# I4AD Technical Whitepaper

## Scope & Objective of this Document

*TPEG has been successful for delivering information to drivers.*
*Automated vehicles have a different expectation from information.*

The Transport Protocol Experts Group (TPEG) set of protocols for traffic and traveller related information has been created as a protocol to deliver information to drivers to support them in their driving task. The range of message goes from safety-related message, to more supporting information of parking, refuelling, or points of interest.

With the advent of automated vehicles, the role of the driver is changing, as is her need for information. The focus for information changes to the vehicle itself. As the vehicle will be controlling its own trajectory, it will need more external Information for Automated Driving (I4AD) to do this safely. This paper focusses on traffic-related aspects of I4AD, but the scope of this is much broader; it aims at supporting the AD vehicle and its passengers in other aspects (e.g. weather) as well.

This paper discusses technical solutions that will solve some relevant technical and business issues in context with automated driving, taking into account that not all vehicles are automated. The paper starts with describing some example use cases and 'TPEG3 as a product' in terms of functional and non-functional/business requirements. After discussing some basic ideas and concepts that address these requirements, a set of solutions is presented.

For an in-depth discussion of the automated driving impact on ITS stakeholders and how TPEG3 plans to position itself in the AD ecosystem, the reader is referred to the **I4AD Business Whitepaper** (TISA19016), which complements this Technical Whitepaper.

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# 1 Business Environment, Stakeholders & Market Drivers in Brief

TISA is a well-networked, recognized and established player in the ITS ecosystem with an efficient, membership-driven process for producing industry-wide accepted solutions for traffic information. Recent developments in the area of AD suggest that now (2019-2020) is a critical time window to take action to secure that TISA:

- can deliver viable technical solutions for AD use cases that solve real customer problems for OEMs, Suppliers and Road Operators/Public Authorities
- stays a relevant actor, also in the area of AD
- continues to facilitate business and create opportunities for all TISA members in the area of AD

Recent developments further suggest that the AD community is likely to solve the core AD challenges (sensor vision, AI, keep the vehicle on the road, avoid any collisions, make safe manoeuvres, etc.) and turn to address issues beyond the current core problems. Considering the financial power of some of the actors, technical solutions that now project on the 'TISA turf' can be produced at a high speed, substituting the existing TISA business model for AD use cases.

The starting position for TISA is favourable, however TISA members now need to embrace change and engage in the development of a TPEG3 solution that addresses the needs of the AD community.

This Business Whitepaper summarized thoughts and conclusions of the past 3 years within the TISA community concerning how to tackle the AD ecosystem. In the Technical Whitepaper, a solution will be proposed that addresses the technology & technological and societal trends and the needs of the AD stakeholders outlined in the Business Whitepaper.

# 2 Example Use Cases for Guiding the Conceptual Work

## *2.1 Use Case 1 – Precise Work Zones (PWZ)*

Precise work zones provide a good practical example where TPEG3 can provide useful information for vehicles outside the scope of the vehicle sensors. Work zones are known worldwide and can vary between simplified cases up to very complicated layouts.

The subject 'road works' is actually of no interest to a vehicle. The vehicle only knows of actions that need to be taken such as to slow down to 90 km/h. The reason of this deceleration is information that could be mentioned to the passenger to explain why certain actions are taken by the vehicle, but is irrelevant for the vehicle itself. Therefore, the goal is to split a work zone into different smaller components each focussing on a specific action a vehicle must take.

A very simple example is given with three actions to be taken:

1. the left lane will disappear, and traffic should merge to the remaining lanes
2. the maximum allowed speed is limited to 90km/h
3. the maximum allowed speed is limited to 70km/h


**Figure 1: Example Roadworks zone**

Note that not all the actions should be performed by all vehicles. If in the above example a vehicle is driving on the right lane with a speed lower then 70km/h (due to dense traffic), no actions are needed. However, for safety reasons it can be very helpful to know merging traffic from the left can be expected.

For each of the actions three phases can be defined. For each of the phases, the vehicle will need a different level of information and will act differently. Depending on the vehicle brand, processing power, passenger settings, the size and level of detail of the phases can vary but still be defined in:

1. **MISSION**: before the vehicle starts driving, a route is calculated to the desired destination. During the route, driving conditions will change (regulations, traffic situations, weather, ...) and a continuously recalculating of the route is ongoing
2. **DECISION**: once rerouting is no longer an option, a plan is created by the vehicle to take the necessary actions
3. **OPERATION**: once the decided location is reached, the actions must be performed

In the MISSION phase, no granular information is needed on cones, road signs, etc. The focus is more on travel time and whether AD is allowed and feasible on a specific route. Additional parameters such as scenery or smoothness of the ride (road surface, sharp turns ...) can be taken into account.

The MISSION phase can start off with a pre-trip planning, where an AD vehicle performs a route planning and needs to know whether relevant traffic situations are to be expected on the route. Then, the vehicle would after starting the trip and before approaching a given traffic situation, monitor the MISSION information channel and receive more specific information.

In the DECISION phase, rerouting is no longer an option. A plan is needed for vehicle to take the necessary actions. In the example, a deceleration must be performed twice before a defined location and the vehicle should have moved away from the left lane before this lane ends. If regulations state AD is not allowed in the road works zone, the passenger must be alerted at a specific location.

Once the locations have been reached that were decided in the DECISION-phase, the actions should be performed. This is the OPERATION phase. In the example, a deceleration is regulated at a specific location and heavy breaking should be avoided, thus the smooth deceleration is executed in time.

If the vehicle is driving on the left lane, actions shall be taken to move the vehicle away from this lane before the end of the lane is reached. Additionally, if the vehicle is driving on an inner or right lane it can be expected other vehicles will merge into this lane and caution is necessary.

In both the DECISION and OPERATION phase, the necessary information must be of a high granularity. The location where the left lane will end does not have much freedom, for obvious reasons.

During and after the road works can be considered as a ‘normal’ driving phase, as defined in the MISSION phase. Actions have been performed and the vehicle can continue its path. The DECISION phase will become active again for the next traffic situation on the route.

# 3 The Product "TPEG3"

### 3.1 TPEG as a connectivity product to support the AD system

Adding connectivity to automated vehicles provides significant potential to extend what is possible with in-vehicle driving automation alone. Connectivity can dramatically improve situation awareness (well in extent of the sensor range), and thus safety of autonomous vehicles. Supplemental information, provided from an external source, may help offset (performance) limitations of the on-board sensors systems, and provide also information from, and about, other road-users. Connectivity can also provide current (possibly dynamic) traffic regulations and traffic control strategies, and support the safe, yet efficient, usage of available road infrastructure.

TPEG3 is positioned as a *connectivity product to support autonomous driving*, both to support and augment in-vehicle situation awareness, as to support an autonomous vehicle's conformance with applicable traffic control strategies and policies (see Figure 2).

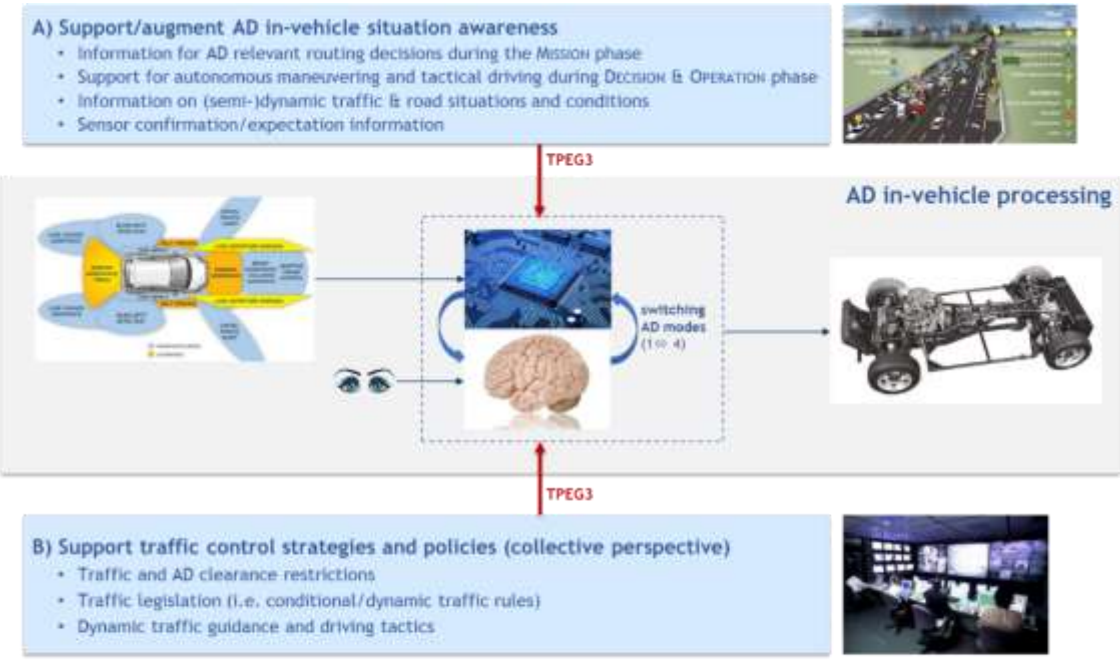


**Figure 2: Positioning of TPEG3 with respect to information for autonomous driving[1]**

An automated driving vehicle operates principally following a *sense – plan – act* paradigm (the middle, grey block in Figure 2). A suite of sensors scans the environment, records vehicle parameters, and creates an internal model of the world. This model of the world encodes the situation awareness of the vehicle and is supplemented typically with the (semi-)static information from an on-board digital road map.

Based on this internal model of the world, the "brain" of the autonomous vehicles determines then the best path to follow (with SAE level 2 or below still supervised or supported by humans). This is then transformed into actuation parameters to control the vehicles speed and steering systems for the automated driving to take effect.

[1] For an explanation of the driving phase model Mission - Decision - Operation (MDO), please refer to Section 4.1

Such AD systems work well on regular roads, in regular conditions. However, non-standard situations and/or non-standard/static traffic control strategies or policies may be beyond the vehicle's ODD (Operational Design Domain), hence automation needs to be turned off in those situations. Here, TPEG3 is aimed at providing supplemental information, early and timely, to support the AD systems driving task where possible, or to provide necessary information well in advance of sensor range to allow an AD vehicle to smoothly hand-over driving back to the human (in an SAE level 3 AD system).

TPEG3 is geared towards supplementing on-board AD systems with supplemental information, both to support and augment situation awareness and to support conformance with traffic control strategies and policies.

The principal features of TPEG3 as a connectivity product are the following.

- **Dynamic information provisioning to support Autonomous Driving through non-standard situations.** TPEG3 focuses on (dynamic) information provisioning to support autonomous driving while driving through non-standard situations or with non-standard traffic control strategies and policies (see Figure 2). This information about non-standard situation supports AD system to either extend their ODD (Operational Design Domain), or be able to timely warn the human to take over control in an SAE level 3 system,
- **Map attachment modus operandi**. TPEG3 has a focus on (dynamic) information provisioning. In doing so, the principal modus operandi is that of a *map attachment*, i.e. temporary information supplementing or correcting the static information (i.e. map) *timely and efficiently*, hence more effective than with incremental map updates.
- **Safe and secure by design.** TPEG3 information targets usage in an Automated Driving System for safety-critical operations, i.e. operations whose failure or malfunction could result in death or serious injury to people, or loss or severe damage to equipment. Therefore, TPEG3 targets to be safe and secure by design, and incorporate relevant meta-information on quality, reliability, and provenance.
- **Generic, interoperable information delivery.** TPEG3 targets interoperable information delivery via different channels and delivery mechanisms. TPEG3 content will be deliverable via unidirectional or bi-directional channels, and support interaction as the information usage may require.
- **Support towards highly dynamic information.** For the safety and control of AD vehicles, information timeliness is key, especially for dynamic information in the immediate vicinity of the vehicle [2] that may affect the imminent control actions of the AD vehicle. TPEG3 content encoding and delivery mechanisms are designed to allow fast local information delivery to support highly dynamic AD use cases.

### *3.2 TPEG3 functions and design aspects*

TPEG3 as a connectivity product is useful only when the information provided "adds value" to information available on-board the AD vehicle or as seen by its sensors.
TPEG3 will add value to on-board AD systems with functionality firstly to augment and support situation awareness and secondly to provide the AD vehicle with information to conform with traffic control strategies and policies.

[2] E.g. locations and movements of road workers in a roadworks zone.

*To augment and support situation awareness*, TPEG3 will provide the following functionality and information.

- **Information for AD relevant routing decisions.** To be fully autonomous, an AD vehicle's routing decisions must consider those roads not 'fit for AD', because of e.g. weather or road conditions, roadworks, or other special situations where regulatory authorities may decide to withdraw permission for Autonomous Driving, at least temporarily.
- **Information on (semi-)dynamic traffic & road situations and conditions.** Typically, with roadworks, weather and road conditions (e.g. black ice), shockwave traffic and other special situations, e.g. accident clearing work, timely information in advance may smoothen the experience for the AD vehicle passengers. The AD vehicle can already can consider timely lane changes, or speed adaptations, well before the causes for such decisions become in range of the AD vehicle's sensors.
- **Support for autonomous manoeuvring and tactical driving.** TPEG3 can provide information about preferred trajectories and preferred driving speeds. These can be based on prior AD vehicle's experience that have driven through these non-standard situations. These preferred trajectories may help AD vehicles to determine their own driving trajectory, either use the preferred one, or adapt it to the specific (dynamic) situation encountered, including other traffic.
- **Sensor confirmation/expectation information.** Knowing what to look for, or knowing what to expect can significantly aid an AD vehicle to build its situation awareness. TPEG3 will be able to provide specific sensor conformation/expectation information to support the AD vehicle in non-standard situations, where e.g. expected landmarks may be removed, or moved, or occluded by temporary barriers. The TPEG3 provided information aims to make the sensor results as reliable and trustworthy for these non-standard, dynamic situations as the regular situations.

*To support traffic control strategies and policies*, TPEG3 will provide the following functionality and information.

- **Traffic and AD restrictions.** Road authorities (but also OEMs) may restrict the ADS to be permitted unsupervised AD operation on specific road sections. Due to e.g. winter weather, road authorities may decide to request human responsibility/oversight of driving. OEMs may consider the specific capabilities of vehicle types and do the same. TPEG3 will be able to provide such traffic and travel, and AD restrictions.
- **Traffic legislation** (i.e. conditional / dynamic traffic rules). Road authorities may impose conditional or dynamic traffic rules to keep traffic safe in changing conditions – whether AD vehicles or manually driven vehicles. A prime example are dynamic speed limits, but also smog-based vehicle restrictions or fuel type specific regulations. TPEG3 will be able to provide such conditional/ dynamic traffic rules, e.g. dynamic speed limits
- **Dynamic traffic guidance and driving tactics**. To support the best usage of the road infrastructure, from a collective perspective: road authorities may issue traffic guidance measures or recommendations to optimize traffic flow, e.g. speed recommendations, or route recommendations to spread traffic, electronic notice for approaching emergency vehicles, or driving tactics (lane choice, following distance, speed) to alleviate shockwaves or improve merging of traffic. TPEG3 will be able to provide such information.

### *3.3 Safety aspects of TPEG3 in context with AD*

The value that TPEG3 adds to the AD ecosystem reflects as well on road safety, specifically in mixed traffic situations and in context with complex situations that are challenging for AD vehicles to interpret and where external information can augment on-board sensor data to increase the probability of a correct interpretation and safe actions derived from these interpretations.

In the whitepaper “Safety First for Automated Driving” (SaFAD) [1], the authors propose a framework with 12 guiding principles for achieving a positive risk balance for AD systems. The SaFAD framework is intended for the *Validation* and *Verification* (V&V) of AD systems, whereas TPEG3 is used to provide information to ensure the safe operation of an AD system under the assumption that it is verified and validated by the system designers. Nevertheless, the SaFAD framework does provide a well-structured thought concept and the domain information provided via TPEG3 relates to some of the SaFAD guiding principles. TPEG3 can provide contextual detailed information of complex road situations ahead of the AD vehicle, and possible temporary changes to the default traffic regulations (as stored on the HD map), if imposed by e.g. road authorities or police and rescue forces. TPEG3 can therefore supplement the safety-related decision-making processes and contribute to achieving a better risk balance for AD systems.

Another aspect worth mentioning is the information of the driver, in particular before an approaching situation where a handover from an ADS to the passenger (then becoming the driver) needs to be performed. Especially on Level 4 and 5, the driver may need to be alerted a long time (e.g. several minutes) before reaching the handover point in order to refocus his/her attention and prepare for the traffic situation to come. Such an *early alert* is very difficult if derived only from on-board sensors, where at high speeds the vehicle may have only a few seconds to alert and inform the driver. The parallelism of TPEG2, intended to be decoded in the infotainment system and to inform the driver, and TPEG3, intended to non-human-comprehensible data to the AD system, can bridge this gap. The driver can be alerted in time using TPEG2 while the AD system processes the TPEG3 data to make a judgement whether driver takeover is needed – but then the driver is already aware that “something may be coming”. The vehicle can then issue an “all clear” message in case it can negotiate the situation ahead without leaving the ODD.

The interested reader is referred to Annex B of this document for further details.

### *3.4 Product aspects*

TPEG3 product aspects need to cover the service discovery and delivery, required precision of the content, required formats (encoding), and required meta-data to support the safe and secure usage of the information in a safety-critical context of autonomous driving.

These key product aspects are graphically detailed a bit more in Figure 3 and explained in the following text.

**Service discovery and delivery** concerns itself with the process of automatically service components available for use and connecting to those for the delivery of the information of interest. What information is available (at which quality or integrity level), where to connect to, and how to obtain the information are the typical issues to be resolved. In TPEG2 connected services, typically an OEM back-end server is the principal entry-point for a vehicle to obtain its information. In TPEG3 this could still be the principal entry-point, however various service components could be routed differently through different channels, or for some components the service delivery could also be done directly from other (e.g. road edge) infrastructure if sub-second to millisecond latency would be crucial. Dynamic service discovery and delivery is also important for load balancing and the infrastructure/service provider side, which in turn is needed to achieve necessary low latency delivery. Finally, flexibility of information sourcing and service interoperability support business goals to avoid vendor-lock-in situations.

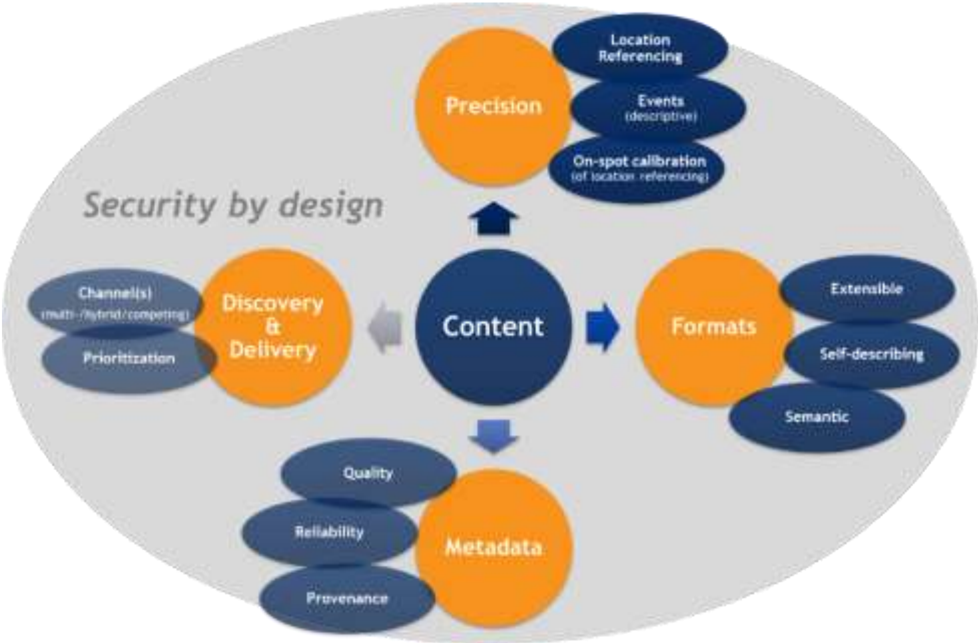


**Figure 3: Relevant product aspects considerations for TPEG3**

**Content encoding** concerns itself with the necessary formats in which to encode service content. Crucial aspects in the format selection are that the selected format is extensible (such that new encoding elements can be added without jeopardising functionality in older recipients), that semantics are clear and unambiguous, that software APIs can be generated from the format description for more easy use, and, if possible, that the format is self-describing, i.e. that the semantics can be documented/derived from the format syntax.

**Content precision** concerns itself with the required precision of the supplied information. Location referencing for guiding automated vehicles through roadworks will need to contain detailed lane and geometry information possibly up to single centimetre accuracy. The same precision standards may apply to event information, i.e. how slippery a given road is, as this may have impact on braking distances and safe curve speeds for the automated vehicle to work with. Finally, some additional information may need to be supplied to the vehicle to calibrate itself, e.g. type of lane marking, a position of a landmark that allows the vehicle to precisely pinpoint an obstacle in its vehicle-bound environment map. The relative location of the obstacle to the vehicle can be calibrated through the vehicle's sensing of the landmark.

**Meta-data** is finally needed for automated vehicles to judge the quality and reliability of the information. What level of accuracy is supplied, which organisation supplied the information, what is the quality (integrity level) of the process that is the source of the information. Automated vehicles may consider the usage only for non-safety critical applications, if this meta-data is not provided.

### *3.5 Key performance parameters*

TPEG3 must be able to provide its "value-add" information timely, in appropriate "chunks" with a clustering relevant to the driving tasks, so that it is easy to isolate and process by the AD vehicle. The required timeliness of information is expected to vary significantly, as to whether the information involves strategic route choices 50km ahead, or whether the information involves a situation 500m ahead of the AD vehicle that possibly could affect driving safety (e.g. black ice on the road).

The timelier the information needs to be, the faster the rate of change, or the refresh time will need to be, especially when the information varies itself frequently. The key performance parameters for *TPEG3 as a product* are the following:

- The data sizes to support a driving task to cope with dynamic or non-standard situation
- Timeliness and refresh rates of information, which should be progressively timelier with more detail/more local scope to support the AD driving task.
- The aggregated bandwidth as product of data size and timeliness and refresh rates for the composition of information elements with the scope varying from global and coarse granularity, to local and high granularity.
- The in-vehicle data information filtering, selection, and processing efficiency.
- The infrastructure-side load balancing/load distribution/provisioning efficiency while matching timeliness and refresh rate targets.

The TPEG3 *map attachment* modus operandi is targeted to be at least *an order of magnitude* more efficient than incremental map updates, while providing for high refresh rates (seconds to sub-seconds) for the most local scope information. Moreover, it is targeted to support easy filtering and easy on-board processing of the information. Appropriate filtering should result in high relevance and applicability of the decoded information for the driving tasks.

# 4 Design & Concepts

## *4.1 Functional concept*

Three phases are defined for each action a vehicle must take:

MISSION: Planning the trip, deciding the route (fast/economic/short/all-AD/…), possibly circumnavigating any issues on the route by a proper route choice depending on the drivers/passengers' preferences; relevant are only a few criteria. Monitoring route choice (further away), "where & what", small/compact information, intended for "judging the situation" and if necessary "wake up the driver"

DECISION: Getting closer, "coarse description of the scene", medium-size information, intended for "preparing a strategy for managing the situation"

OPERATION: Situation directly ahead, "very fine-grained description of the scene", heavy information, intended for "detailed tactics how to negotiate obstacles", may include bounding boxes and free-space descriptions, used for correlating with sensor inputs to validate the situation and increase reliability / minimize system error

The granularity of the information differs in each of the phases, and this for multiple "dimensions". For TPEG3 we distinguish the following dimensions:

- location
- time, and applicable time window
- cause: nature of event
- effect: the consequence of this event, and impact on automated driving
- advice: non-binding recommendations and support
- metadata: information on quality, reliability and source of information

- rationale: explanation to the 'passenger' of the automated vehicle why the vehicle may drive differently than expected or customary on this road

Table 1 illustrates the expected information content for each dimension as function of the phases.

**Table 1: Phased approach with scalable information density**

| | Mission | Decision | Operation |
|---|---|---|---|
| **Location** | ▪ for routing purposes<br>▪ signpost locations, restriction zones, merging zones etc. to initiate the Decision-phase<br>▪ lane topology + lane width | ▪ meters accuracy<br>▪ signpost locations, lane geometry, lane markings | ▪ cm accuracy<br>▪ lane markings |
| **Time** | ▪ evolving time window<br>▪ applicable for my route<br>▪ dynamic/moving work zone that requires info about the dynamics | ▪ dynamic/moving work zone with a higher precision | ▪ less relevant as location is essential here |
| **Cause** | ▪ only for display to the passenger if AD feasible and<br>travel time impact | ▪ type of road furniture (e.g. cones, barriers)<br>▪ moving people/road workers | ▪ type of road furniture (e.g. cones, barriers)<br>▪ moving people/road workers |
| **Effect** | ▪ lane reduction<br>▪ narrow lanes<br>▪ restrictions<br>▪ AD clearance (per lane) | ▪ longer braking distance<br>▪ slippery surfaces<br>▪ degraded road | ▪ degraded road<br>▪ sensor impact such as dust |
| **Advice/ recommendation** | ▪ traffic mgmt. centre advice *(e.g. dangerous goods avoid)*<br>▪ lane choice<br>▪ lane speed(s)<br>▪ safe distance | ▪ where in zipper-zone to merge<br>▪ preferred trajectory<br>▪ Minimal Risk Condition (MRC) info | ▪ staggered driving patterns in lane<br>▪ no overtaking<br>▪ position in lane<br>▪ shockwave reduction<br>▪ emergency lane<br>▪ MRC info |
| **Metadata** | ▪ Unsupervised AD operation confidence level<br>▪ quality on location<br>▪ lane width + variation(s) | ▪ quality on location<br>▪ lane width + variation(s) | ▪ additional information for the sensors |
| **Rationale** | ▪ "Roadworks upcoming"<br>▪ reason for lane change & speed reduction | ▪ success rate of prior AD vehicles | ▪ information to the driver about situation-awareness and intentions of the AD vehicle |

The *dimensions* of the information should in this context be understood as components of a service or message. Each message contains the basic set *Location-Time-Cause-Effect-Advice-Metadata-Rationale* in always the same order such that the way to encode and decode it is implicitly defined. If a component is not needed, it will be empty. With increasing detail/granularity from MISSION to OPERATION, the components will grow in size and may contain more and more sub-components.

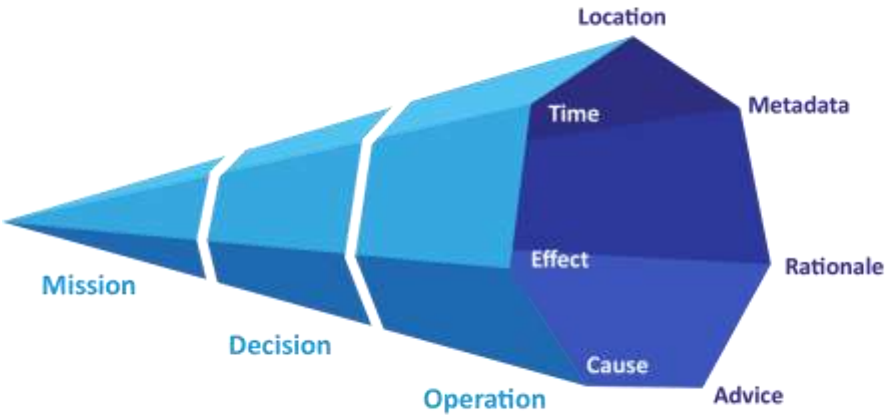


**Figure 4: The MDO paradigm for hierarchical information encoding**

The required granularity of the information necessary in each phase increases when the vehicle reaches the location of the action required. In the MISSION phase more information is needed on multiple traffic situations on different areas but the specific details for each of them would be an immense amount of data, useless at that moment. Reaching the specific locations (DECISION and OPERATION) would require more detailed information but only for this local situation.

The trigger for the information also differs between these phases.

- MISSION is mostly **time-triggered**. A vehicle requests with a specific time-interval updated information on the global situation around the route, and to obtain a renewed view on the global situation, yet monitoring of specific situations for impact on the plan is **location-triggered.**
- DECISION and OPERATION are **location-triggered**. The definition of a lane ending, or a regulated speed reduction is performed in the space-domain. The speed of the vehicle is clearly an important factor in this.

Figure 4 visualizes the MDO concept, showing that all information components (Location, Time, Cause, Effect, Advice/recommendation, Metadata and Rationale) are present in all phases. This structural coherence should facilitate a fast decoding and interpretation of the information, even if the amount and granularity of information increased from MISSION to OPERATION.

The overall amount of information for the seven information dimensions does not increase linearly. Figure 5 shows the expected increase of information content throughout the phases. During this conceptual phase of TPEG3 development, we expect that information bearing time and cause may increase linearly while information about effect, advice and the metadata (quality/reliability indicators, such as expectation, confidence intervals, or data source qualifiers) double for each phase. The most significant increase in information density, granularity and amount will likely be seen with the location information. The underlying assumption is that during the MISSION phase, a small amount of information will suffice (e.g. for road works the start and end point on a road segment), while during the OPERATION phase, many objects in a road works setting need to be accurately identified with their position (barriers, traffic cones, construction machinery, lane markings, all the way to road workers signalling traffic).

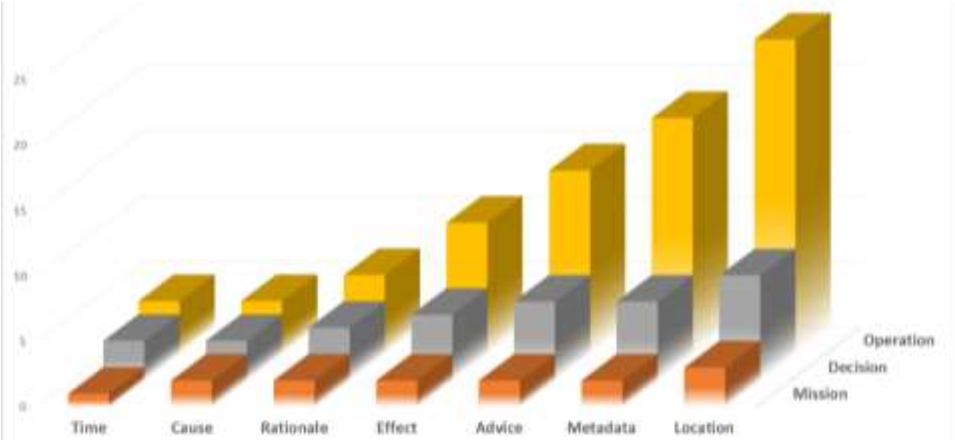


**Figure 5: Expected relative information growth for the MDO phase model**

### *4.2 Key design aspects and parameters*

The key design parameters for TPEG3 reflect the choices to be made on the realisation of functional concept (see Section 4.1) with respect to the identified product aspects (see Section 3.4). This section provides an overview of some key design aspects and parameters to be considered for a TPEG3 solution. With respect service discovery and delivery, key design parameters are the following.

TRANSPORT LEVEL

- Appropriate partitioning and size of information chunks on the individual MDO levels
- Efficient bandwidth usage
- Service concept versatility (applicable for V2V and I2V, as handling the range of low-latency tactical information, to slow-changing strategic information)
- Bearer independence, supporting different *over-the-wire* protocols

IN-VEHICLE

- Fast and easy service discovery and delivery
- Limited processing and storage needed for decoding
- Fast filtering, parsing and selection of relevant information
- Clear separation as well as synchronicity between driver-oriented (infotainment) information and AD vehicle-oriented (AD subsystems) information

INFRASTRUCTURE/SERVER SIDE

- Load balancing and load distribution / provisioning efficiency
- Efficient scheduling and prioritisation of information delivery
- Encoding and service scalability over a fleet of connected vehicles

CONTENT ENCODING

- Cross-Linking and referencing efficiency to relate information on the various MDO levels
- Efficiency of data encoding/decoding versus format descriptiveness and content extensibility
- Efficiency of filtering and selection to obtain relevant parts of information

- Automatic generation of software APIs for relevant programming languages

CONTENT PRECISION

- Scalable methods, e.g. for location referencing (cf. Section 6.2) and data precision as function of the MDO levels

META DATA

- Quality quantifiers to facilitate probabilistic processing of information
  - Data verified (yes/no/partially)
  - Reliability of the information (in %)
  - Probability of occurrence (i.e. how likely is it that the vehicle will encounter a given traffic situation) and prediction (i.e. how will the probability change in the future)
  - Information age
- Provenance
  - Data source (e.g. road authority, police, crowd-sourced, aggregated by certified service provider)
  - Authoritative (i.e. an instruction/order) or Guiding (advice/recommendation)
  - How is the data generated/processed and by whom?
- Domain(s) – Is information specifically targeted to:
  - specific automation levels [2] or AD capabilities (e.g. degraded mode detection & operation, execute actions to reach a Minimal Risk Condition (MRC), communicate/interact with other road users, …)
  - for specific Automotive Safety Integrity Levels (ASIL)
  - specific AD vehicle types or configurations (e.g. presence or absence of certain types of sensors)
- Situation awareness – Is information specifically targeted to:
  - certain states of the passenger(s) (e.g. alert, asleep, absent)
  - resolving known ambiguities (e.g. conflicting road signage)

The above list is preliminary and will be extended in the course the development of TPEG3.

# 5 TECHNOLOGY

## *5.1 Innovation*

LIMITED VISUAL HORIZON

Sensors currently used for ADS typically use electromagnetic signals (radar, LiDAR, camera) to provide an image of what is around them. The range of these sensors is limited. Moreover, their functioning can be inhibited by environmental factors, e.g. dense fog, rain, or obstructions from buildings, or even cars around the vehicle. The aim for TPEG3 is to enhance this horizon by providing information that can help assess the impact of events beyond the horizon of vehicle's sensors. In this sense, information provided by TPEG3 can be seen as an extra sensor for the vehicle's ADS.

#### Qualifying Information

For information to be used by an ADS, it has to be clear how trustworthy the information is. For TPEG2, this assessment is done by the human driver. An ADS is not as capable in assessing the quality of the information as a human driver. Our aim is to make information captured by TPEG3 to be actionable, thus we need to make sure that it is clear what the quality/trustworthiness of the information is. Therefore, a quality level should be part of the TPEG3 specification.

#### More than TPEG2

As mentioned, TPEG3 information should be actionable. It therefore needs to contain more detailed information than a typical TPEG2 application:

- A higher location accuracy; to safely navigate, locations, they need to have lane-level accuracy
- Detailed information of the road ahead with respect to blocked lanes, road condition, weather. These can have an impact on the sensor's capabilities to traverse a road segment.

TPEG2's origins are in the broadcast world. Its model of communication is the distribution of a large set of messages every few minutes to all cars that can receive it. For TPEG3 we want to use a more flexible approach. Vehicle should be able to request for relevant information, as well as subscribe to such changes in relevant information.

#### Flexible Open Source Toolchain

TPEG3 aims at an easy adoption of its concept to AD research and development. It must therefore be easy to use and deploy TPEG3. To help this, TPEG3 will use open source toolchains. The most important change is that the current binary format will not be used, as this not help in the adoption of TPEG3. Toolchains under consideration are:

- encoding schemes/tools (e.g. Google Protobuf, EXI)
- communication (e.g. AMQP, MQTT)
- multiple language bindings: python, C/C++, etc.

Note: given that this domain is rapidly evolving, the focus needs to be a flexible use of protocols.

#### Accurate Location

Automated vehicles need to be informed on which lane to take. Moreover, they need more accurate information on the geometry of the road. To support this, better methods need to be developed for accurate location referencing as part of the TPEG3 development activities.

### *5.2 Critical components & aspects*

#### Low Latency

Low latency is a key requirement for TPEG3 messages. We want to make sure that information arrives in time. Decoding a message should be fast. This implies an encoding scheme that has a low memory footprint, and ideally fits to the formats used within the vehicle

#### Information Ordering

TPEG2 information is packaged in 2 parts - application information: *What is it? What is happening* – and the location reference: *Where is it?* It is not clear of this model still holds for TPEG3; locations are not opaquer in TPEG3, as they should also convey changes of the roads inside a location reference. Also, some information is not relevant any more for an ADS: the cause of an event. Moreover, some information is related to elements inside the location reference: advice to move a lane left in a specific part of the referenced road.

COMMUNICATION EFFICIENCY

Next to low latency, also the size of messages needs to be small. This has a positive effect on latency, as well as on the overhead of using the message. To be a viable alternative to map updates, TPEG3 message size needs to be an order of magnitude smaller than an NDS map tile update. Next to this, it is key not to overload an ADS with irrelevant information. Accurate information about e.g. a work-zone does not need to be sent hundreds of kilometres before the vehicle reaches that site. However, it does want to know about this long before it arrives there. To support this, the information on one event needs to be tailored to the location of the vehicle: less detailed when far away, very detailed when approaching the location.

### *5.3 Constraints*

BIDIRECTIONAL COMMUNICATION

As discussed above a bi-directional communication channel is essential.

EFFICIENT PROTOCOLS AND COMMUNICATION

To address latency and effective decoding, the protocol and communication channel selection chosen should support this. Also, selectively sending information to a vehicle is needed in order not overload the ADS with irrelevant message content.

## 6 FIRST SKETCH OF THE TECHNICAL SOLUTION(S)

This first sketch of a technical solution addresses the following topics with their options and issues:

- Interaction paradigm between vehicle and infrastructure/service providers
- Location referencing
- Encoding and serialization
- Over-the-write protocol

Furthermore, the TISA benchmarking and testbench approach for evaluation of options and trade-off analysis towards a technical solution is described.

### 6.1 *A hybrid Interaction paradigm between vehicle and infrastructure/service providers*

Multiple interaction paradigms can be envisioned for the information interchange between vehicle and infrastructure/service providers. Early on in TPEG1 and TPEG2 development, a broadcast paradigm (via digital radio) was assumed. However, with the advent of mobile networks offering wireless, mobile data transport, much of the connectivity between vehicles and infrastructure/service providers moved to connected services, offering the possibility of bi-directional and tailored communication/information transfer to the vehicle.

The previous section (Section 5) highlighted the need for bi-directional communication. For such bi-directional communication two principal message exchange patterns apply:

1. **Request-response**: a message exchange pattern in which a requestor (typically the vehicle in TPEG) sends a request message to a replier system (typically the infrastructure/service provider in TPEG) which receives and processes the request, ultimately returning a message in response.
2. **Publish-subscribe**: a message exchange where senders of messages, called publishers, do not target the messages to be sent directly to specific receivers, called subscribers, but instead categorize published messages into classes without knowledge of which subscribers, if any, there may be. Similarly, subscribers express interest in one or more classes ('topics') and only receive messages that are of interest to them, without knowledge of the publishers.

Current TPEG2 connected services implement the request-response pattern in a synchronous periodic fashion using web service calls over HTTP. A web service call typically holds a connection open and waits until the response is delivered, or the timeout period expired. For TPEG3 also low latency information may need to be delivered, hence interaction paradigm and exchange pattern needs to be examined.

**Table 2: comparison of request-response and publish-subscribe message exchange patterns**

| Request-response | Publish-Subscribe |
|---|---|
| One-2-one **connection to information provider** | Many-to-one connection to information provider |
| Initiative with requestor | Initiative with information provider |
| Information o**n-request, typically time-triggered** with periodic polling | Information on-demand, event-based, as information is updated |
| Variable information age/latency determined by length of polling period | Low information age/latency, new information published as it becomes available |
| Information in response c**an be** precisely **tailored to needs of requestor** | Information tailoring limited to defined classes of information ('topics') |
| Infrastructure/server system load (replier system load) scales with number of requests[3] | Infrastructure/server system load independent on number of vehicles; dependent on number of topics |
| Little a **priori knowledge needed** to request information | More a priori knowledge needed, or discovery of topics, needed to subscribe to these |

Table 2 compares these two message exchange patterns, request-response and publish-subscribe, on a number of aspects. Comparing these aspects to the four phases identified in Section 4.1, we note the following:

- The *request-response* pattern fits well with MISSION phase identified in Section 4.1, which is (mostly) time-triggered;
- The *publish-subscribe* pattern fits well with the DECISION and OPERATION phases identified in Section 4.1, which are (mostly) location-triggered.

This suggest a hybrid approach. TPEG3 benefits from the *request-response* interaction for the mostly time-triggered interaction (and service discovery) when longer times between updates and higher information age/latency are acceptable. TPEG3 benefits from the *publish-subscribe* interaction for the mostly

[3] However, techniques exist to limit the impact of number of same/similar requests originating from multiple requestors.

location-triggered interaction, where low information age/latency is important, yet much detail may stay unchanged.

**TPEG3 hybrid interaction paradigm**

- *Request-Response* for time-dominant information exchange and service discovery
- *Publish-Subscribe* for location-dominant information exchange

PUBLISH-SUBSCRIBE INTERACTION FOR LOCATION-DOMINANT INFORMATION TPEG3

Location-dominant information will be handled through publish-subscribe information exchange in TPEG3. The main benefit of this scheme is that updated information is pushed to the vehicle immediately, such that the information age/latency is as low as possible. Furthermore, this scheme avoids repeated polling for the same information just to find out nothing has changed, thus lowering bandwidth.

A consistent and downwards referenceable definition of topics (the *subscribable entities*) between at least the levels MDO (MISSION-DECISION-OPERATION) is then a prerequisite to move easily to a more detailed level when the course of the vehicle would warrant so.

On top-level, the collective set of topics (the *subscribable entities*) must achieve a complete coverage of the map. Hence, a grid-like top-level tiling is required. Top-level tiles could be indexed by geo-hashes (see also Section 6.2).

The top-level tile topics then must reference other topics, which could be the following:

- **Static topics** reflecting e.g. a more detailed tiling or partitioning of the road network (Sections of roads or intersections for e.g. flow or restrictions);
- **Dynamic topics** reflecting e.g. dynamic non-standard situations (roadworks, accidents, road weather, slow-moving maintenance vehicles).

The various PDE levels then see topics with increasing level of granularity and precision of information. Specific topics may be subdivided at a more detailed level to keep the information quantity/data size manageable.

REQUEST-RESPONSE INTERACTION FOR TIME-DOMINANT INFORMATION IN TPEG3

Time-dominant information will be handled through request-response information exchange in TPEG3. The MISSION level initiates and monitors a journey. Most of this level can be left at the initiative of the vehicle to obtain information at lower rates, and in time for key decision points for e.g. routing.

The request-response interaction paradigm then also can be used to for service and topic discovery and update publish-subscribe topics as relevant for the vehicle's journey.

### *6.2 Location Referencing*

A critical component of TPEG3 is the location referencing, which unlike TPEG2 will not rely on the approach to select one out of several possible methods for a given service. While TPEG2 compiles information based on type (e.g. incident, flow, weather), TPEG3 uses a different approach, where information from different domains is aggregated into a "situation", such as "roadworks" or "accident", each of which containing a compilation of information concerning obstacles blocking the driving path, road surface conditions, changes in road layout and lane structure, speed & driving restrictions, temporary suspension of traffic rules (e.g. “cross a solid line for driving around an accident scene”) and many others.

Furthermore, as each phase (MISSION-DECISION-OPERATION) requires different resolution and accuracy of location information, a one-size-fits-all will not meet the requirements of TPEG3. A situation description will therefore contain a number of different location referencing schemes for different information dimensions and data elements, where there will be an underlying trend to use coarse resolution, compact schemes for the MISSION phase, then with increasing resolution for the DECISION phase all the way to the most comprehensive and data-intensive schemes for the OPERATION phase.

Possible location referencing approaches are:

- geo-hashes[4] for the coarse, yet efficient, referencing of areas for certain information types and the initial part of the MISSION phase;
- on-the-fly location referencing schemes for situations and objects that are not embedded on HD maps (e.g. temporary road geometries or lane layouts, temporary street furniture such as barriers or traffic cones, temporary road signage overriding the permanent road signs) during the DECISION and OPERATION phases;
- HD map-based Link-ID schemes for identifying objects that are embedded on HD maps (e.g. permanent road furniture, default road geometry and lane layout, permanent road signage) during the DECISION and OPERATION phases.

Geo-hashes are a very efficient method, where areas are subdivided and the spatial resolution increases with the length of the hash. However, geo-hashes are nonlinear due to the curvature of the earth and distances need to be calculated using the Haversine formula[5], or alternately with a local linear approximation.


- **Figure 6: Example for a geo-hash based referencing of a road layout [3]**

On-the-fly location referencing methods, such as Agora-C [4] or OpenLR[6] are proven techniques for referencing roads, intersections and road segments on digital maps. They are interoperable, i.e. they even

[4] https://en.wikipedia.org/wiki/Geohash

[5] https://en.wikipedia.org/wiki/Haversine_formula

[6] https://www.openlr-association.com/

work reliably if the source map at the service provider and target map in the mobile device are supplied from different vendors or have different versions. Due to the higher complexity of HD maps and the increased location accuracy of AD vehicles (lane level and sub-lane level), on-the-fly methods have limitations when used on HD maps. Suitable methods for referencing to HD maps are using map-specific IDs, which are not interoperable so that identical source and target maps need to be used.

The approach used for TPEG3 is still in the research phase, but it is safe to say that there will not be a "one-size-fits-all" solution, but rather a set of different methods, from which a suitable method is chosen depending on the AD Level, the required accuracy, bandwidth/latency constraints related to transmission and parsing/processing/memory constraints of the AD system in the vehicle.

Selection of location-referencing methods in the MDO phase model will be guided by the following considerations:

- compact, low-resolution, interoperable and fast-decoding methods will likely be used for the Mission phase, since a large number of AD vehicles will request such information for their route planning, even when still being far away from a given traffic situation;
- very accurate, but bandwidth-consuming methods will be used in the Decision and Operation phases, as only a limited number of vehicles will be in the direct approach or inside the traffic situation, however planning a safe path requires very high-resolution detailed information about almost everything in the proximity of a given vehicle;
- interoperable and relatively accurate on-the-fly methods may be used during the Mission phase, where accuracy and level of detail are not of highest importance, but rather an "overall judgement" of the situation, facilitating a decision-making process regarding whether to continue in an AD mode or hand-over the DDT to the driver.


**Figure 7: Example for a possible scaled location referencing approach**

Summarizing the discussion in this section: investigations concerning universal, compact and scalable map-dependent (e.g. link ID) and map agnostic (e.g. on-the-fly) location referencing schemes is still ongoing. A challenge in this context will be the linkage of infotainment maps and their location referencing schemes with new approaches used for HD maps, where the former is used for driver information and the latter by the AD algorithms for controlling the vehicle movements.

### *6.3 Serialization*

PROTOBUF

Google Protocol Buffers[7] aka Protobuf is a method of serializing structured data. It serializes information based on an interface description language. It was developed by Google and is used for many applications that involve interchanging information. It has been open sources by Google under a BSD license. Protobuf is being used within the Apollo Auto framework[8]and SENSORIS[9]. Given this it is the first choice for encoding with the I4AD activities.

UBJSON

Universal Binary JSON[10] is an attempt to standardize a binary version of the popular JSON format. UBJSON is a proposed successor to BSON, BJSON and others. UBJSON is fully compatible with the JSON specification Its data representations are (roughly) 30% smaller than their compacted JSON counterparts and are optimized for fast parsing. Streamed serialization is supported, meaning that the transfer of UBJSON over a network connection can start sending data before the final size of the data is known.

EXI

Although XML is a popular protocol for encoding information, its disadvantage is the size of messages. Efficient XML Interchange (EXI)[11] is an attempt by the W3C to develop a binary version of XML. Currently this encoding also supports the efficient encoding of JSON formats (EXI4JSON)

OTHER ENCODINGS

Next to the encoding mentioned, there are others that warrant further research in future. Based on the comparison on Wikipedia[12], the following have a relevance in our area:

- **ASN.1**
  It is used with C-ITS, and therefore a possible contender in our work as well. Key issue with efficient encoding of ASN.1 using Packed Encoding Rules (PER) is the inflexibility for adding unforeseen extension elements afterwards.
- **CBOR**
  A JSON-like binary protocol, specified in RFC 7049.
- **CDR (Common Data Representation)**
  A format specified by OMG as part of DDS, an underlying technology of ROS2. The robotic operating system that is used for a number of open source Automated Driving frameworks.

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[7] https://developers.google.com/protocol-buffers/
[8] http://apollo.auto/
[9] https://sensor-is.org/
[10] http://ubjson.org/
[11] https://www.w3.org/XML/EXI/
[12] https://en.wikipedia.org/wiki/Comparison_of_data-serialization_formats

- **ZSERIO**
  An efficient serialization protocol developed by the NDS community[13].

### *6.4 Example code in JSON*

This section aims at illustrating how the information could like for the different phases as mentioned in Section 4. It is by no means intended to make this into a standard.

MISSION

```
{
  "id": "ev-1",
  "rationale": "PreciseWorkZone",
  "mmt": {
    "messageExpiryTime": "2019-12-25T15:00Z",
    "cancel": "False"
  },
  "mission": {
    "time":
  {
  "start": "2019-12-19T15:00Z",
  "duration": "2:00"
  },
  "effect": {
    "effect": "delay",
     "timeToTraverse": "1800"
  },
  "advice": {
    "ADAllowed": "true",
  },
  "location": {
    "type": "OLR",
    "location": "..."
  }
  },
    "decision": {
    "event": "ev-2"
  }
}
```

Information affecting the route planning

Automated driving is allowed in this work zone

More detailed for the DECISION phase

DECISION

```
{
"id": "ev-2",
  "rationale": "PreciseWorkZone",
  "mmt": {
    "messageExpiryTime": "2019-12-25T15:00Z",
    "cancel": "False",
    "relevantLocation": "u15u"
  },
  "mission": {
    "event": "ev-1"
  },
  "decision": {
    "cameraVisibility": "restricted",
    "roadLayout": [
      {
        "startOffset": 0,
        "barrier": "cones",
        "speedLimit": 70,
        "lanesBlocked": [0],
        "AD": true,
        "laneChanges": [
          [0, "blocked"]
        ]
      },
      {
        "startOffset": 250,
        "lanesBlocked": [0],
        "laneDivider": "yellow",
        "laneChanges": [
        {
          "lane": 1,
          "offset": 200,
          "width": 300,
          "speedLimit": 50,
          "AD": false
        },
        {
          "lane": 2,
          "AD": true,
          "ADSpeedLimit": 50
        }
       ]
     },
     {
       "end": 1200,
       "AD": true
     }
   ],
   "locationReference": {
     "type": "ADL",
```

Reference to Information affecting the route planning

Information affecting the works zone

Camera imaging is unreliable

Detailed information on the work zone

No automated driving on lane 1

13 https://github.com/ndsev/zserio

```
        "location": {}
      }
    }
}
```


**Figure 8: Mission Phase information**

**Figure 9: Decision Phase information**

OPERATION


```
{
  "id": "ev-3",
  "rationale": "PrecizeWorkZone",
  "mmt": {
    "messageExpiryTime": "2019-07-25T15:00Z",
    "cancel": "False",
    "relevantLocation": "u15u"
  },
  "mission": {
    "event": "ev-1"
  },
  "decision": {
    "event": "ev-2"
  },
  "operation": {
    "cameraVisibility": "restricted",
    "advice": [
      {
        "startOffset": 0,
        "locationReference": 1,
        "speedLimit": 70,
        "lanesPreferred": [1,2],
        "lanesBlocked": [
          0
        ]
      },
      {
        "startOffset": 250,
        "locationReference": 4,
        "lanesPreferred": [2],
        "lanesBlocked": [0],
        "laneDivider": "yellow",
        "laneChanges": [
          {
            "lane": 1,
            "offset": 200,
            "width": 300,
            "speedLimit": 50,
            "AD": false
          },
          {
            "lane": 2,
            "AD": true,
            "ADSpeedLimit": 50
          }
        ]
      },
      {
        "end": 1200,
        "locationReference": 42,
          "AD": true
        }
        ]
      },
```


The operation phase contains advice on how to traverse the works zone, e.g. which lanes are preferred, speed limit

Due to the high level of detail required, the advice will also refer to a location inside the attached location reference.

```
        "locationReference": {
        "type": "ADL",
        "location": {}
      }
    }
}
```


**Figure 10: OPERATION Phase information**

### 6.5 *Over-the-wire protocol*

MQTT

MQTT[14] *Message Queuing Telemetry Transport* is an ISO standard (ISO/IEC PRF 20922) publish-subscribe-based messaging protocol. It is designed for connections with remote locations where a *small footprint* is required, or the network bandwidth is limited. The publish-subscribe messaging pattern requires a message broker. Inherently, it is a lightweight protocol with few features for reliability or security.

AMQP

As MQTT, AMQP[15] is a publish-subscribe messaging protocol. However, it also supports other communication patterns, e.g. request/response. Next to this, it focusses more on reliability and security by introducing e.g. message queues, and supporting SSL/TLS.

Others

Next to these protocols, **http** is also an option. However, it does not support publish-subscribe properly, also it is not very lightweight. A further option would be to base I4AD on **Data Distribution Services (DDS)**[16], an OMG standard. Although powerful, its less open that other solutions, and could make it more difficult for it to be adopted.

### 6.6 *Testbench & Benchmarking results*

For the evaluation of the performance of different serialization schemes and over-the-wire protocols with respect to different Key Performance Indicators (KPI), a testbench has been developed that at the time of this writing can

- process TPEG2 XML files as input,
- then perform a serialization using Protobuf,
- send the data over some network using AMQP,
- then de-serialize the data and,
- create a CSV output file with information for later statistical evaluation.

KPIs that are currently of interest are:

- message size (min/max/median)

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[14] https://mqtt.org/

[15] https://www.amqp.org/

[16] https://en.wikipedia.org/wiki/Data_Distribution_Service

- processing required for serialization (ops)
- processing required for de-serialization (ops)
- memory footprint for de-serialization
- latency for the over-the-wire message transport for given network characteristics

In a later phase, a TPEG3 input interface will be added as well as other serialization schemes (EXI, UBJSON, Zserio, ASN.1, …) and over-the-wire protocols (MQTT, …). This is to facilitate a comparison of the performance for different serialization vs. over-the-wire protocol combinations and to optimize the structural efficiency of TPEG3. Furthermore, logging of data for additional KPIs will be added to analyse the performance of randomly parsing information at the client side, or to study the influence of the MDO grouping of information on the encoding-decoding performance.

The following Figure 11 shows a flow diagram of the testbench. The code is available at TISA's GitHub I4AD-protocol repository[17] and can be run in a terminal using command line switches on computers with Python3 and some additional support packages installed. For details, please refer to the Readme files on GitHub.

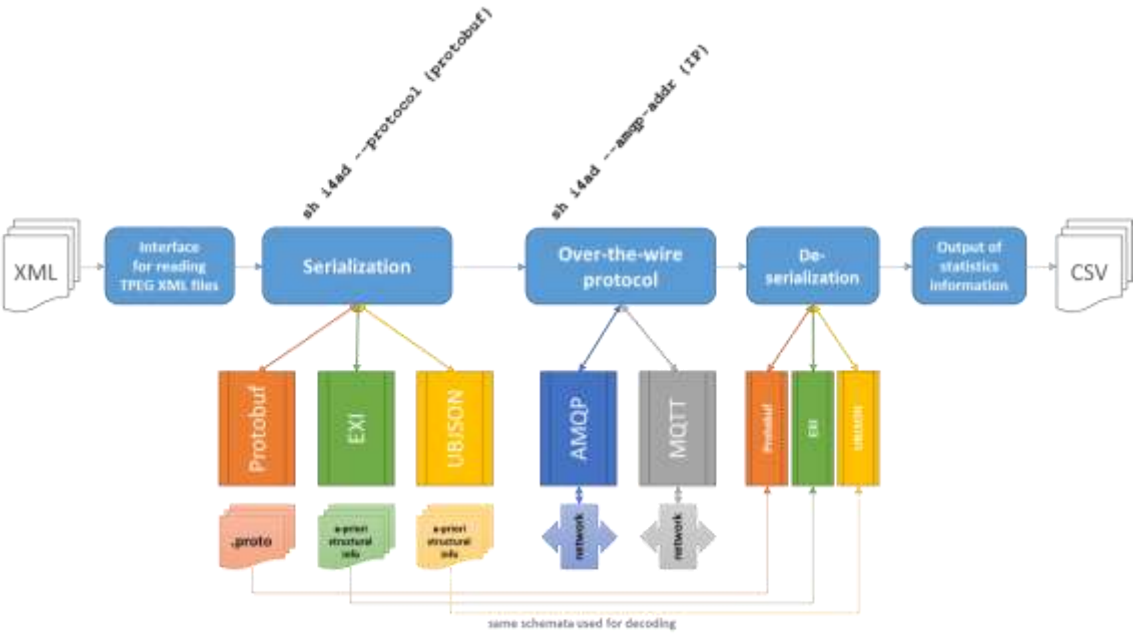


**Figure 11: I4AD testbench**

Initial performance results for some tests with synthetic TPEG TEC messages (i.e. not real services) are shown in the following Table 3.

**Table 3: Comparison of TPEG2 and Protobuf transcoding for 2 message sets with 714 messages each**

| | TEC with<br>Advices Restrictions | TEC with<br>Systematic Cause Enumeration |
|---|---|---|

[17] https://github.com/tisa-asbl/I4AD-protocol/

| | TPEG binary | Protobuf | TPEG binary | Protobuf |
|---|---|---|---|---|
| **Mean size of a message** | 53.86 Bytes | 59.32 Bytes | 38.65 Bytes | 43.67 Bytes |
| **Median size of a message** | 54 Bytes | 60 Bytes | 39 Bytes | 43 Bytes |
| **Min/max size of messages** | 51 / 55 Bytes | 55 / 64 Bytes | 37/ 39 Bytes | 40 / 47 Bytes |
| **Protobuf-to-TPEG-bin size ratio** | 1.1 | | 1.1 | |

**Table 4: TPEG2 message set used for the testbench evaluation**

| | TEC with Advices Restrictions | TEC with Systematic Cause Enumeration |
|---|---|---|
| **Size of binary TPEG file (uncompressed)** | 38,966 Bytes | 28,106 Bytes |
| **Size of binary TPEG file (zlib compressed)** | 10,950 Bytes | 7,857 Bytes |
| **Size of TPEG XML file** | 1,718,595 Bytes | 1,357,045 Bytes |

Overall, TPEG binary message size is approx. 10% smaller than Protobuf's size. However, the sample size of this test set is with 700 messages too small for drawing definite conclusions. Furthermore, the a-priori structural information for the Protobuf serialization (schemata stored in .proto files) could be further optimized as well as other TPEG overhead (e.g. SNI) be considered. TPEG compression at TPEG frame level (a TPEG frame clusters ~100 TPEG message plus some service information) makes compressed TPEG frame bandwidth a factor 3 to 3.5 more efficient than uncompressed TPEG messages.

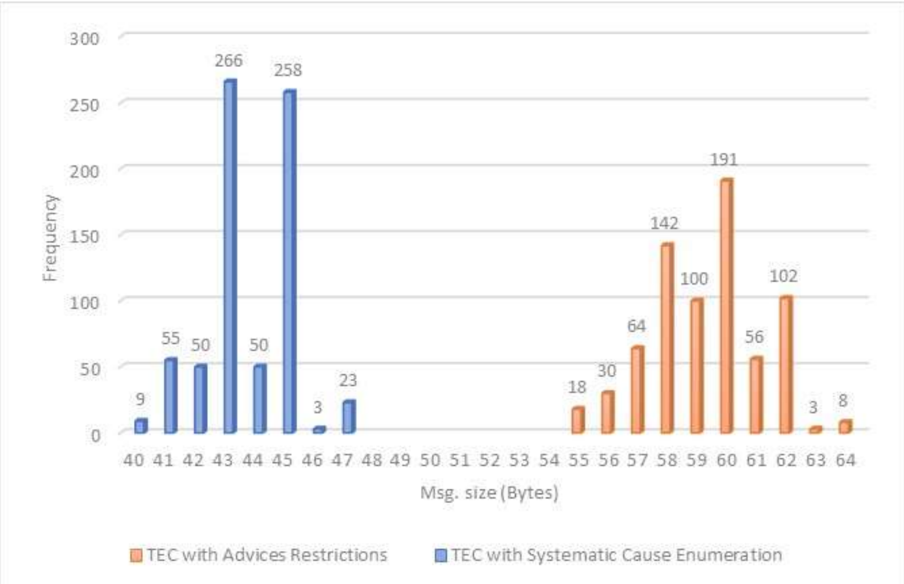


**Figure 12: Distribution of message sizes for 714 TPEG2 messages, transcoded using Protobuf**

# 7 References

[1] „Safety First For Automated Driving“, Aptiv, Audi, Baidu, BMW, Continental, Daimler, Fiat Chrysler Automobiles, HERE, Infineon, Intel, Volkswagen, available e.g. at https://newsroom.intel.com/wp-content/uploads/sites/11/2019/07/Intel-Safety-First-for-Automated-Driving.pdf

[2] *“Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles”* (J3016_201806), SAE International, 15.06.2018, www.sae.org

[3] Itamar Landsman, *“How to Count Large Scale Geohashes”*, 03.06.2019, Otonomo website, https://otonomo.io/how-to-count-large-scale-geohashes/

[4] Wevers, Kees & Hendriks, Teun. (2006), *„AGORA-C map-based location referencing“*, Transportation Research Record. 1972. 115-122. 10.3141/1972-16.

## Annex A – Acronyms

| Acronym | Verbose description | Comments |
|---|---|---|
| AD | Automated Driving | Refers to both automated (SAE levels 1 to 4) and fully autonomous (SAE level 5) driving |
| ADS | Automated Driving Systems | |
| AMQP | Advanced Message Queuing Protocol | An open standard application layer protocol for message-oriented middleware |
| ASIL | Automotive Safety Integrity Level | |
| ASN.1 | Abstract Syntax Notation | Standard for serialization/deserialization of data, standardized by ITU-T |
| C-ITS | Cooperative ITS | |
| DAB | Digital Audio Broadcasting | A digital radio broadcasting system |
| DATEX II | | Standard for exchanging traffic information between traffic management centres, maintained by CEN Technical Committee 278, see www.itsstandards.eu |
| DDT | Dynamic Driving Task | As defined in [2] |
| EBU | European Broadcasting Union | www.ebu.ch |
| EXI | Efficient XML Interchange | Binary XML format, defined by the W3C |
| GPS | Global Positioning System | |
| HD maps | High-definition maps | Digital maps primarily used in context with AD vehicles |
| ISO | International Standardisation Organisation | www.iso.org |
| ITS | Intelligent Transport Systems | |
| ITU | International Telecommunications Union | www.itu.int |
| MRC | Minimal Risk Condition | As defined in [2] |
| MQTT | Message Queuing Telemetry Transport | Publish-subscribe-based messaging protocol |
| ODD | Operational Design Domain | As defined in [2] |
| OEM | Original Equipment Manufacturer | In the context of this document, OEM refers to automobile manufacturers |
| PWZ | Precise Work Zones | A road work zone that has an impact on the traffic flow and for which detailed information is available, currently *work in progress* within TISA |

| Acronym | Verbose description | Comments |
|---|---|---|
| PA | Public Authority | |
| RO | Road Operator | |
| SAE | Society of Automotive Engi-neers | www.sae.org |
| TISA | Traveller Information Services Association | www.tisa.org |
| TPEG | Transport Protocol Experts Group | A set of standards published by TISA and by ISO for the distribution of traffic and traveller related infor-mation |
| TPEG2 | TPEG version 2 | A version of the TPEG standard destined to human drivers |
| TPEG3 | TPEG version 3 | A version of the TPEG standard destined to AD vehi-cles – currently under development within TISA |
| V2I | Vehicle-to-Infrastructure | |
| V2V | Vehicle-to-Vehicle | |
| V2X | Vehicle-to-“anything” | |
| VMS | Variable Message Signs | Road signs that can dynamically changed to indicate changing speed limits or lane closures |
| W3C | World Wide Web Consortium | www.w3.org |
| XML | Extensible Markup Language | A markup language for encoding documents, defined by W3C |

## Annex B – Relation between TPEG3 and the SaFAD Framework

In the whitepaper "Safety First For Automated Driving" (SaFAD) [1], the authors propose a framework with 12 guiding principles for achieving a positive risk balance for AD systems. The SaFAD framework is intended for the *Validation* and *Verification* (V&V) of AD systems, whereas TPEG3 is used to provide information to ensure the safe operation of an AD system under the assumption that it is verified and validated by the system designers. Nevertheless, the SaFAD framework does provide a well-structured thought concept and the domain information provided via TPEG3 relates to some of the SaFAD guiding principles.

The following Table B1 summarizes the guiding principles of the SaFAD framework [1] and outlines the areas to which TPEG3 information relates and can contribute to achieving such positive risk balance by providing contextual and detailed information of complex road situations ahead of the AD vehicle. This may also include temporary changes to the default traffic regulations (as stored on the HD map) if imposed by e.g. road authorities or police and rescue forces. TPEG3 can therefore supplement the safety-related decision-making processes and contribute to achieving a better risk balance for AD systems.

**Table B1: How TPEG3 relates to the Guiding Principles in the SaFAD framework (cf. [1], Table 2)**

| SaFAD guiding principle | Addressed by TPEG3 | | Relevance |
|---|---|---|---|
| **Safe Operation**: How the system reacts if critical components become unstable or cease functioning. | indirectly | ▪ Providing information about complex situations ahead of the AD vehicle, supporting the decision-making whether safe operation can be continued. | medium |
| **Operational Design Domain (ODD)**: The operating conditions in which the system is designed to function. | **directly** | ▪ Providing information about complex situations ahead of the AD vehicle, supporting the decision-making whether the ODD limit may be reached soon. | high |
| **Behaviour in Traffic**: The system behaviour needs to be easy to understand and predictable for surrounding road users. | **directly** | ▪ Providing information for situation-aware driving path planning and execution. | high |
| **User Responsibility**: The user's state must be suitable for a takeover procedure. | **directly** | ▪ Alerting the driver sufficiently ahead of time;<br>▪ Providing contextual information about the situation ahead of the AD vehicle to facilitate proper handover by the driver. | high |
| **Vehicle-Initiated Handover**: If the driver does not comply with a takeover request, the automated driving system must perform a manoeuvre to minimize risk. | **directly** | ▪ Providing contextual information about the situation ahead of the AD vehicle to facilitate a suitable manoeuvre for reaching a Minimal Risk Condition (MRC). | **critical** |
| **Driver-Initiated Handover**: Activating and deactivating the automated driving system shall require an explicit driver's intent. | **directly** | ▪ Providing contextual information about the situation ahead of the AD vehicle to facilitate a situation-aware activation of AD functions (or vice-versa explain to the driver why activation is not possible). | medium |

| SaFAD guiding principle | Addressed by TPEG3 | | Relevance |
|---|---|---|---|
| **Effects of Automation**: Overall evaluation of system safety shall take automation effects on the driver into account. | indirectly | ▪ Providing information about the situation ahead and motivating intentions of the AD vehicle in context with the upcoming traffic situation. | medium |

From the 12 guiding principles, the following are not relevant for / affected by TPEG3:

- Safety Layer: The system recognizing its limits and minimizes risk in returning control to the driver
- Data Recording: When an event or incident is recognized, automated vehicles shall record relevant data in a manner that complies with applicable privacy laws
- Security: Steps shall be taken to protect the automated driving system from security threats
- Passive Safety: Vehicle layout shall accommodate changes to crash scenarios brought about by vehicle automation
- Safety Assessment: Verification and validation shall be used to ensure that the safety goals are met

The following Fig. B1 maps the guiding principles onto capabilities of an AD system. It is derived from Table B1, the guiding principles to which TPEG3 relates, and the capabilities that may be affected by information provided via TPEG3 are highlighted.

| ID | Safe Operation | Safety Layer | Operational Design Domain | Behavior in Traffic | User Responsibility | Vehicle-Initiated Handover | Veh.-Op.-Initiated Handover | Interdep. Veh. Op. & ADS | Data Recording | Security | Passive Safety | Safety Assessment |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FS_1 Determine location | | | X | X | | | | | | X | | X |
| FS_2 Perceive relevant objects | | | | X | | | | | | X | | X |
| FS_3 Predict the future behavior of relevant objects | | | | X | | | | | | X | | X |
| FS_4 Create a collision-free and lawful driving plan | | | | X | | | | | | X | | X |
| FS_5 Correctly execute the driving plan | | | | X | | | | | | X | | X |
| FS_6 Communicate and interact with other (vulnerable) road users | | | | X | | | | | | X | | X |
| FS_7 Determine if specified nominal performance is not achieved | | X | X | | | | | | | X | | X |
| FD_1 Ensure controllability for the vehicle operator | X | | | | X | X | X | X | | X | | X |
| FD_2 Detect when degraded performance is not available | X | | | | | | | | | X | | X |
| FD_3 Ensure safe mode transitions and awareness | X | X | | | X | X | X | X | | X | | X |
| FD_4 React to insufficient nominal performance and other failures | X | X | | | | | | | | X | | X |
| FD_5 Reduce system performance in the presence of failures | X | X | | | | | | | | X | | X |
| FD_6 Perform degraded mode within reduced system constraints | X | X | X | | | X | | | | X | | X |

**Figure B1: Capabilities matrix (cf. [1], Table 2) indicating the relevance of the 12 guiding principles for AD vehicle capabilities. Areas with TPEG3 contributions are highlighted.**

The following Table B2 provides a more detailed description of the relation between the SaFAD capabilities and supplementary traffic information provided by TPEG3.

**Table B2: TPEG3 supplementing the Capabilities in the SaFAD framework (cf. [1], Table 2)**

| **SaFAD Capabilities** | | **Contribution by TPEG3** |
|---|---|---|
| **FS-2**: Perceive relevant static and dynamic objects in the proximity of the automated vehicle. | All entities that an automated driving system requires for its functional behaviour should be perceived, optionally pre-processed, and provided correctly. The highest priority is placed on entities with an associated risk of collision. Sample entities include dynamic objects (e.g. (vulnerable) road users and characteristics of the respective movement), static instances (e.g. road boundaries, traffic guidance and communication signals) and obstacles. | ▪ Provide contextual information about the traffic situation ahead of the AD vehicle.<br>Example:<br>▪ Semi-static obstacle (road works, accidents);<br>▪ Changes in road geometry and lane layout (roadworks);<br>▪ Temporarily overriding local traffic rules by road authorities or police. |
| **FS-3**: Predict the future behaviour of relevant objects. | The relevant environment model needs to be extended by the predicted future state. The aim is to create a forecast of the environment. The intention of the relevant objects should be interpreted in order to form the basis for predicting future motion. | ▪ Support correct interpretation of the traffic situation by providing an additional, independent and validated source, complementing the sensor data.<br>Example:<br>▪ Support classification of objects by providing information about e.g. road furniture, building construction machinery on-site at road works;<br>▪ Provide applicable traffic rules (if different from standard rules) to allow a reliable forecast of coming traffic patterns or traffic management interventions (e.g. by the police). |

| SaFAD Capabilities | | Contribution by TPEG3 |
|---|---|---|
| **FS-4**: Create a collision-free and lawful driving plan. | To ensure a collision-free and lawful driving policy, the following should be respected:<br>▪ Maintain safe lateral & longitudinal distance to other objects;<br>▪ Comply with all applicable traffic rules within the ODD;<br>▪ Consider potential areas where objects may be occluded;<br>▪ In unclear situations the right of way is given, not taken;<br>▪ If a crash can be avoided without endangering third parties, traffic rules may be prioritized if necessary. | ▪ Provide information beyond sensor reach and where sensors visibility is obstructed;<br>▪ Provide temporary changes to local traffic rules.<br>Example:<br>▪ Support classification of objects in a work zone by providing information about e.g. road furniture, building construction machinery on-site at road works;<br>▪ Provide information about applicable traffic rules (if different from standard rules) at an accident scene to allow a reliable forecast of coming traffic patterns and traffic management interventions e.g. by the police. |
| **FS-5**: Correctly execute and actuate the driving plan. | The corresponding actuation signals for lateral and longitudinal control should be generated based on the driving plan. | ▪ Provide information about the traffic situation ahead of the AD vehicle such that a correct and timely (early) signalling of AD vehicles intentions and driving plan is possible.<br>Example:<br>▪ Acknowledging that the AD vehicle is aware of the situation ahead;<br>▪ Perform clear manoeuvres that match the given road situation (even if non-standard) and any temporary changes to the traffic regulation. |
| **FS-6**: Communicate and interact with other (vulnerable) road users. | Automated driving vehicles are required to communicate and interact with other (vulnerable) road users, depending on the ODD and the use cases. | ▪ Provide information about the traffic situation ahead of the AD vehicle such that a correct and timely (early) signalling of AD vehicles intentions and driving plan is possible<br>Example:<br>▪ Acknowledging that the AD vehicle is aware of the situation ahead by signalling (visual or acoustically) and through clear driving manoeuvres (early slowing down or turning). |

<table>
<tr><th colspan="2">SaFAD Capabilities</th><th>Contribution by TPEG3</th></tr>
<tr><td>FS-7: Determine if specified nominal performance is not achieved.</td><td>Any element of the automated driving system can, either on its own or in combination with others, result in adverse behaviour. Therefore, mechanisms are required to detect the adverse nominal performance of the system. FD-4 covers the reaction to detected adverse behaviour. Typical aspects for influencing the nominal performance are:<br>▪ Unwanted human factors, incl. misuse and manipulations;<br>▪ Deviation of the intended functionality;<br>▪ Technological limitations;<br>▪ Environmental conditions;<br>▪ Systematic and random failure modes.</td><td>▪ Provide contextual information about the traffic situation ahead of the AD vehicle to support early detection and reliable judgement if the AD vehicle despite the adverse behaviour of the concerned element can continue or if an ODD exit is required (and if yes, which is the most appropriate exit strategy for a given traffic situation).<br>Example:<br>▪ Comparing two mismatching sensor outputs may not be conclusive;<br>▪ External information from an independent source may assist in deciding which of the two sensors is malfunctioning and whether the traffic situation ahead of the AD vehicle is benign (vehicle may continue) or to complex to negotiation with a single sensor (exit ODD and perform MRC action).</td></tr>
<tr><td>FD-1: Ensure controllability for the vehicle operator.</td><td>The vehicle operator’s level of control varies depending on the automation level as per SAE J3016 and the use case definition and should therefore be ensured.</td><td>▪ early alert of the driver ahead of a challenging traffic situation where takeover of the driving take by the driver may be required<br>▪ provide contextual information to the driver about<br>  ○ why take over is required<br>  ○ what to expect and which manoeuvres are recommended<br>Example:<br>▪ alert the passenger(s) early (“wakeup call”) before a work zone where the AD vehicle cannot drive through by itself (e.g. due to lack of capabilities, or because it is forbidden by the road authority for safety reasons since there are workers on the street)<br>▪ provide a reason why takeover by the driver is required and detailed information about what is happening, when, and possible recommended driving actions</td></tr>
</table>

<table>
<tr><th colspan="2">SaFAD Capabilities</th><th>Contribution by TPEG3</th></tr>
<tr><td>FD-3: Ensure safe mode transitions and awareness.</td><td>Ensure that mode transitions are performed correctly and controlled by the vehicle operator affected if necessary. The vehicle operator affected should also be aware of the current mode and their responsibility deriving from it. For example, actuating an automated mode is permitted only when inside the ODD, and it will be deactivated prior to leaving the ODD or as a result of the vehicle operator taking control again.</td><td>▪ provide contextual information about the traffic situation ahead of the AD vehicle to support early and reliable judgement if the AD vehicle can enter an AD mode, continue, or may need to exit<br>▪ provide contextual information to the driver<br><br>Example:<br>▪ a vehicle may be in a traffic situation that would permit activation of an AD mode (obvious context to the driver), but may approach a traffic situation that will result in exiting the AD mode shortly (opaque to the driver), hence decide to not permit activating the AD mode while informing the driver why (because the frequent AD mode switch may compromise traffic safety)</td></tr>
</table>

### *B1* TPEG3 *addressing the Reliable Map Attribute issues*

The following text takes a stance to some issues outlined in [1] concerning Reliable Map Attributes (RMA) on pages 49 ff.

*“Multiple map attributes are utilized in location-based ODD determination, such as <u>lane markings</u>, <u>road markings</u>, <u>traffic signs</u>, light poles, guardrails or artificial markers. However, some attributes are not always “reliable” to detect due to reasons including <u>occlusion</u>, <u>abrasion</u> or <u>frequent changes</u>. Therefore, reliable map attributes (RMAs) should be detected correctly in safety-relevant use cases, so that collectively they can meet the low location-based ODD determination false positive rate requirement. RMAs should have the following properties:*

- *<u>Fused with on-board sensor inputs</u>, a combination of RMAs should be a sufficient condition to <u>infer that the automated vehicle is reaching the boundary of the ODD</u>.*
- *RMAs should be reliably detectable by on-board sensors within the ODD.*
- *[…]*

`-- underlining of text by the authors of this paper --`

TPEG3 acts in this context as an additional sensor, supplying dynamic information that may be outdated on the HD map and providing an additional, independent information source that increases the reliability in detecting the traffic-related environment and reduces the risk of misinterpretation of:

- temporary road signs and road furniture that may be partially damaged, obstructed, misaligned or placed where visual sensors would normally not expect them;
- dynamic road signs, such as traffic lights or variable messages signs (VMS).

*“Due to its nature of being <u>offline but not processed in real time</u>, a HD map has the advantage of being less probabilistic compared to on-board sensors. However, this also results in the <u>limitations of a HD map when employed in safety-related use cases</u>. RMA failure occurs due to deviations between the map and reality, possibly arising from:*

- *[…]*
- *Errors introduced due to real-world changes, which can further be classified as:*
  - *INTENDED CHANGES: Typically by a <u>local road authority</u> (e.g. <u>planned road construction</u>)*
  - *UNINTENDED CHANGES: Typically due to <u>external forces or normal wear</u> (e.g. a piece of guardrail is damaged in a collision and not recovered before the next road maintenance)*
  - *MALICIOUS CHANGES: Typically due to an <u>unauthorized/malicious action</u> (e.g. unauthorized removal of a speed limit sign)*

*The above errors should be addressed appropriately to ensure that the automated driving system is able to reach an accepted risk level. “*

`-- underlining of text by the authors of this paper --`

As traffic information is real-time by nature, provided by a trusted source (traffic service provider, road authority, public broadcasters, etc.) and usually quality-controlled throughout the content and service distribution chain, it addresses the above deficiencies of HD maps.

*"V2X may provide valuable information to the automated driving system. […]An example for this could be providing redundancy for the detection of traffic signal state that else could be detected only by camera. There is currently no redundant method for detecting traffic signal states without additional communication from the infrastructure."*

`-- underlining of text by the authors of this paper --`

Due to the fact that AD vehicles are expected to be *always connected*, even if latency and bandwidth may fluctuate, TPEG3 will be able to provide this type of information in an efficient way and in a format that can be easily processed[18] by AD systems. Forming it as an international standard approved and published by ISO ensures a global footprint and interoperability between OEMs, Tier1/2 suppliers, system and software vendors, content and service providers as well as road operators and public authorities.

[18] In contrast to TPEG2, which is intended to be understood by humans, TPEG3 will be tailored to the information processing requirements of AD systems.