intelligent transport systems, http://intercor-project.eu/. January 2019.

Morsink, P., Klem, E., Wilmink, I. & de Kievit, M. (2016). Zelfrijdende auto's: Ontwikkelagenda ZRAen wegontwerp (version 03, final). Retrieved from the Kennisplatform CROW website: https://www.crow.nl/downloads/pdf/verkeer-en-vervoer/wegontwerp/zelfrijdende-autos-verkenning-vanimplicaties-op-h.aspx?ext=.pdf

Clapaud, A. (2017, May). Qui dit voiture autonome dit route intelligente. L'atelier BNP Paribas: Smart city. Retrieved from https://www.aitf.fr