INFRASTRUCTURE CONNECTIVITY TO IMPROVE AUTOMATED DRIVING SAFETY AND INFORMATION QUALITY

Ilkka Kotilainen
Risto Kulmala
Traficon Ltd
Finland

Hironao Kawashima
Keio University
Japan

Sven Maerivoet
Transport & Mobility Leuven Ltd
Belgium

Siddartha Khastgir
University of Warwick
United Kingdom

Steven Shladover
UC Berkeley
United States

Jaap Vreeswijk
Tom Alkim
Anton Wijbenga
MAPtm Ltd
Netherlands

Paper number 23-0294

ABSTRACT

All actors in road transport share and aim for the same mutual goal of safe, clean, and efficient Connected and Automated Driving (CAD). The aim of the research was to study how infrastructure connectivity improves Automated Vehicle (AV) safety in three selected motorway environment use cases of traffic jam, adverse weather and static/dynamic road works as well as quality indicators and requirements for the communication. Information priority with safety criticality in mind was assessed for the three actors of road works or (winter) maintenance operator, traffic manager and AV or Automated Driving System (ADS) developer. The results present Operational Domain Design (ODD) and local condition attributes information priority recommendations, ADS developers trust issues when using information via infrastructure communication, information quality recommendations as well as quality monitoring and management methods.

INTRODUCTION

The safe operation of Automated Vehicles (AV) requires understanding of the conditions in which the Automated Driving Systems (ADS) are capable of operating, i.e., Operational Design Domain (ODD). Because of ADS systems' need of constant monitoring of the current and near future ODD attributes, such as incidents or weather conditions, real-time information is essential to the relevant actors of road works or (winter) maintenance operator, traffic manager and AV (or ADS) developer. This research refers to the automated driving system actor as an ADS developer. However, in practice the primary automated driving system actor ensuring the ODD awareness of the ADS will likely be the fleet operator responsible for the ADS-operated vehicle in question.

Infrastructure communication can be one of the sources of real-time information. Local condition information shared by the local traffic manager may benefit the ADS and vice versa; exchange of information between the actors provides mutual benefits for safe, efficient, and clean automated driving. The values of ODD attributes, which the road operator or traffic manager can regard as local condition attributes, such as weather or traffic flow conditions that the ADS cannot measure or sense by itself, may be provided by off-board sensor infrastructure. The real-time sharing of ODD related data can be accomplished with a concept that we call the Distributed ODD Awareness (DOA) Framework.

We wished to study how infrastructure connectivity improves AV safety in three selected use case scenarios, and the related quality indicators and requirements for the communication. To improve the safety of AV with connectivity, the right kind of information needs to be available at the right time for the vehicle to help its decision making and manoeuvre. The right kind of information relates to what kind of information is needed by the vehicle and what is the source of the information. Furthermore, even with the right kind of information from a reliable source, the information needs to be delivered on time and the quality must be sufficiently high. Therefore, four research questions were formulated to further specify the aim of the research:

1. What kind of information is to be transmitted in the interaction (in both directions) between the traffic management centre (TMC) and vehicle?
2. Which information is to be provided by the National Road Authorities (NRA)/roadside and which information can be obtained by the sensors of the moving vehicle itself?
3. When and how should such information be available?
4. How to define and measure the quality/correctness of such information?

METHODOLOGY

The research was part of the Traffic Management for Connected and Automated Driving (TM4CAD) project funded by the Conference of European Directors of Roads' (CEDR) Call 2020 Impact of Connected and Automated Driving (CAD) on Safe Smart Roads, aiming to prepare the national road authorities for the future challenges of connectivity, digitalization, and automation [1]. Qualitative methods of research project members' expert analysis, literature review, survey, workshop, and feedback review were used.

The expert analysis and literature review of ODD information needs, and importance were completed for three actors: road works or (winter) maintenance operator, traffic manager and ADS developer. The actors were selected based on their close collaboration with road operator or AV as well as their status as a data provider and consumer for the local condition and ODD attribute information. Three use cases of traffic jam, adverse weather and static/dynamic road works were selected based on their relevance in highway and motorway environment as well as evaluated increased information need by the ADS in such environment. The use cases vehicles are cars with connectivity and access to infrastructure communication via various technologies, but other motor vehicles with similar equipment would be applicable as well. The vehicles were assumed to have SAE Level 3 or 4 automated driving capability for the highway auto pilot type use case. The following ODD attribute clusters used in the analysis were taken from the project's earlier analysis of the attributes: physical attributes of the roadway and its environs, digital infrastructure support, dynamically varying ambient environmental conditions, and operational attributes of the roadway [2].

The prioritisation of the ODD (or local condition) information needs of the three actors were assessed based on three criteria. First, expert assessment was completed for information need importance in the three use cases for the three actors in four levels of none, low, medium, or high. Then an average was calculated for each of the actors, and the aggregated information need importance (or priority) for the actor was qualitatively analysed to avoid any bias between the scenarios. Secondly, ODD attribute safety criticality was assessed as if the information would not be available, and then its impact to the actor in similar four levels from no safety impact to high impact. Third, additional/reduced costs for the actor were assessed. Finally, an overall information priority was qualitatively assessed for each of the ODD attributes (local condition) based on

- three actors of maintenance operator, traffic manager and automated vehicle or Automated Driving System developer,
- actor's need for the information and information safety criticality,
- three scenarios of traffic jam, adverse weather area and static/dynamic road work zone.

Two workshops were held, one together with the automated vehicle industry members and the other with CEDR Connected and Automated Driving (CAD) Working Group Road authority members to validate the ODD attribute prioritisation of information needs results. Furthermore, discussions were held, and written feedback collected from the CEDR CAD Working Group. Before the AV industry members workshop, a survey was conducted to collect feedback of the information priority analysis and to refine the content of the workshop. The survey was circulated via the Hi-Drive consortium (Hi-Drive 2022) involving all major vehicle manufacturers and ADS developers in Europe; as the consortium is research oriented the views do not present the views of the vehicle manufacturers, but more of individual ADS use case developers.

RESULTS

Infrastructure connectivity and information priority

The results concerning the ODD (local condition for the road operators and traffic managers) attributes' information priority levels are presented in Tables 4.-7. (Appendix of paper) where each of the previously mentioned four ODD attribute clusters are presented. The following is a summary of the analysis, pre-workshop survey, workshops, and written feedback results, aiming to validate the information priorities and limitations.

The assessed information priority among the three actors and use cases was most of the time comparable to the evaluated safety criticality of the information. Therefore, if the information was safety critical, it was most likely to be considered priority information as well.

Aiming to validate the information priority results, an online survey was sent to the ADS developers before the workshop. Total of 8 responses were received. The developers were requested to answer whether they agree or disagree with the ODD attributes' prioritisation presented to them (Appendix 1). Provision of no response for an attribute would indicate agreement with the analysis of the researchers. In case of disagreement, the developers were requested to specify whether the attribute in question should have, on average, a low, medium, or high priority instead. Also, an open field response option was provided to enable respondents to further elaborate the answer. The survey results were further reflected in the workshops and written feedback. [3]

The survey results indicated mostly agreement with the researchers' analysis as over half of the respondents were in full agreement with the analysis of information priority levels and the feedback indicated high priority in general for most of the ODD attributes. [3]

One survey respondent's answer included over 90 % of the attribute's priority level being low. Also, some of the survey's open-field answers and discussion in the workshop among the ADS developers supported this feedback. The survey and workshop feedback stated, that use of external information requires not only trustworthiness of data both in terms of correctness and cybersecurity but also resolving any liability issues. For example, even if external information contributes to a crash of the vehicle in automated mode, the responsibility still resides with the ADS developer. [3]

Regarding the individual attributes, the remote human support ODD attribute (such as remote supervision of the automated vehicle), which was evaluated as high priority information in the research analysis, was considered low priority by half of the developers in the survey. Written and workshop feedback indicates that remote human support was partly considered being a more distant future service. Also, attributes that had slight deviation of priority level compared to the analysis were GNSS coverage unavailability, wind speed range, special challenging lightning conditions, wet pavement surface and road surface friction. For example, sudden wind speed changes can be very local and therefore changing in different parts of road sections as indicated in some of the comments and discussions. Other comments suggested that landmarks and GNSS positioning on the other hand would require highly accurate digital maps in order to provide benefits. The quality of pavement marking visibility was raised as an example by both the ADS developers and road authorities on how the ADS development is a constantly changing dynamic domain and reducing the importance of some attributes that were earlier identified as very important. [3]

Data and information quality

The Distributed ODD Awareness (DOA) framework's quality criteria and needs for the traffic information for the three use cases were extracted after analysis from the European ITS Platform projects (EU EIP) [4], EU EIP C-ITS quality package [5], and Finnish Transport Infrastructure Agency reports [6]. The proposed quality criteria with explanation are presented in the Appendix 2 Table 8.

After the quality criteria analysis, tentative quality needs of the three use cases for the DOA framework were analysed. Finally, quality recommendations for the three use cases, presented in Table 1. below, were given. The recommendations are targeting a future situation when enough SAE Level 4 CAD vehicles are operating on the road to provide reasonable quality vehicle probe data. Therefore, the quality recommendations may be higher than the quality levels that road operators can provide today. [3]

Table 1 Quality recommendations for the Distributed ODD Awareness framework concerning various variables.

Quality Criteria for Distributed ODD Awareness Framework	Traffic jam	Adverse weather	Road works
Geographical coverage	100% on designated motorways with high traffic volumes	100% on designated highways with frequent weather issues	100% on highways at road works locations
Availability	99%	99%	99%
Performance conditions	-50…+60℃	-50…+60℃	-50…+60℃
Coverage of data types	traffic flow speed, occupancy	visibility, precipitation intensity and state of matter, road surface condition, wind (gust) speed, friction	location, status, local traffic management, lane availability, detour, trajectory
Timeliness (start)	< 2 min	<5 min	< 2 min
Refreshment rate	< 2 min	< 20 min	< 5 min
Data transfer delay	< 100 ms	< 100 ms	< 100 ms
Timeliness (update)	< 2 min	< 5 min	<2 min
Latency (content side)	<1 s (C-ITS) <10 s (NAP) <1 min (NAP event info)	<1 s (C-ITS) <10 s (NAP) <1 min (NAP event info)	<1 s (C-ITS) <10 s (NAP) <1 min (NAP event info)
Location accuracy	10 m	100 m	10 cm (trajectory) … 10 m (others)
Monitoring point density	each link between major intersections	critical microclimate spots, otherwise 50 km	start and end of road works
Measurement accuracy	depends on indicator	depends on indicator	depends on indicator
Reporting accuracy	± 5%	± 10%	± 5%
Error Rate	< 5%	< 8%	< 5%
Classification correctness (non-false positives)	96%	92%	99%
Event coverage (true positives)	94%	90%	98%
Missed events (false negatives)	4%	5%	2%
Report coverage	97%	97%	97%

The road operators have compiled the quality monitoring and management methods currently used for the information services used by them or utilising their own information systems in the EU EIP Quality Package [4]. The methods compiled are listed below in Table 2. [3]

Table 2 Quality recommendations for the Distributed ODD Awareness framework concerning various variables.

Nr	Method	Objective				Coverage of value chain				Assessm ent / assu-rance		Event / status		Type of service / equip-ment	
		Assessment of service	Acceptance testing	Feasibility / testing new procedure of algorithm	Internal quality control / monitoring	Content detection	Content processing	Service provision	Service presentation	Quality assurance	Quality assessment	Event	Status	Equipment	Process
1	Continuous monitoring of equipment performance and availability	X	X	X	X	X				X		X	X	X	
2	Manual verification of events or conditions	X	X	X	X	X	X	X	X		X	X		X	X
3	Reference testing of data collected	X	X	X	X	X	X	X	X	X	X	X	X	X	X
4	Time-space oriented reference test methods	X			X	X		X			X	X			X
5	Monitoring of data completeness and latency	X			X	X	X	X		X	X	X	X	X	X
6	Regular sampling of message or data content comp-leteness and correctness				X		X			X		X			X
7	Verification and calibration of traffic / weather conditions prognosis	X	X	X	X		X	X	X	X	X	X	X		X
8	Surveys of perceived quality by users	X			X	X	X	X	X		X	X	X	X	X
9	Collection of direct user feedback	X				X	X	X	X	X		X	X	X	X
10	Monitoring of service use statistics	X						X	X	X	X	X	X		X

DISCUSSION

The first research question of the study was ´what kind of information is to be transmitted in the interaction (in both directions) between traffic management centre (TMC) and vehicle? ´ The results are presented in the Appendix 1 Tables 4.-7. where information to be transmitted as a priority has an attribute information priority level HIGH. According to the survey, which was distributed to the Automated Driving System (ADS) developers before workshop, over half of the ADS developer respondents agreed with the information priority level analysis. Uncertainty and the dynamic nature of the AV development was reflected some responses, where some uncertain future developments were considered less important for that reason.

The second research question was ‘which information is to be provided by the National Road Authorities (NRA)/roadside and which information can be obtained by the sensors of the moving vehicle itself?’
The ADS developers indicated trust concerns on infrastructure communication data reliability and possible liability issues if an accident happens due to faulty information. Therefore, infrastructure information quality can have high importance, but possible backup and redundancy of the infrastructure information monitoring would be required. If the information would come from inside the vehicle sensor range, it could be used for redundancy. On the other hand, information coming from outside of the vehicle's sensor range could be used to extend the geographical area of the ODD if the ADS is convinced of the veracity and reliability of the information. Also, the dynamic nature of weather conditions and possible variations in measuring these conditions such as the pavement friction and wet conditions also relates to the first mentioned trust issues with the information. [3]

The long-term assessment of the importance and need of the ODD attributes is considered difficult due to the wide range of the attributes and possible data fusion between attributes, i.e., when multiple data attributes are combined to produce more accurate information for the use of ADS decision making. Also, governance and harmonisation of data exchange between the actors need to be considered. The best indication of the current and possible future development can be gathered from the latest development projects addressing the key challenges currently hindering the progress of developments in vehicle automation and ODD continuity. [3]

The third research question was ´when and how should such information be available? ´ Table 3. below presents the time-related quality recommendations picked from the Results chapter's table 1. The overall DOA information exchange was evaluated of being available for Level 3 and 4 vehicles for 99% of the time in the future with considerable traffic flow penetration of such vehicles. [3]

Table 3 Time-related quality recommendations for the Distributed ODD Awareness framework in the future concerning various use cases on highways and motorways.

Quality Criteria for Distributed ODD Awareness Framework	**Traffic jam**	**Adverse weather**	**Road works**
Availability	99%	99%	99%
Timeliness (start)	< 2 min	<5 min	< 2 min
Refresh interval	< 2 min	< 20 min	< 20 min
Data transfer delay	< 100 ms	< 100 ms	< 100 ms
Timeliness (update)	< 2 min	< 5 min	<2 min
Latency (content side)	<1 s (C-ITS) <10 s (NAP) <1 min (NAP event info)	<1 s (C-ITS) <10 s (NAP) <1 min (NAP event info)	<1 s (C-ITS) <10 s (NAP) <1 min (NAP event info)

The fourth research question was ´how to define and measure the quality/correctness of such information? ´ The quality recommendations followed the EU EIP Quality Package [4], which can be found from the Appendix 2 Table 8. As discussed above, the data quality has an important role on possible ADS developers' trust issues towards the infrastructure communication and should therefore be further developed and tested in future.

Limitations of the survey answers include some of the open field written answers that highlighted urban use case examples and role of the road operator. The research and survey scope were oriented only to highway and motorway use cases and the ADS developers' views. Also, difficulties and cost for providing each of the individual ODD attribute information elements was reflected, which were not considered part of the information priority analysis. [2]

CONCLUSIONS

The study investigated how infrastructure connectivity could contribute toward improving AV safety in three selected use case scenarios of traffic jam, adverse weather and static/dynamic road works, and quality indicators and requirements for the communication. Three actors were selected for the use case evaluation: road works or (winter) maintenance operator, traffic manager and ADS developer.

The main findings of the research can be found from the Appendix 1 Tables 4.-7. where the assessed ODD attributes' priority levels are presented: attributes with 'HIGH' priority level were considered important information to transfer. The evaluated priority attributes were also consistently being evaluated as safety critical. Also, survey and workshop inputs and the ADS developers supported the results as a majority of the answerers agreed with the research evaluation.

According to the AV industry feedback in the survey and workshop, the vehicle manufacturers and ADS developers mainly rely on the information that the vehicle's own sensors provide. This is done especially for road safety and liability reasons. Any external ODD or local condition information from infrastructure can bring redundancy, i.e., backup for the automated driving systems, but the trustworthiness of the information is a concern because the manufacturer bears the responsibility of the outcome of using the information when the vehicle is used in the automated mode. [3]

ACKNOWLEDGEMENTS

The research was part of the Traffic Management for Connected and Automated Driving (TM4CAD) project funded by the Conference of European Directors of Roads (CEDR) Transnational Research Programme (TRP) Call 2020 Impact of CAD on Safe Smart Roads.

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APPENDIX 1

Table 4 Priority levels of physical attributes of the roadway and its environs.

Physical attributes of the roadway and its environs	**Priority level**
Locations of road boundaries	HIGH
Zone boundaries	HIGH
Roadside landmarks	HIGH
Special-purpose localization references	LOW
Quality of pavement marking visibility	HIGH
Load-bearing capacity of roadway or bridge structures	MEDIUM
Road surface damage	MEDIUM
Game fence locations and condition	LOW
Vegetation obscuring sight angles or visibility of signs	MEDIUM
Road geometry constraints	HIGH
Road shoulder conditions on both sides	HIGH
Notifications of locations with occluded visibility	HIGH

Table 5 Priority levels of digital infrastructure support variables.

Digital infrastructure support	**Priority level**
Variable message sign contents	HIGH
Locations where V2I/I2V communications are available	HIGH
Locations where GNSS differential correction signals are available	MEDIUM
Locations where GNSS coverage is NOT available now, by GNSS service	MEDIUM
Electronic toll collection systems and their associated pricing	LOW
Locations of incidents that represent traffic impediments or safety hazards	HIGH
Emergency vehicle locations and direction/speed of travel of each one	MEDIUM
Current average traffic speed and density by lane and road section	HIGH
Current percentage of heavy vehicles in traffic stream, by lane and road section	LOW
Special events creating abnormal traffic conditions and their locations	HIGH
Temporarily blocked or closed road locations	HIGH
Locations with high density of pedestrians	LOW
Locations with high density of cyclists or users of micro-mobility devices	LOW
Highway shoulder locations occupied by vehicles or debris	HIGH
Locations with dynamic traffic access changes	HIGH
Remote human support	MEDIUM

Table 6 Priority levels of dynamically varying ambient environmental condition variables.

Dynamically varying ambient environmental conditions	**Priority level**
Wind speed range	MEDIUM
Visibility range with rain/snow/sleet/hail in visible light spectrum	HIGH
Visibility range with rain/snow/sleet/hail in lidar infrared spectrum	HIGH
Rainfall rate in mm/hr	HIGH
Snowfall rate in qualitative ranges	HIGH
Visibility range with other particulate obscurants in visible light spectrum	HIGH
Visibility range with other particulate obscurants in lidar infrared spectrum	HIGH
Predicted significant changes in key weather attributes	HIGH
Qualitative ambient lighting conditions	LOW
Quantitative ambient lighting conditions	MEDIUM
Special challenging lighting conditions	MEDIUM
Electromagnetic interference	HIGH
Wet pavement surface	HIGH
Ice on pavement surface	HIGH
Cold pavement surface (potential for ice if wet)	HIGH
Road surface friction	HIGH
Light to moderate snow/slush accumulation on surface	HIGH
Heavy snow/slush accumulation on surface	HIGH
Light to moderate flooding (puddles) on surface	HIGH
Heavy flooding – potentially impassable to low-profile vehicles	HIGH

Table 7 Priority levels of operational attributes of the roadway.

Operational attributes of the roadway	**Priority level**
Temporary static signs	HIGH
Maintenance vehicles using portions of carriageway	HIGH
Work zones	HIGH
Incident recovery events (crash scenes, crime scenes, dropped loads, landslides, avalanches…)	HIGH
Availability of specific C-ITS information services	HIGH
Availability of real-time merging guidance or assistance at motorway interchanges or entrance ramps	HIGH
Real-time lane-specific speed limit information availability at specific locations.	HIGH
Obstacles or debris on road surface	HIGH
Roadside objects that change their locations over time, such as parked vehicles or trash cans	MEDIUM
Routing advisory information	MEDIUM
Traffic rules and regulations in digital form, updated in real time	HIGH

APPENDIX 2

Table 8 Proposed quality criteria for the Distributed ODD Awareness framework and the data exchanged.

Definition of Quality Criteria for Distributed ODD Awareness Framework		**Applicable for**		
		Event Information	**Status-Oriented Information**	**DOA Framework**
Geographical coverage	Percentage of the road network or link covered by the (content provision) service	-	-	X
Availability	Percentage of the time the (content provision) service is available	-	-	X
Performance conditions	The conditions in which the system operation and performance is guaranteed	-	-	X
Coverage of data types	Data or sensor types required	-	-	X
Timeliness (start)	The time between the occurrence of an event and the acceptance* of the event	X	-	
Refreshment rate	Time interval for refreshing / updating the status reports coming from a data sender	-	X	
Data transfer delay	The time from transmission of data from monitoring station to the receipt of data at server	X	X	
Timeliness (update)	The time between the end or (safety) relevant change of condition and the acceptance* of this change	X	-	
	The average age of the sensor data used in the most recent reporting period	X	X	
Latency (content side)	The time between the acceptance of the event or its end or (safety) relevant change of condition and the moment the information is provided by the content access point	X	-	
	The time between the calculation of the reporting data and the moment the information is provided by the content access point	-	X	
Location accuracy	The relative accuracy of the referenced location with respect to the actual location of the actual event	X	X	
Monitoring point density	Minimum density of monitoring stations on road section or maximum link length for link-related data in operating environment	X	X	
Measurement accuracy	Minimum accuracy for displaying data monitored	-	X	
Reporting accuracy	The relative accuracy of the reported quantity (speed or travel time) versus the actual value (average experience of road users in a given reporting period)	-	X	
Error Rate	Percentage of published status reports which fall below a minimum accuracy	-	X	
Classification correctness (non-false positives)	100% - percentage of the published events which are known to be not correct (concerning actual occurrence of this event type / class), and which result in a consequence for the user behaviour	X	-	
Event coverage (true positives)	Percentage of the events which are known to be correctly detected and published by type / class, time and location (i.e. detection rate)	X	-	
Missed events (false negatives)	Percentage of occurred events that were not published (and perhaps not even detected)	X		
Report coverage	The percentage of reporting locations for which a status report is received in any given reporting period	-	X	