New Concepts to Improve Mobility by Digitization and Virtualization: An Analysis and Evaluation of the Technical Feasibility

Louis Calvin Touko Tcheumadjeu[1](✉), Katrin Stuerz-Mutalibow[2], Janis Hoeing[2], Dennis Harmann[3], Julian Glaab[4], and Robert Kaul[1]

[1] German Aerospace Center (DLR), Institute of Transportation Systems, Rutherfordstr. 2, 12489 Berlin, Germany
louis.toukotcheumadjeu@dlr.de
[2] AVL Software and Functions GmbH, Im Gewerbepark B29, 93059 Regensburg, Germany
[3] Technical University Braunschweig, NFF Institut für Verkehr und Stadtbauwesen, Hermann-Blenk-Straße 42, 38108 Braunschweig, Germany
[4] Bliq GmbH, Mariendorfer Damm 1, 12099 Berlin, Germany

Abstract. Traffic infrastructures are one of the central elements of today's mobility. They are crucial for road traffic and offer road users space and orientation for mobility to move within public space. Road infrastructure is currently designed for non-autonomous vehicles. To be able to support new technologies and services related to autonomous driving, adaptation and enhancement of the capability of current traffic infrastructures is necessary. An innovative solution is the digitization and virtualization of conventional traffic infrastructures. In this paper, the possibilities of digitization and virtualization of current traffic infrastructure elements are presented and discussed in the form of an implementation concept. The paper illustrates the most significative use cases, where digitization and virtualization may lead to the improvements in the efficiency of traffic flow and management. Part of this contribution is also an analysis and evaluation of the technical feasibility of single-use cases for digitizing and virtualizing traffic infrastructures.

Keywords: Digitization and virtualization · Traffic infrastructure · Automated and connected driving · Mobility services

1 Introduction

The contribution presented in this paper describes the activities of the research project ViVre [1]. The integration of digitized and virtualized traffic infrastructure and automated driving functions for central traffic hubs in order to develop building blocks for innovative and sustainable mobility solutions is the aim of this project. In this context, stakeholders play an important role and need to be involved in the entire process (see Fig. 1).

The traffic infrastructure (TI) represents one of the central elements of today's mobility. It is decisive for road traffic and provides road users with space and orientation for

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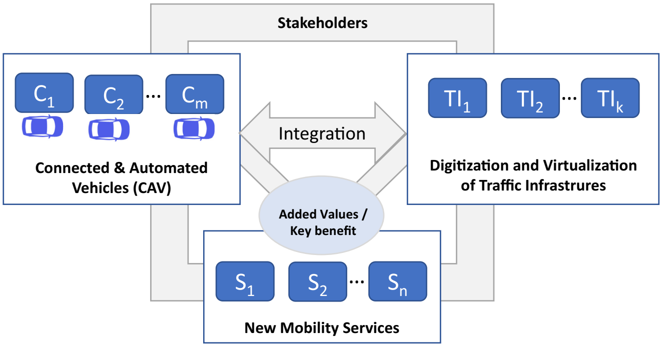

Fig. 1. Storyboard showing the integration CAV digitization and virtualization of traffic infrastructure and the generated mobility services

the realization of mobility to move within the public space. Currently, road infrastructure is designed for non-autonomous vehicles. However, with increasing progress in the field of autonomous driving and the spread of new forms of mobility, such as on-demand bus services, car-sharing or bicycle rental systems, the question arises whether the transport infrastructure in its current form is suitable for these new technologies and services or to what extent it can be adapted to their needs and potentials. Within the last years, many other studies investigated a change of road infrastructure due to new possibilities for connection and communication, i.e. [2–5]. However, still missing is an approach to assess whether certain infrastructure elements are still needed at all, regarding autonomous vehicles. The definition of the terms TI elements, digitization and virtualization are necessary for good understanding. Traffic infrastructure elements are all objects in road traffic that influence and control road traffic functionally and organizationally. The process of digitizing analogue information, i.e. converting it into a machine-readable form consisting of discrete values, is called digitization. The term virtualization refers to the transformation of digital information in such a way that it can be perceived by the user at an abstract level. From the definitions, it follows that virtualization presupposes digitization, but not vice versa. A digital instance of a traffic infrastructure element thus represents the information of an analogue (physical) traffic infrastructure element in an IT (information technology) system. A virtual instance maps this information to an abstraction level so that the structure, meaning and functionality of the element can be perceived by the user.

Under certain circumstances, a digital or virtual traffic infrastructure element no longer has a physical representation. Information can then only be exchanged with elements that are also integrated into or networked with the higher-level traffic management system.

The paper is structured as follows: The work is introduced in Sect. 1. In Sect. 2, the concept of the digitization and virtualization possibilities of traffic infrastructure elements is described. Next, in Sect. 3 the methodology for analyzing and evaluating the technical feasibility of the concepts developed in Sect. 2 is presented. After identifying the relevant aspects, evaluation criteria are developed in the form of research questions. In Sect. 4, the results of the technical feasibility assessment survey, which is based on the research question in Sect. 3 is presented and discussed. Finally, the work is concluded in Sect. 5.

2 Digitization and Virtualization Possibilities of Traffic Infrastructure Elements

2.1 Overview of the Conventional Traffic Infrastructures

The classic or conventional TI (traffic infrastructure) elements exchange information with the analogue driver in an analogue way. Before elaborating on the digitization and virtualization concepts, an overview of currently existing traffic infrastructure elements is provided first. The results are obtained using exploratory methods and research. The TI elements can be divided into five groups: A. stopping & parking, B. traffic signals, C. traffic signs, D. road users, and E. road network.

Each of these groups includes several elements, which in turn can be specified in different levels of details. An overview of the content thus identified is summarized as follows.

Group A: The stopping and parking group consists of parking lots in different categories (parking garage, roadside parking, underground car parking), the stops with special traffic function (e.g. bus stop) and loading area

Group B: The traffic signals group consists of traffic lights (TL) in different constellations (e.g. Three colours TL, pedestrian TL, bus and tramway TL, road works TL)

Group C: The Traffic Signs (TS) group can be categorized in traffic warning signs (e.g. pedestrian crossing), regulatory TS, guide TS, road surface marking (e.g. Boundary marking for stopping or parking prohibitions), or TS like lane marking and additional TS (e.g. boom gate)

Group D: The traffic participants/road users group consists of means of transport like vehicles (e.g. fire-fighting vehicle, police, motorized individual traffic, shuttle, ambulance) and vulnerable road users (VRU) including pedestrians, bicyclists

Group E: Road network group consists of traffic (e.g. traffic situation), roadway delimitation/boundary (direction separation, crash barrier), road (road damage, road surface, weather conditions) and traffic guidance (e.g. intersection/junction, tunnel, bridge, railroad crossing).

2.2 Concept of the Digitization and Virtualization of Traffic Infrastructure

Based on the existing conventional traffic infrastructure elements presented in the previous section, the next step is to develop the digitization and virtualization concepts. To this end, the following subsections outline how the information on the 'classic' analogue traffic infrastructure elements can be digitized and virtualized in the future and made accessible to road users. In this contribution, twenty-five mobility solutions related to the digitization and virtualization of TI elements have been proposed as use cases (see Table 1) and the concept of each use case has been described. The flow of information between the entities acting as system players, e.g. the connected/autonomous vehicle and a traffic sign, is illustrated graphically in each use case (see Fig. 2).

Table 1. Overview of the considered mobility solutions & use cases based on the digitization & virtualization of traffic infrastructure elements

UC No	Use case group	Mobilitys solution/Use cases (UC)	Digitization (D)/Virtualization (V)
UC1	A) Stopping & Parking [6, 12]	Digital mapping of stopping and parking places	D
UC2		Digital occupation monitoring	D
UC3		Digital payment and controlling of parking places	D
UC4	B) Traffic Lights (TL) [6, 13]	Traffic light prioritization control for connected (emergency) vehicles and busses	D
UC5		Digital constriction/bottleneck signalization	D
UC6	C) Traffic Signs (TS) [14–17]	Virtual pedestrian crossing	D&V
UC7		Digital traffic signs	D
UC8		Digital road work zone signs	D
UC9		Traffic signs without physical representation	D&V
UC10		Digital delineator	D
UC11	D) Traffic participants/Road Users [18, 25, 26]	Transparent wall	D
UC12		Digital turn signal/Digital brake light	D
UC13		Digital siren and blue light	D
UC14		Traffic jam warning	D
UC15		Connected warning triangle	D
UC16		Red light violation warning	D
UC17		Warning of pedestrian crossing	D
UC18		Cooperative adaptive cruise control ACC	D

(*continued*)

Table 1. (*continued*)

UC No	Use case group	Mobilitys solution/Use cases (UC)	Digitization (D)/Virtualization (V)
UC19		Public Transportation – Position and Capacity	D
UC20	E) Road Network (RN) [19–24]	Digital road traffic	D
UC21		Virtual lane and lane boundary	D&V
UC22		Digital road	D
UC23		Virtual traffic guidance	D&V
UC24		Digital construction zone	D
UC25		Digital local restricted traffic	D

The "Stopping and Parking" group (A) includes traffic infrastructure elements that serve the temporary or long-term parking of vehicles (e.g. cars, bicycles). Stopping places, parking spaces and loading zones could be identified as elements. While stopping places and loading zones are exclusively used for passengers to get on and off the bus or for loading and unloading vehicles, parking places also offer the possibility to park vehicles for a longer period.

The digital occupancy information of stops or parking spaces (UC2), which provide their availability at a certain time is decisive information for the use of parking or stop space. Within the scope of this concept, a "distributed" occupancy detection is to be carried out by a vehicle swarm. A vehicle swarm is understood to be the set of all vehicles that can detect parking and stopping possibilities by sensors (Camera-based occupancy detection for example). Thus, an overall view of the occupancy situation in an observed area can be generated. The advantages of the outlined concept for occupancy detection are the high scalability and the low costs per parking space compared to alternative solutions (e.g. LiDAR, Radar, ground sensor).

The "Traffic Lights" group (B) includes infrastructure elements traffic lights, which are used to control traffic efficiently and safely [5, 6], and pedestrian lights, which are used to enable pedestrians to cross roads safely. Warning signal, special signal and bottleneck signal systems also belong to this group and are used, for example, at railroad crossings, road work sites and dangerous locations to increase the attention of road users. In this group the digitalization concept of two use cases (UC 4 and 5) have been described.

The digital constriction/bottleneck signalization (UC5) is related to the transportable traffic signal systems ("road works traffic lights"), which are used to secure and regulate traffic at bottlenecks for a limited period, especially at road work sites. This means that each direction of travel can be cleared alternately to be able to drive safely through the bottleneck. If such a system is installed, the connected automated vehicle should be informed by the traffic management system about the location and the stop line of the traffic light and any associated changes in the traffic flow. The resulting delays can thus be considered when creating and selecting routes. If such a vehicle approaches a TL, the TL should inform the vehicle of its current and future status in advance.

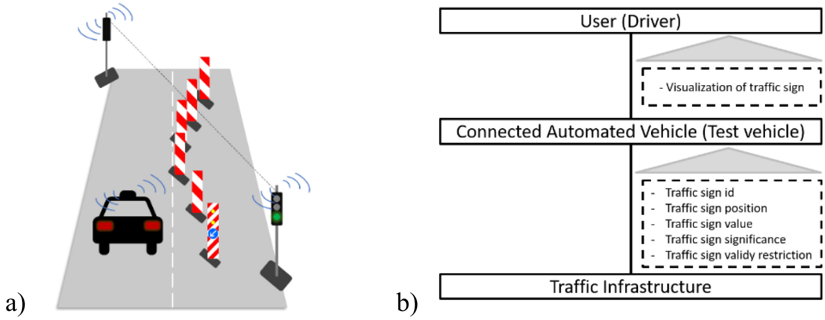

Fig. 2. a) Diagram showing how digital bottleneck signalling works b) Information exchange traffic signs without physical instance

The "Traffic Signs" group (C) comprises the infrastructure elements, which fulfil the task of communicating traffic rules to road users. In this group five use cases have been considered but only two have been described.

The concept of "digital traffic signs" (UC7) provides for the information inherent in traffic signs to be made available to vehicles directly in digital form, instead of being recognized by on-board cameras as was currently the case. In the case of a permanently installed traffic sign, its data can be integrated into a digital map that is stored in the vehicle's memory. This must be updated regularly if there are any changes to the signage. However, it can be assumed that shortly after a new sign is installed or an existing sign is changed, the map data cannot be updated immediately. It is therefore recommended that recently placed but permanently installed traffic signs be equipped for a certain period with a V2I transmitter unit that transmits data directly to surrounding vehicles. This data transmission concerns the traffic sign ID and its meaning, the position of the sign, the displayed value and any validity restrictions such as clock times.

The virtualization of traffic signs (UC9) without physical representation provides a lot of potentials, as traffic signs could be dynamically adjusted to traffic safety and traffic flow requirements. Permanently valid traffic signs can be stored on digital maps just as they are already in the concept of digital traffic signs. Updates to the map can be provided regularly as digital data networks become more powerful. For temporary traffic signs, it makes more sense to set up a V2I broadcast unit [7, 8] that provides an update for the region or route being travelled. However, since traffic signs are no longer installed, it is necessary to make them accessible to manually-controlled vehicles. For this purpose, the traffic signs must be virtualized for the drivers of these vehicles (e.g. using mobile phone application).

The "Traffic Participants or Road Users" group (D) makes the distinction between non-vulnerable and vulnerable road users. The first includes motor vehicles of all types. The second group (Vulnerable Road User, VRU) includes pedestrians, drivers of bicycles and very small electric vehicles. The digitization and virtualization concepts have been done for nine use cases (UC11 to UC19), and offer solution ideas for automated interaction within and between these two groups. But in this paper only the concept of two use cases has been presented.

The concept of the "digital turn signal/digital brake light" (UC12) is to transmit important information directly via V2V communication to the involved interacting traffic participants and thus to augment the information of the vehicle-side sensor system. In order to keep the information density low, enable a broad market introduction and be able to establish upgrade solutions, this concept is selected to the two most important indicators of driving intention. First, the direction indicator, which indicates a turn or lane change intention, and second, the brake light, which signals a braking operation. Vehicles equipped with this technology send a digital signal in addition to the visual signal. If the concept is extended to include virtualization, the information made available can also be used to provide warnings and instructions to manually controlled vehicles.

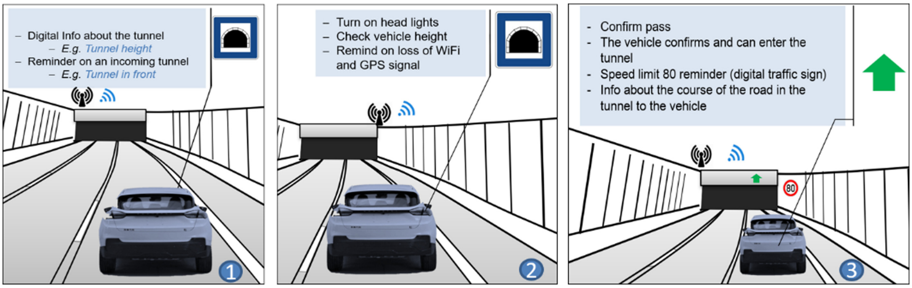

Fig. 3. Virtual traffic guidance in tunnel

The concept of the "connected warning triangle" (UC15) is to warn surrounding road users of a stationary vehicle on the route. However, this is not limited to the highway and can also be used on rural roads and in urban traffic in the event of a vehicle breakdown. If the vehicle user sets up a warning triangle in the event of a breakdown, this sends a warning to surrounding vehicles and its position. Approaching automated vehicles can thus brake or change lanes at an early stage, reducing the risk of accidents for people in and around the broken-down vehicle. If virtualization options such as HUD (head-up-display) or VR (virtual reality) are also available in non-automated vehicles, their drivers can be made aware of the situation much earlier than with conventional warning triangles and even in poor visibility conditions.

The "Road Network" group (E) comprises the infrastructure elements, which affect the roadway and its use. The infrastructure elements include the road surface, road boundaries and the course of the road, but also the traffic and the associated utilization of the road network.

The "digital road traffic" (UC21) is a more advanced form of digital traffic information in which all road users (e.g. CAV) are digitally recorded. Digitized road traffic also makes it possible to react flexibly to a changing traffic situation while driving. Routing programs can react ad-hoc to a changing traffic situation. The traffic information to be digitized can be divided into three categories: current traffic conditions (congestion information, traffic situation information), prediction information (congestion forecast) and traffic events (e.g. accidents, traffic situation during events).

Virtual traffic guidance (UC23), such as virtual markings on the ground in bridge and tunnel guidance (see Fig. 3) or in complex intersections, should offer the possibility to support the driver or the autonomous vehicle when confronted with complex traffic guidance dangerous situations (e.g., sharp or tight curves, uneven roadways, or steep gradients). Such virtual markers show only the road course that is relevant for the vehicle and can be displayed on the head-up display (HUD) for the driver. The driver is thus supported in finding his way by detailed information about the road layout. Traffic guidance information can be provided for such traffic infrastructure elements as tunnels, intersections, curves, road junctions, etc. There are various situations in which virtualized traffic guidance can support the user. At complex intersections for example, lane selection or lane changes can be prepared. Further examples are bridges, which indicate low permitted speeds and a maximum permitted total weight, as well as underpasses, which can lead to changing light conditions (change from light to dark and back) (also see [10]). In order for vehicles and drivers to be able to react to this complex situation, the corresponding symbols must be virtualized for the corresponding situation. The goal for the traffic management of the future will be that the traffic management centre (TMC) can control each vehicle and ensures that each vehicle receives the digital traffic guidance information based on the current trajectory and the vehicle profile (car, truck, motorcycle, etc.).

3 Method for the Analysis and Evaluation of Technical Feasibility

3.1 Identification of Relevant Aspects for the Evaluation

The implementation of digitization and virtualization concepts and the provision of the obtained information for road users before or during the journey as a contribution to the "traffic management of the future for connected and automated driving" (Traffic 2.0) is complex. It involves various stages in the realization and operation of such services. Figure 4 depicts the levels identified so far, which are required for the technical implementation. These are described briefly below:

Stage1: Identification of infrastructure elements and requirements analysis
In this stage, the individual transport infrastructure elements are systematically identified, digitized and/or virtualized. The question of the necessity and advantages of digitization and/or virtualization of the selected transport infrastructure elements is addressed here, including the problems that can be solved as a result. This step has already been outlined in Sect. 2.
Stage 2: Digitization and virtualization technology
This stage addresses the concept of digitization and virtualization of the selected transportation infrastructure element. This includes the processes for data acquisition, processing and generation of the digitized and virtualized information. It also looks at the technologies and standards used for digitization and virtualization solutions.

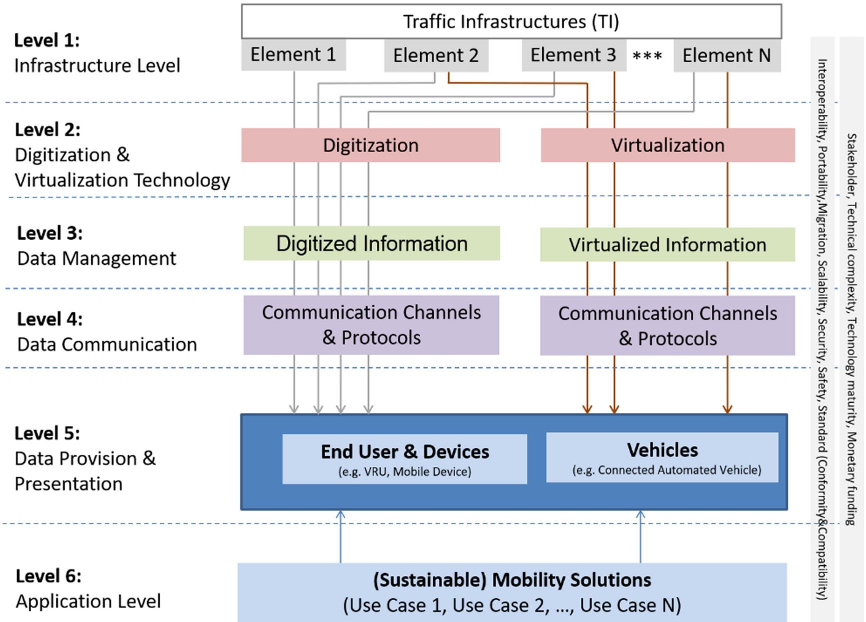

Fig. 4. Levels of technical implementation of digitization and virtualization of transport infrastructures on the data level

Stage 3: Data management
This stage addresses the concept of modelling, storing and managing the data in a digitized and virtualized form. Data protection and security (replicability, backup, access), data availability (24/7 operation) as well as the operation of the data (e.g. in the cloud platform, Big Data) and data quality (timeliness, validity, completeness, correctness, consistency) are addressed.
Stage 4: Data communication
This stage addresses the design and implementation of the communication interfaces to exchange digitized and virtualized information between data providers (e.g., the TMC) and data users (e.g., connected and automated vehicle). This includes securing the communication, the technologies used for the communication networks (e.g., LTE, Wi-Fi, 5G) and protocols (e.g., V2X, REST, SOAP, etc.), and the type and quality of data communication (data volume, data rate, real-time transmission).
Stage 5: Data provisioning and presentation.
This stage addresses the concept for receiving, interpreting (e.g., decoding), and displaying (e.g., visualizing) the digitized and virtualized information on end devices (e.g., virtual reality goggles), or in the connected and automated vehicle (human-machine interface (HMI)). The requirements for visualization devices are also being investigated. Since most services require information about the current position of the vehicle or road user (e.g., for navigation), GNSS technology is relevant for location.

In addition to the purely technical aspects, the cross-level factors - such as interoperability, financial feasibility and safety - also play an important role and must be considered in the design and realization of such intelligent transport systems.

3.2 Technical Realization of the New Mobility Services

The technical realization of the new mobility services listed in Table 1 is based on digitized and virtualized information about road infrastructure elements and requires the expansion and adaptation of the current services at the traffic management, infrastructure, vehicle (e.g., the adaptation of the automation function), terminal, and application levels. Figure 5 visualizes this relationship between the traffic management system, the traffic infrastructure elements as mobility applications, and the traffic infrastructures.

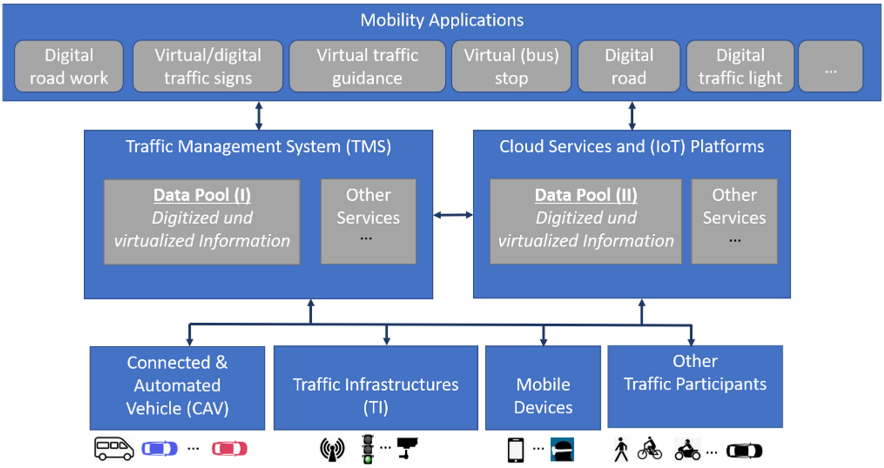

Fig. 5. System components of the mobility services

3.3 Stakeholder Participation

In addition, the need to involve various stakeholders in different areas and their interests must be considered. In the first step, the stakeholders that play an important (decision-making) role in the implementation of the mobility applications, or are involved in implementation processes, were identified. These include Road Authority, Automobile Manufacturers/Vehicle Developers, Municipalities, States, Federal Government, Traffic Data Operators, End Device App Developers, Police, Policy, Legislation, Road Users, End Users, Fire Services, Traffic Managers, Innovators & Authorities, Mobility Providers & Operators (public and private), Traffic Engineers & Planners, Consultants & System Integrators, Civil Engineers and Urban Planners, and Telecommunication Network Operators (also see [11]).

3.4 Formulation of the Added Values for the New Mobility Services

The digitization and virtualization of traffic infrastructures will supplement and expand the available traffic information. From the combination between intelligent traffic systems, improved traffic information and intelligent traffic management of the future, new added values (see Table 2) can arise, which contribute to sustainable mobility, such as: Increasing traffic safety, improving traffic flow, increasing traffic efficiency, increasing driving comfort, reducing emissions, driving new business models, and innovation potential.

Table 2. Overview of some selected added values

No	Added value	Description
AV1	Increasing traffic safety	Avoidance of conflicts/dangerous situations, e.g. by early execution of driving manoeuvres thanks to communication with other road users or by the information about road damage provided by the digital roadway
AV2	Improving traffic flow	Shortening or avoiding unnecessary routes or better distribution of traffic volumes (digital road works or traffic situation information)
AV3	Increasing traffic efficiency	Efficiency gains in the form of money saved (e.g. due to optimized driving behaviour) or time gained (time saved due to short distances)
AV4	Increasing driving comfort	The user can relax (stress reduction) or work and socialize while driving and does not need to worry about dangerous traffic situations (complex intersections or dangerous curves) while driving
AV5	Reduce of emissions	More environmentally friendly traffic by reducing emissions (optimized driving behaviour, shorter travel times)
AV6	Driving new business models	Digitization and/or virtualization provide an optimal framework for the "autonomous vehicle" and thus allow new business models to emerge (e.g., demand-oriented transportation service with virtual stops)
AV7	Innovation potential	Digitization and/or virtualization create the prerequisites for further developments and novel ideas

3.5 Formulation of the Evaluation Criteria

The approach developed in [9] served as the basis for the development of the evaluation methodology. Basically, after the development of a suitable target system, the evaluation criteria are determined. Depending on the characteristics, constraints and parameters are defined and possible alternatives are investigated. Furthermore, the data collection, the weighting of the evaluation criteria and the discounting of the costs may be necessary. In particular, the evaluation raises the question of which method category (non-formalized, partially formalized or formalized) is suitable for evaluating the technical feasibility of the digitization and virtualization of transport infrastructures and the resulting mobility services. Each of these method categories requires a certain degree of mathematization. While the non-formalized methods operate on an argumentative or qualitative level, the implementation of the formalized methods requires the determination of measurement and characteristic variables and the associated data collection in order to be able to make quantitative statements. Also, especially in the case of formalized methods, further components such as determination of the degree of target fulfilment, the definition of assignment rules, aggregation of the results and creation of a ranking are of importance.

Along with the process shown in Fig. 4, many research questions arose concerning the technical realization of digitization and virtualization of TI elements. The research questions including the indicators have been collected and grouped thematically in five evaluation criteria groups. An overview of the formulation of the evaluation criteria of each group is presented in Tables 3, 4, 5, 6, and 7.

Table 3. Technical Complexity (TC)

Research question			Rating
What is the complexity of the technical realization?			1 to 5
No	Indicators	Description	
TC1	Networking	What is the degree of interconnection of the concept? Do several systems have to cooperate to realize the concept?	
TC2	Number of systems	How many subsystems are required for the concept to function?	
TC3	Information processing	Does the system need to be able to grasp and interpret complex relationships?	
TC4	Structural changes	Are structural changes to the traffic infrastructure necessary to realize the concept?	
TC5	Market penetration	How high must the market penetration of the technology be, for the concept to be useful?	
TC6	Data users	For which road users must the digitized and/or virtualized information be made available? [Pedestrian, cyclist, motorcyclist, car driver, non-networked vehicle, networked or automated vehicle, car passengers, etc.]	
TC7	Form of presentation	In what form is the digitized and/or virtualized information presented (on the vehicle or terminal side)? [textual, linguistic, visual, etc.]	

Table 4. Technology Status (TS)

Research question		Rating
Can available technologies be used for the realization of the concept?		1 to 5
No	**Indicators**	**Description**
TS1	Traffic infrastructure	Can existing traffic infrastructure be used for the concept?
TS2	Additional sensors	Do additional sensors have to be integrated for the realization of the concept on the side of the vehicles and the traffic infrastructure?
TS3	Technology status	Is it possible to integrate the concept into existing systems?
TS4	New development	Are new developments in the area of hardware and software or traffic infrastructure required for the implementation of the concept?
TS5	Standardization	Do technical standards exist on which to base the development of the concept?
TS6	Data model	Can (standardized) existing data models be reused for modeling the digitized and virtualized information?
TS7	Reuse of research results	Can existing research results (e.g. from previous systems or concepts) be used?

Table 5. Funding and Monetization (FM)

Research question		Rating
How high are the costs for the realization of the concept to be estimated?		1 to 5
No	**Indicators**	**Description**
FM1	Hardware costs	Is expensive hardware needed to realize the concept?
FM2	Construction costs	Will construction costs be incurred as a result of structural changes to the transport infrastructure when the concept is implemented?
FM3	Monetization concept	Are there attractive monetization concepts to compensate for high investment costs?
FM4	Development effort	Are extensive efforts needed to realize the concept?
FM5	Operating costs	What are the running costs (e.g. for monitoring the system, maintenance, servicing costs)?
FM6	Scalability	Is there a chance that scaling effects can reduce the costs of implementing the concept?

Table 6. Safety and Security (SS)

Research question			Rating
How high do you assess the risks in the area of safety and security and the associated need for appropriate countermeasures?			1 to 5
No	Indicators	Description	
SS1	Personal data	Do personal data of the user have to be collected and stored for the realization of the concept/service?	
SS2	Safety relevance	Does the concept influence safety-relevant functions of the vehicles (e.g. longitudinal or lateral guidance)?	
SS3	Interfaces	Are interfaces to publicly available systems required for the concept?	
SS4	Data storage	Can sufficiently secure storage be guaranteed for the volume of data (Big Data)?	
SS5	Safety risk	Is there increased risk on the vehicle and user side if the system fails during real-time operation?	

Table 7. Interoperability and Portability (IP)

Research question			Rating
How do you assess the interoperability and transferability of the concept?			1 to 5
No	Indicators	Description	
IP1	Portability	Is the concept transferable to other traffic situations?	
IP2	Data reuse	Can information/data from the concept be reused for other purposes?	
IP3	Interoperability	Do you see the possibility of linking or extending the concept with other digital or virtual traffic infrastructure elements?	
IP4	Extensibility	Is the concept easily extensible to a larger number of users or a different user group?	

4 Presentation of the Evaluation Results

Based on the method and criteria for evaluating the feasibility of identified digitization and virtualization concepts of transport infrastructures presented in Sect. 3, a total of twenty-five online questionnaires were developed. One questionnaire per concept is available, covering all five research questions listed in the Tables 3, 4 and 5. The indicators associated with each research question are also listed in the questionnaires to alert participants to relevant aspects. The answer to each research question is to be given on a mandatory scale of 1 to 5, with 1 being the lowest (worst) score and 5 being the highest (best) score. In addition, a comment box is available where participants are encouraged to justify their decision. The questionnaires were made available to participants via an online link. Participants were not given a time limit for completion.

4.1 Participants Analysis

An online survey was conducted with experts in the area of mobility and transportation, both from industry and research. Twenty-five questionnaires were sent to 14 experts. Despite a few drop-outs and merely lurking participants, a total of 1030 valid ratings had been submitted. (see Fig. 6).

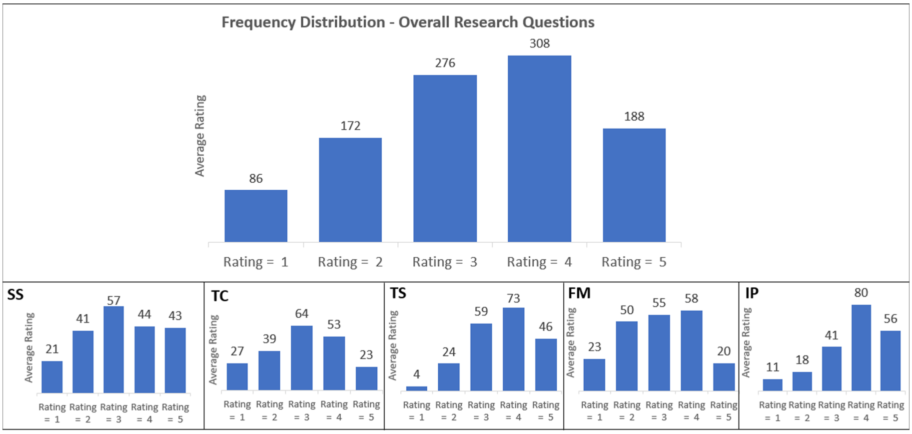

Fig. 6. Frequency distribution of all ratings

4.2 Overall Analysis

To make a final evaluation of the technical feasibility of the concepts presented, their performance across all research questions was analyzed. Instead of calculating the mean value across all ratings, it was looked at which concepts scored above or below average in many research questions. In this way, a bias due to strongly differing ratings in the research questions can be ruled out. The lowest and the highest rating for each use case between all research questions have been picked and presented.

Figure 7 shows the lowest rating of each concept across all research questions. The concepts of digital "turn signal and brake light" (UC12), "connected warning triangle" (UC15) and "construction site" (UC24), which are highlighted in green, thus achieved at least the value shown in the diagram in all research questions. These concepts are thus considered to have good technical feasibility.

In contrast, Fig. 8 shows the highest rating across all research questions. With the exception of the research question "Interoperability and transferability", the concepts "virtual pedestrian crossing" (UC6), "virtual lane & lane boundary" (UC21) and "digital

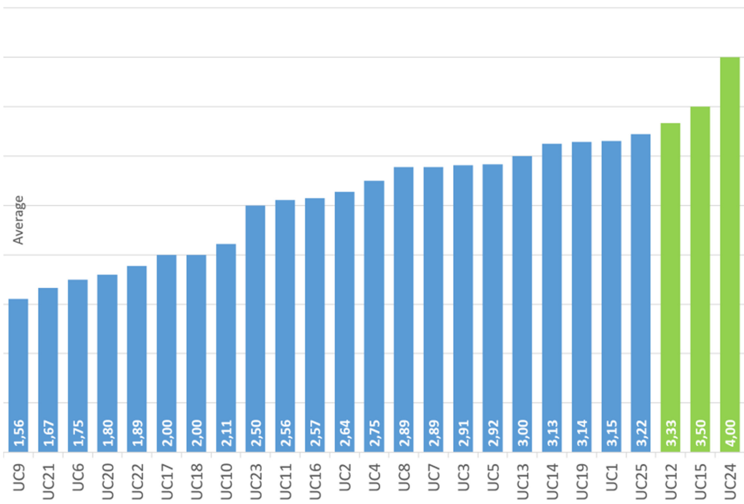

Fig. 7. Lowest rating result across all research questions

warning of pedestrian crossing" (UC17) each received a rating lower than 3.00 and are marked in yellow. (Since all concepts scored above average in the Interoperability and Transferability research question, it was not considered for the overall rating). These three concepts are thus classified as costly in terms of technical feasibility.

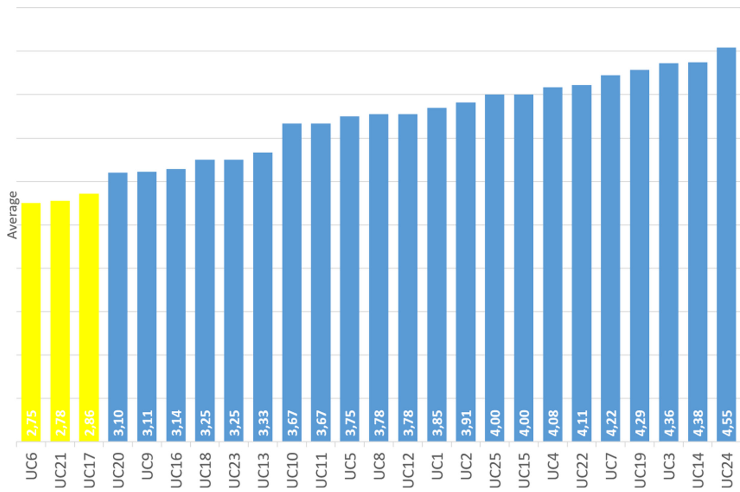

Fig. 8. Highest rating result across all research questions

5 Conclusion and Outlook

The digitization and virtualization of traffic infrastructures will supplement and expand the available traffic information. From the combination between intelligent traffic systems, improved traffic information and intelligent traffic management of the future, new added values can arise, which contribute to sustainable mobility, such as increasing traffic safety, improving traffic flow, increasing traffic efficiency, increasing driving comfort, reducing emissions, driving new business models, and innovation potential. In this paper, the possibilities for digitization and virtualization of traffic infrastructure elements were presented and discussed in the form of application concepts. First concepts were identified, which have a good technical feasibility by a first online survey with 14 experts in the area of mobility and transportation, both from industry and research. But further research is needed to verify these results. In a second step the online survey will be conducted using a bigger sample of participants.

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