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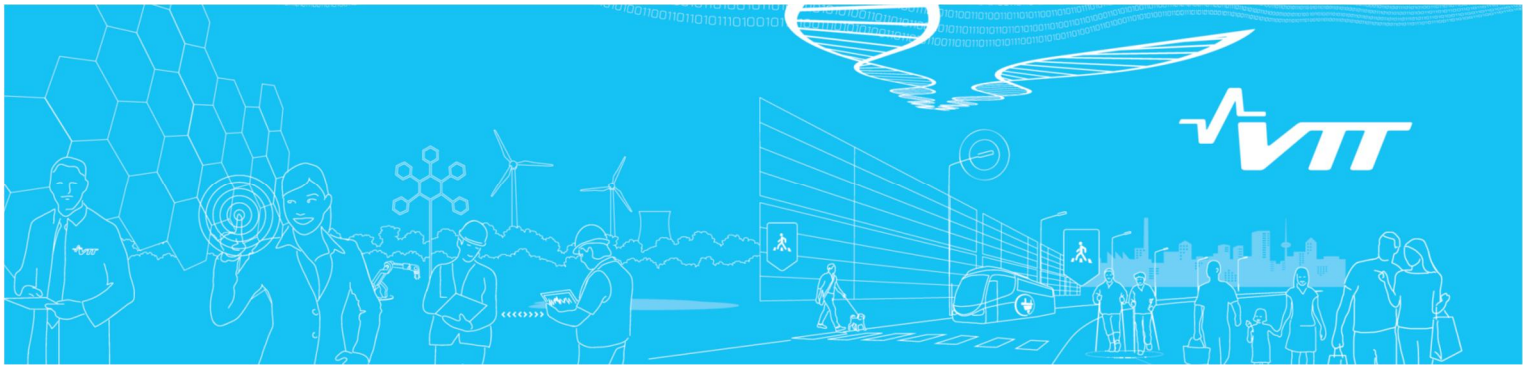

RESEARCH REPORT

VTT-R- 01054-18

Key performance indicators for assessing the impacts of automation in road transportation

Results of the Trilateral key performance indicator survey

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Summary

This report documents the survey, which was designed to investigate views on the importance of different key performance indicator (KPIs) for expressing the impact of automation in road transportation in several impact areas. It documents the rating results and additional KPIs proposed by the 77 experts in Europe, US and Japan who filled in the survey.

The Trilateral Impact Assessment Subgroup of ART WG will use these results when deciding the recommendations for the KPIs to be used in the impact assessment studies. The recommendations and a full list of potential KPIs (KPI repository) will be added to the version 2.0 of their impact assessment framework (expected in April 2018).

Confidentiality	Public

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Preface

This key performance indicator (KPI) survey for the impacts of automated driving was conducted as part of work in development of the harmonized high-level impact assessment framework of the Trilateral Impact Assessment Subgroup of the European Union-United States-Japan Trilateral Working Group on Automation in Road Transportation (ART WG) The resulting recommendations on KPIs will be provided in version 2.0 of the Trilateral Impact Assessment Framework, which will be published in April 2018.

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Espoo 27 February 2018

Authors

Contents

1. Introduction

Automated vehicles have the potential to transform the world's road transportation system. Members of the European Union-United States-Japan Trilateral Working Group on Automation in Road Transportation (ART WG) are working to address the complexity of impacts of automated driving. To coordinate assessments of the various types of impacts of automated driving, the ART WG established an Impact Assessment Subgroup in 2015. The motivation was the realization that, as field tests are expensive and mostly done on a small scale, international harmonization would be in everyone's interest. With a harmonized approach, tests and studies can be designed to maximize the insight obtained and to arrange complementary evaluation across the world. Harmonization would also facilitate meta-analysis.

The trilateral ART WG has published a framework (Innamaa et al. 2017, based partially on Smith et al., 2015) which aims for high-level harmonization of impact assessment studies globally. It is the first attempt to do harmonization by the three regions (EU, US and Japan). As there are so many concepts of automated driving, the framework does not give detailed methodological recommendations (i.e., methods to apply for calculating the impact) but it aims to facilitate meta-analysis across different studies. Therefore, the focus is on providing recommendations on how to describe the impact assessment study in such a way that the user of the results understands what was evaluated and under which conditions.

To be able to provide recommendations on the most important key performance indicators (KPIs) for measuring and expressing the impacts, the Trilateral Impact Assessment subgroup conducted an international survey. This report documents the survey and presents results. The resulting recommendations on KPIs will be provided in version 2.0 of the Trilateral Impact Assessment Framework which will be published in April 2018.

2. Survey

The survey was conducted with the Questback Essentials online questionnaire tool. An invitation to answer the survey was sent to stakeholder groups in Europe, the US and Japan. In addition, the CARTRE project website in Europe included a link to the survey. The survey was open for answers from June to November 2017. In total, 77 answers were obtained.

The first questions on the survey asked the respondent to identify him- or herself. The responses showed that 69% of the respondents were from Europe, 19% from Japan and 12% from the US. Of the respondents, 56% represented research organizations, 18% policy makers or authority and 14% automotive or other industry. There were a few responses also from consultants and from the public transport sector.

The respondent was then asked to select impact areas of interest. For those areas (s)he would be asked later about KPIs. The listed impact areas were:

- Vehicle operations / automated vehicles
- Use of automated driving
- Safety
- Energy or environment
- Personal mobility (modal choice, time spent travelling, travelling quality, etc.)
- Travel behavior (modal share, distribution on routes, etc.)
- Network efficiency
- Asset management (physical and digital infrastructure)
- Costs
- Public health

- Land use
- Economic impacts

Since the importance of a KPI may vary depending on the type of automated vehicle and the SAE level, respondents were then asked to select a vehicle type and SAE level that they would assume when answering the questions. For the vehicle type, 49% selected an automated passenger car, 4% an automated shuttle bus/pod, 4% an automated truck, and 42% mixed traffic that included vulnerable road users. For the automation level, 22% selected SAE 1-2, 29% SAE 3 and 49% SAE 4-5.

The respondents were also asked whether they own data. The motivation for this question was to ask the data owners about their willingness to share data in raw/detailed format or as processed data. However, only 12 respondents (16%) identified themselves as data owners. Thus, there were too few responses to make reliable conclusions on the willingness to share data in different formats.

The respondents were then asked to rate KPIs for areas in which they had indicated having expertise. They were also asked to propose additional KPIs for the impact area. Data owners were then asked about willingness to share data related to the indicators in the list. The questions followed the same pattern for all the impact areas:

- Please assess the importance of different KPIs for evaluating the impact on 'IMPACT AREA', the scale is from 0 = 'not at all important' to 6 = 'extremely important', N/A = 'not applicable'

- If you had the data in question, would you be willing to share it for impact assessment studies? If yes, please specify in which formats you think it can be shared.

The next section presents the results of the survey, organized by impact area. The statistical significance of the results was not determined. The distributions for ratings are presented in Annex I.

3. Results

3.1 Vehicle operations

Vehicle operations / Automated Vehicle (control) operations include acceleration, deceleration, lane keeping, car following, lane changing and merging in adjacent lane. Relevant automation applications include those which provide longitudinal and/or lateral control of the vehicle taking into consideration the road and other vehicles.

The average rates for the proposed KPIs are shown in Table 1. The averages were also calculated separately for different levels of automation (Table 2) and for passenger cars and mixed traffic (Table 3). The ratings were measured with a scale from 0 = 'not at all important' to 6 = 'extremely important'.

Table 1. Average ratings for the vehicle operation KPIs in descending order, top 3 highlighted

KPI	Rating	N
Number of instances where the driver must take manual control / 1000 km or miles	5.69	29
Mean and maximum duration of the transfer of control between operator/driver and vehicle (when requested by the vehicle)	5.63	30
Mean and maximum duration of the transfer of control between operator/driver and vehicle (turning automated driving system on/off, manual overrule)	5.03	29
Number of emergency decelerations per 1000 km or miles	4.97	32
Mean and minimum time-headway to the vehicle in front in car following situations	4.75	32
Minimum accepted gap at intersections or in lane changes	4.70	30
Mean and minimum distance to the vehicle in front in car following situations (headway 5 s or less)	4.63	32
Mean and maximum longitudinal acceleration and deceleration	4.48	31
Lateral position variation (st. dev. of distance from the center of the lane) while travelling within a lane	4.41	32
Speed variation (st. dev. of speeds) while travelling at constant speed (on link section, single speed limit)	4.31	32
Variance of the time-headway to the vehicle in front in car following situations	4.29	31
Maximum jerk (rate of change in acceleration, longitudinal and lateral)	4.25	32
Proportion of correct use of turning indicator/signal	4.11	28
Mean lateral acceleration during lane change	3.84	32
Proportion of distance driven when speeding	3.79	29

Table 2. Average ratings for the vehicle operation KPIs for different level of automation, top 3 highlighted

KPI	SAE 1-2		SAE 3		SAE 4-5	
	Rating	N	Rating	N	Rating	N
Number of instances where the driver must take manual control / 1000 km or miles	5.33	6	5.86	7	5.75	16
Mean and maximum duration of the transfer of control between operator/driver and vehicle (when requested by the vehicle)	5.33	6	6.00	7	5.59	17
Mean and maximum duration of the transfer of control between operator/driver and vehicle (turning automated driving system on/off, manual overrule)	5.17	6	5.29	7	4.88	16
Number of emergency decelerations per 1000 km or miles	4.50	6	5.00	8	5.11	18
Mean and minimum time-headway to the vehicle in front in car following situations	4.50	6	4.88	8	4.78	18
Minimum accepted gap at intersections or in lane changes	5.00	6	5.13	8	4.38	16
Mean and minimum distance to the vehicle in front in car following situations (headway 5 s or less)	4.67	6	4.50	8	4.67	18
Mean and maximum longitudinal acceleration and deceleration	4.67	6	5.00	7	4.22	18
Lateral position variation (st. dev. of distance from the center of the lane) while travelling within a lane	4.67	6	4.00	8	4.50	18
Speed variation (st. dev. of speeds) while travelling at constant speed (on link section, single speed limit)	4.50	6	4.75	8	4.06	18
Variance of the time-headway to the vehicle in front in car following situations	4.33	6	4.71	7	4.11	18
Maximum jerk (rate of change in acceleration, longitudinal and lateral)	4.17	6	4.38	8	4.22	18
Proportion of correct use of turning indicator/signal	4.33	6	3.38	8	4.43	14
Mean lateral acceleration during lane change	4.83	6	3.50	8	4.00	18
Proportion of distance driven when speeding	3.50	6	3.25	8	4.20	15

Table 3. Average ratings for the vehicle operation KPIs for passenger cars and mixed traffic

KPI	Automated passenger car		Mixed traffic	
	Rating	N	Rating	N
Number of instances where the driver must take manual control / 1000 km or miles	5.64	14	5.75	12
Mean and maximum duration of the transfer of control between operator/driver and vehicle (when requested by the vehicle)	5.69	16	5.67	12
Mean and maximum duration of the transfer of control between operator/driver and vehicle (turning automated driving system on/off, manual overrule)	5.07	15	5.00	12
Number of emergency decelerations per 1000 km or miles	4.94	16	5.08	13
Mean and minimum time-headway to the vehicle in front in car following situations	5.06	16	4.31	13
Minimum accepted gap at intersections or in lane changes	4.73	15	4.62	13
Mean and minimum distance to the vehicle in front in car following situations (headway 5 s or less)	4.75	16	4.38	13
Mean and maximum longitudinal acceleration and deceleration	4.53	15	4.23	13
Lateral position variation (st.dev. of distance from the center of the lane) while travelling within a lane	4.44	16	4.38	13
Speed variation (st.dev. of speeds) while travelling at constant speed (on link section, single speed limit)	4.75	16	3.62	13
Variance of the time-headway to the vehicle in front in car following situations	4.53	15	3.85	13
Maximum jerk (rate of change in acceleration, longitudinal and lateral)	4.31	16	4.08	13
Proportion of correct use of turning indicator/signal	4.21	14	3.92	12
Mean lateral acceleration during lane change	4.06	16	3.54	13
Proportion of distance driven when speeding	3.80	15	3.75	12

The respondents suggested the following additional KPIs:

- Average speed vs average speed of the rest of traffic flow (or just heavy vehicles)
- Variance in journey time
- Vehicle emissions (CO2/NOx)
- Down time frequency (for mechanical servicing/cleaning in the case of ride share autonomous vehicles)
- Driver frustration/aggressiveness in the presence of AVs (i.e. frequency of drivers abusing the safety-first mechanisms in AVs)
- AV fairness in behaviour (do AVs behave favourably to other AVs? Is this to the detriment of other road users?)
- Number of mechanical/sensor failures per 1000 km
- Number of handovers from autonomous to manual driving at the vehicles' request per 1000 km (how often does the AV system get confused)
- Location of handovers (Urban/Roundabout/Highway)
- Frequency of discretionary lane changes
- Speed variations attributable to accommodating lane changes by other vehicles
- Frequency of occurrence of TTC (time to collision) below a safety threshold value such as 1 sec.
- Achievable highway throughput per lane

3.2 Use of automated driving

Use of automated driving in an L1-L3 system, where the driver can choose to use automated driving functions, is a key factor in scaling up the impacts. The use includes aspects like availability, actual use, and usability.

The average rates for the proposed KPIs are shown in Table 4. The averages were also calculated separately for different levels of automation (Table 5) and for passenger cars and mixed traffic. (Table 6). The ratings were measured with a scale from 0 = 'not at all important' to 6 = 'extremely important'.

Table 4. Average ratings for the use of automated driving KPIs in descending order

KPI	Rating	N
Number of instances where the driver must take manual control / 1000 km or miles	5.55	31
Use of automated driving functions (% of km of maximum possible use)	5.32	31
Comprehensibility of user interface (expressed on a Likert scale, e.g. 1–9, low–high)	5.21	29
Feeling of safety (expressed on a Likert scale, e.g. 1–9, very dangerous – very safe)	5.14	28
Interaction with other road users (expressed on a Likert scale, e.g. 1–9, failure–perfect)	5.03	31
Inappropriate use of automated driving functions (number of events per 100 km or miles)	5.00	30
Requirement of attention and concentration (number of events per 100 km)	5.00	31
Trust (expressed on a Likert scale, e.g. 1–9, low–high)	4.93	30
Reliability (subjective perception, expressed on a Likert scale, e.g. 1–9, low–high)	4.79	29
Mental workload (expressed on a Likert scale, e.g. 1–9, low–high)	4.52	31
Feeling of being able to control the vehicle (expressed on a Likert scale, e.g. 1–9, failure-perfect)	4.31	29
Feeling of frustration (expressed on a Likert scale, e.g. 1–9, low–high)	4.23	30
Intended use (statement of interest, % of maximum possible use, by driver, identify relevant journey types)	4.16	31
Feeling of pressure because of many parallel tasks (number of events per 100 km)	4.00	31

Table 5. Average ratings for the use of automated driving KPIs for different level of automation

KPI	SAE 1-2		SAE 3		SAE 4-5	
	Rating	N	Rating	N	Rating	N
Number of instances where the driver must take manual control / 1000 km or miles	5.30	6	5.67	9	5.56	16
Use of automated driving functions (% of km of maximum possible use)	5.50	6	5.33	9	5.25	16
Comprehensibility of user interface (expressed on a Likert scale, e.g. 1–9, low–high)	5.40	5	5.11	9	5.20	15
Feeling of safety (expressed on a Likert scale, e.g. 1–9, very dangerous – very safe)	5.30	5	5.00	8	5.13	15
Interaction with other road users (expressed on a Likert scale, e.g. 1–9, failure–perfect)	5.33	6	4.89	9	5.00	16
Inappropriate use of automated driving functions (number of events per 100 km or miles)	5.20	5	4.67	9	5.13	16
Requirement of attention and concentration (number of events per 100 km)	4.83	6	5.11	9	5.00	16
Trust (expressed on a Likert scale, e.g. 1–9, low–high)	5.20	5	5.22	9	4.69	16
Reliability (subjective perception, expressed on a Likert scale, e.g. 1–9, low–high)	5.00	5	4.78	9	4.73	15
Mental workload (expressed on a Likert scale, e.g. 1–9, low–high)	5.33	6	4.44	9	4.25	16
Feeling of being able to control the vehicle (expressed on a Likert scale, e.g. 1–9, failure-perfect)	4.60	5	4.33	9	4.20	15
Feeling of frustration (expressed on a Likert scale, e.g. 1–9, low–high)	5.17	6	4.22	9	3.87	15
Intended use (statement of interest, % of maximum possible use, by driver, identify relevant journey types)	4.17	6	4.11	9	4.19	16
Feeling of pressure because of many parallel tasks (number of events per 100 km)	5.00	6	4.67	9	3.25	16

Table 6. Average ratings for the use of automated driving KPIs for passenger cars and mixed traffic

KPI	Automated passenger car		Mixed traffic	
	Rating	N	Rating	N
Number of instances where the driver must take manual control / 1000 km or miles	5.60	15	5.54	13
Use of automated driving functions (% of km of maximum possible use)	5.53	15	5.00	13
Comprehensibility of user interface (expressed on a Likert scale, e.g. 1–9, low–high)	5.23	13	5.23	13
Feeling of safety (expressed on a Likert scale, e.g. 1–9, very dangerous – very safe)	5.14	14	5.00	12
Interaction with other road users (expressed on a Likert scale, e.g. 1–9, failure–perfect)	5.13	15	4.77	13
Inappropriate use of automated driving functions (number of events per 100 km or miles)	4.71	14	5.31	13
Requirement of attention and concentration (number of events per 100 km)	4.73	15	5.31	13
Trust (expressed on a Likert scale, e.g. 1–9, low–high)	4.93	14	4.69	13
Reliability (subjective perception, expressed on a Likert scale, e.g. 1–9, low–high)	4.64	14	4.92	12
Mental workload (expressed on a Likert scale, e.g. 1–9, low–high)	4.40	15	4.38	13
Feeling of being able to control the vehicle (expressed on a Likert scale, e.g. 1–9, failure-perfect)	4.29	14	4.42	12
Feeling of frustration (expressed on a Likert scale, e.g. 1–9, low–high)	4.07	14	4.31	13
Intended use (statement of interest, % of maximum possible use, by driver, identify relevant journey types)	4.53	15	4.00	13
Feeling of pressure because of many parallel tasks (number of events per 100 km)	3.93	15	3.77	13

The respondents suggested the following additional KPIs:

- Frequency of mis- or dis-communication with other players, like pedestrians, bicyclists, etc. [per 100km] rate
- Experienced ease of use of an automated vehicle (9 point low-high scale)
- Driver alertness (esp. regarding takeovers related to the L3 system)
- Number of instances where the car did not do what the driver expected the car to do based on the L3 system
- Minimum time required to take control
- Number of Incidents where the car must operate in safe mode

3.3 Safety

Ultimately, safety is measured as number of fatalities, injuries or property damage for vehicle occupants and other road users. Other road users may include pedestrians, bicyclists, slow-moving vehicles, construction workers and first respondents.

The average rates for the proposed KPIs are shown in Table 7. The averages were also calculated separately for different levels of automation (Table 8) and for passenger cars and mixed traffic (Table 9). The ratings were measured with a scale from 0 = 'not at all important' to 6 = 'extremely important'.

Table 7. Average ratings for the safety KPIs in descending order

KPI	Rating	N
Number of crashes (distinguishing property damage, and crashes with injuries and fatalities), in total and per 100 million km or miles	5.73	40
Number of instances where the driver must take manual control / 1000 km or miles	5.36	39
Number of conflicts encountered where time-to-collision (TTC) is less than a pre-determined threshold / 100 million km or miles	5.30	40
Number of instances with hard braking (high deceleration) / 1000 km or miles	5.21	39
Number of false positives / 1000 km or miles, i.e. instances where the vehicle takes unnecessary collision avoidance action	5.13	39
Number of instances rated by a human as being of increased risk or not correctly handled by the automated vehicle / 1000 km or miles	5.11	38
Proportion of time when time-to-collision (TTC) is less than a pre-determined threshold	5.00	40
Distribution of TTC at brake onsets	4.89	38
Number of selected traffic violations / 1000 km or miles of driving	4.89	38

Table 8. Average ratings for the safety KPIs for different level of automation

KPI	SAE 1-2		SAE 3		SAE 4-5	
	Rating	N	Rating	N	Rating	N
Number of crashes (distinguishing property damage, and crashes with injuries and fatalities), in total and per 100 million km or miles	5.45	11	5.67	15	6.00	14
Number of instances where the driver must take manual control / 1000 km or miles	5.40	10	5.27	15	5.43	14
Number of conflicts encountered where time-to-collision (TTC) is less than a pre-determined threshold / 100 million km or miles	5.18	11	5.60	15	5.07	14
Number of instances with hard braking (high deceleration) / 1000 km or miles	5.45	11	5.07	15	5.15	13
Number of false positives / 1000 km or miles, i.e. instances where the vehicle takes unnecessary collision avoidance action	5.60	10	4.93	15	5.00	14
Number of instances rated by a human as being of increased risk or not correctly handled by the automated vehicle / 1000 km or miles	4.90	10	5.36	14	5.00	14
Proportion of time when time-to-collision (TTC) is less than a pre-determined threshold	4.82	11	5.07	15	5.07	14
Distribution of TTC at brake onsets	5.09	11	4.77	13	4.86	14
Number of selected traffic violations / 1000 km or miles of driving	4.91	11	4.79	14	5.00	13

Table 9. Average ratings for the safety KPIs for passenger cars and mixed traffic

KPI	Automated passenger car		Mixed traffic	
	Rating	N	Rating	N
Number of crashes (distinguishing property damage, and crashes with injuries and fatalities), in total and per 100 million km or miles	5.70	20	5.72	18
Number of instances where the driver must take manual control / 1000 km or miles	5.21	19	5.50	18
Number of conflicts encountered where time-to-collision (TTC) is less than a pre-determined threshold / 100 million km or miles	5.10	20	5.44	18
Number of instances with hard braking (high deceleration) / 1000 km or miles	5.21	19	5.17	18
Number of false positives / 1000 km or miles, i.e. instances where the vehicle takes unnecessary collision avoidance action	4.89	19	5.39	18
Number of instances rated by a human as being of increased risk or not correctly handled by the automated vehicle / 1000 km or miles	4.89	19	5.29	17
Proportion of time when time-to-collision (TTC) is less than a pre-determined threshold	4.90	20	5.11	18
Distribution of TTC at brake onsets	4.85	20	4.88	16
Number of selected traffic violations / 1000 km or miles of driving	5.05	19	4.76	17

The respondents suggested the following additional KPIs:

- Speed difference distribution or speed profiles compared to conventional vehicles
- Perception of safety by pedestrians, bicyclists, and others sharing the road with AVs.
- Time to take over vehicle control when system cannot provide support / handle the driving situation
- Quality/type of drivers' reaction to a take-over request by the system
- Time to react to take-over request
- Standard deviation of speed
- Number of instances when not reacting to a pedestrian appropriately (% of all pedestrians encountered)
- Number of instances when not reacting to a cyclist appropriately (% of all cyclists encountered)

3.4 Energy or environment

The energy and emissions category includes both the energy consumption of the vehicle through a driving cycle, and tailpipe emissions of pollutants including greenhouse gases. The direct energy/emissions impacts come from the change in the driving cycle. Changes in vehicle propulsion (e.g., electric vehicles) may also have a significant effect on tailpipe emissions.

The average rates for the proposed KPIs are shown in Table 10. The averages were also calculated separately for different levels of automation (Table 11) and for passenger cars and mixed traffic (Table 12). The ratings were measured with a scale from 0 = 'not at all important' to 6 = 'extremely important'.

Table 10. Average ratings for the energy or environment KPIs in descending order

KPI	Rating	N
Energy consumption of a vehicle (liters/100km or miles per gallon or electric equivalent)	5.29	21
Tailpipe carbon dioxide (CO2) emissions in total per year and per vehicle-km or mile	5.00	21
Tailpipe criteria pollutant emissions (NOX, CO, PM10, PM2.5, VOC) in total per year and per vehicle-km or mile	5.00	21
Total fossil (gasoline, diesel, compressed and liquefied natural gas) energy consumption from highway transportation (tonnes/year)	4.75	20
Annual traffic CO2 emissions (tonnes/year) on a route or in a region	4.48	21
Energy consumption of a vehicle (kWh/year)	4.24	21
Personal energy consumption (annual average kWh/person-km and kWh/person)	4.05	21
Annual average of the proportion of time when noise level above threshold	4.00	20

Table 11. Average ratings for the energy or environment KPIs for different level of automation

KPI	SAE 1-2		SAE 3		SAE 4-5	
	Rating	N	Rating	N	Rating	N
Energy consumption of a vehicle (liters/100km or miles per gallon or electric equivalent)	5.40	5	5.29	7	5.22	9
Tailpipe carbon dioxide (CO2) emissions in total per year and per vehicle-km or mile	4.60	5	5.14	7	5.11	9
Tailpipe criteria pollutant emissions (NOX, CO, PM10, PM2.5, VOC) in total per year and per vehicle-km or mile	4.60	5	5.14	7	5.11	9
Total fossil (gasoline, diesel, compressed and liquefied natural gas) energy consumption from highway transportation (tonnes/year)	5.40	5	4.86	7	4.25	8
Annual traffic CO2 emissions (tonnes/year) on a route or in a region	4.60	5	4.00	7	4.78	9
Energy consumption of a vehicle (kWh/year)	4.60	5	3.86	7	4.33	9
Personal energy consumption (annual average kWh/person-km and kWh/person)	4.20	5	4.14	7	3.89	9
Annual average of the proportion of time when noise level above threshold	3.20	5	4.43	7	4.13	8

Table 12. Average ratings for the energy or environment KPIs for passenger cars and mixed traffic

KPI	Automated passenger car		Mixed traffic	
	Rating	N	Rating	N
Energy consumption of a vehicle (liters/100km or miles per gallon or electric equivalent)	5.50	8	5.18	11
Tailpipe carbon dioxide (CO2) emissions in total per year and per vehicle-km or mile	4.75	8	5.09	11
Tailpipe criteria pollutant emissions (NOX, CO, PM10, PM2.5, VOC) in total per year and per vehicle-km or mile	4.63	8	5.18	11
Total fossil (gasoline, diesel, compressed and liquefied natural gas) energy consumption from highway transportation (tonnes/year)	4.38	8	4.80	10
Annual traffic CO2 emissions (tonnes/year) on a route or in a region	3.75	8	4.91	11
Energy consumption of a vehicle (kWh/year)	4.75	8	3.74	11
Personal energy consumption (annual average kWh/person-km and kWh/person)	3.88	8	4.18	11
Annual average of the proportion of time when noise level above threshold	3.63	8	4.20	10

The respondents suggested the following additional KPIs:

- Space needed for road transport and parking
- Portion of electric vehicles
- Energy use/emissions per second
- BTUs per completed trip -- with trips broken out by length and type of trip.
- BTUs per value of trip (e.g. by trip purpose)

3.5 Personal mobility

Mobility from a user's standpoint includes journey quality (comfort, use potential of in-vehicle time), travel time, cost; and whether the travel option is available to someone (e.g., a non-motorist). It also includes equity and accessibility considerations.

The average rates for the proposed KPIs are shown in Table 13. The averages were also calculated separately for different levels of automation (Table 14) and for passenger cars and mixed traffic (Table 15). The ratings were measured with a scale from 0 = 'not at all important' to 6 = 'extremely important'.

Table 13. Average ratings for the personal mobility KPIs in descending order

KPI	Rating	N
Type and duration of in-vehicle activities when not operating the vehicle (high levels of automation)	5.12	33
User perceptions of travelling quality (expressed on a Likert scale, e.g. 1–9, low–high)	5.06	35
User perceptions of travelling reliability (expressed on a Likert scale, e.g. 1–9)	4.88	34
Mean distance traveled per day	4.80	35
User perceptions of travelling comfort (expressed on a Likert scale, e.g. 1–9)	4.74	35
Total time spent travelling per day per person	4.66	35
User perception of travel time savings (min per day)	4.65	34
Number of journeys made per day	4.49	35

Table 14. Average ratings for the personal mobility KPIs for different level of automation

KPI	SAE 1-2		SAE 3		SAE 4-5	
	Rating	N	Rating	N	Rating	N
Type and duration of in-vehicle activities when not operating the vehicle (high levels of automation)	4.60	5	5.08	13	5.33	15
User perceptions of travelling quality (expressed on a Likert scale, e.g. 1–9, low–high)	5.57	7	5.00	13	4.87	15
User perceptions of travelling reliability (expressed on a Likert scale, e.g. 1–9)	5.57	7	4.75	12	4.67	15
Mean distance traveled per day	5.00	7	4.46	13	5.00	15
User perceptions of travelling comfort (expressed on a Likert scale, e.g. 1–9)	5.57	7	4.62	13	4.47	15
Total time spent travelling per day per person	5.29	7	3.92	13	5.00	15
User perception of travel time savings (min per day)	5.33	6	4.23	13	4.73	15
Number of journeys made per day	4.71	7	4.54	13	4.33	15

Table 15. Average ratings for the personal mobility KPIs for passenger cars and mixed traffic

KPI	Automated passenger car		Mixed traffic	
	Rating	N	Rating	N
Type and duration of in-vehicle activities when not operating the vehicle (high levels of automation)	5.13	15	5.29	14
User perceptions of travelling quality (expressed on a Likert scale, e.g. 1–9, low–high)	5.00	16	5.13	15
User perceptions of travelling reliability (expressed on a Likert scale, e.g. 1–9)	4.80	15	4.87	15
Mean distance traveled per day	4.81	16	5.07	15
User perceptions of travelling comfort (expressed on a Likert scale, e.g. 1–9)	4.31	16	5.13	15
Total time spent travelling per day per person	4.69	16	4.73	15
User perception of travel time savings (min per day)	4.44	16	4.71	14
Number of journeys made per day	4.56	16	4.53	15

The respondents suggested the following additional KPIs:

- Types of travelers (children, elderly, disabilities) who are able to use the vehicle without assistance
- Waiting time for vehicle
- Time at interchanges
- Time for detour/load/unload other passengers
- Variation in total time spent travelling and distance travelled per day
- Travel costs (absolute value or as share of personal/household income)
- Reliability
- Trip importance
- Accessibility for disadvantaged or impaired travelers (such as ability to get to essential destinations and ability to get to desirable destinations)
- Total distance traveled per day
- Travel time savings (from distance and time spent traveling)
- Impact on mode choice (e.g. number of journeys made per mode each day)
- User preferences on different modes
- Number of journeys / Distance traveled per mode
- Accessibility to new users (e.g. amount of users for which driving a high level automation vehicle is available)
- Number of new types of trips made per year

3.6 Travel behavior

A traveler may respond to automated transport options, including new service offerings, by changing travel behavior. There may be more or fewer trips. Modes, routes and destinations may change. Higher-level automation applications that have a significant effect on personal mobility or labor could have a significant effect on travel behavior.

The average rates for the proposed KPIs are shown in Table 16. The averages were also calculated separately for different levels of automation (Table 17) and for passenger cars and mixed traffic (Table 18). The ratings were measured with a scale from 0 = 'not at all important' to 6 = 'extremely important'.

Table 16. Average ratings for the travel behavior KPIs in descending order

KPI	Rating	N
Share of transport modes (modal split) per week (based on number of trips)	5.09	32
Number and type of trips per week (in total and per inhabitant)	4.84	32
Total duration of trips per week (in total and per inhabitant)	4.69	32
Total kilometers or miles travelled per week in a region	4.69	32
Network-level journey time per week	4.55	31
Share of used road types per week (based on km or miles travelled)	4.22	32

Table 17. Average ratings for the travel behavior KPIs for different level of automation

KPI	SAE 1-2		SAE 3		SAE 4-5	
	Rating	N	Rating	N	Rating	N
Share of transport modes (modal split) per week (based on number of trips)	5.38	8	4.67	9	5.20	15
Number and type of trips per week (in total and per inhabitant)	4.63	8	5.11	9	4.80	15
Total duration of trips per week (in total and per inhabitant)	5.25	8	4.56	9	4.47	15
Total kilometers or miles travelled per week in a region	5.50	8	4.33	9	4.47	15
Network-level journey time per week	4.38	8	4.38	8	4.73	15
Share of used road types per week (based on km or miles travelled)	4.88	8	3.44	9	4.33	15

Table 18. Average ratings for the travel behavior KPIs for passenger cars and mixed traffic

KPI	Automated passenger car		Mixed traffic	
	Rating	N	Rating	N
Share of transport modes (modal split) per week (based on number of trips)	5.00	15	5.25	12
Number and type of trips per week (in total and per inhabitant)	4.93	15	5.00	12
Total duration of trips per week (in total and per inhabitant)	4.47	15	4.83	12
Total kilometers or miles travelled per week in a region	4.80	15	4.33	12
Network-level journey time per week	4.36	14	4.58	12
Share of used road types per week (based on km or miles travelled)	4.07	15	4.50	12

The respondents suggested the following additional KPIs:

- Average vehicle occupancy rates (persons/vehicle)
- Relation of travel times and costs from public transport, PT-AV-Shuttles and private cars
- Change in day period for the travel
- “These are not KPIs, but KPIs need to get to individual traveler decisions”:
- How traveler decides to make trips and which kinds of trips
- Does the availability of an AV make it more or less likely that you will take a discretionary trip?
- Does the availability of an AV make a longer commute trip more tolerable?
- Vehicle kilometers/miles traveled per person/individual
- Vehicle kilometers/miles traveled per vehicle

3.7 Network efficiency

Network efficiency refers to lane, link and intersection capacity and throughput in a regional transport network. It also refers to travel time and travel time reliability.

The average rates for the proposed KPIs are shown in Table 19. The averages were also calculated separately for different levels of automation (Table 20) and for passenger cars and mixed traffic (Table 21). The ratings were measured with a scale from 0 = 'not at all important' to 6 = 'extremely important'.

Table 19. Average ratings for the network efficiency KPIs in descending order

KPI	Rating	N
Throughput i.e. number of vehicles per hour through a particular road section or intersection approach, normalized to number of lanes and proportion of green time (where relevant)	5.38	24
Maximum road capacity (for a given road section)	5.00	24
Peak period travel time along a route	4.83	23
Average travel time (minutes) per road-km or mile	4.79	24
Road capacity at design speed (for a given road section)	4.73	22
Lowest and highest 5th percentile speed (on a given road section) - addresses "worst case" reliability	4.58	24
Total travel time and distance travelled per road section or route	4.52	23
95th percentile travel time (minutes) per road-km or mile	4.50	24
Median speed (on a given road section)	4.42	24
Free flow speed (on a given road section)	4.25	24

Table 20. Average ratings for the network efficiency KPIs for different level of automation

KPI	SAE 1-2		SAE 3		SAE 4-5	
	Rating	N	Rating	N	Rating	N
Throughput i.e. number of vehicles per hour through a particular road section or intersection approach, normalized to number of lanes and proportion of green time (where relevant)	5.60	5	5.14	7	5.42	12
Maximum road capacity (for a given road section)	5.00	5	5.29	7	4.83	12
Peak period travel time along a route	5.25	4	5.00	7	4.58	12
Average travel time (minutes) per road-km or mile	4.80	5	5.29	7	4.50	12
Road capacity at design speed (for a given road section)	3.25	4	5.29	7	4.91	11
Lowest and highest 5th percentile speed (on a given road section) - addresses "worst case" reliability	5.40	5	4.43	7	4.33	12
Total travel time and distance travelled per road section or route	4.00	4	5.29	7	4.25	12
95th percentile travel time (minutes) per road-km or mile	4.40	5	4.57	7	4.50	12
Median speed (on a given road section)	4.20	5	4.29	7	4.58	12
Free flow speed (on a given road section)	3.80	5	4.57	7	4.25	12

Table 21. Average ratings for the network efficiency KPIs for passenger cars and mixed traffic

KPI	Automated passenger car		Mixed traffic	
	Rating	N	Rating	N
Throughput i.e. number of vehicles per hour through a particular road section or intersection approach, normalized to number of lanes and proportion of green time (where relevant)	5.45	11	5.27	11
Maximum road capacity (for a given road section)	5.09	11	5.09	11
Peak period travel time along a route	4.60	10	5.00	11
Average travel time (minutes) per road-km or mile	4.91	11	4.55	11
Road capacity at design speed (for a given road section)	4.91	11	4.67	9
Lowest and highest 5th percentile speed (on a given road section) - addresses "worst case" reliability	4.55	11	4.55	11
Total travel time and distance travelled per road section or route	4.45	11	4.70	10
95th percentile travel time (minutes) per road-km or mile	4.36	11	4.55	11
Median speed (on a given road section)	4.82	11	3.82	11
Free flow speed (on a given road section)	4.27	11	4.00	11

The respondents suggested the following additional KPIs:

- Travel time variability (5^{th}; 95^{th} percentile travel time, to determine certainty in travel time)
- Effective capacity (an increase in capacity will also increase access -- to jobs/labor; health facilities, family/friends; recreation etc. Access to more jobs (and access to larger labor pool) has a direct, positive impact on economic productivity and economic activity)
- Full distributions of travel times and speeds for highway section or network
- Ratios of peak to average travel times and speeds help show severity of peaking
- Average following times between vehicles
- Rate of traditional vehicles/automated vehicles

3.8 Asset management

Assets include physical and digital infrastructure of road transportation.

The average rates for the proposed KPIs are shown in Table 22. The averages were also calculated separately for different levels of automation (Table 23) and for passenger cars and mixed traffic (Table 24). The ratings were measured with a scale from 0 = 'not at all important' to 6 = 'extremely important'.

Table 22. Average ratings for the asset management KPIs in descending order

KPI	Rating	N
V2I infrastructure for automation	5.18	11
Frequency of pothole occurrence (number of potholes per 100 km or miles)	4.91	11
Use of hard shoulder (for hard-shoulder running or as emergency stop area for mal-functioning automated vehicles)	4.90	10
Mean rut depth (mm or inch with 2 decimals)	4.73	11
Size and weight implications of changed fleet composition	4.64	11
Pavement damage (level of damage, damaged area, % of road km or miles)	4.45	11
Number of lanes and lane widths	4.40	10
Minimum bearing capacity on a road section (tonnes)	4.27	11

Table 23. Average ratings for the asset management KPIs for different level of automation

KPI	SAE 1-2		SAE 3		SAE 4-5	
	Rating	N	Rating	N	Rating	N
V2I infrastructure for automation		0	4.00	3	5.63	8
Frequency of pothole occurrence (number of potholes per 100 km or miles)		0	5.33	3	4.75	8
Use of hard shoulder (for hard-shoulder running or as emergency stop area for mal-functioning automated vehicles)		0	5.33	3	4.71	7
Mean rut depth (mm or inch with 2 decimals)		0	5.00	3	4.63	8
Size and weight implications of changed fleet composition		0	4.67	3	4.63	8
Pavement damage (level of damage, damaged area, % of road km or miles)		0	4.67	3	4.38	8
Number of lanes and lane widths		0	4.50	2	4.38	8
Minimum bearing capacity on a road section (tonnes)		0	4.33	3	4.25	8

Table 24. Average ratings for the asset management KPIs for passenger cars and mixed traffic

KPI	Automated passenger car		Mixed traffic	
	Rating	N	Rating	N
V2I infrastructure for automation	4.60	5	5.67	6
Frequency of pothole occurrence (number of potholes per 100 km or miles)	5.20	5	4.67	6
Use of hard shoulder (for hard-shoulder running or as emergency stop area for mal-functioning automated vehicles)	5.20	5	4.60	5
Mean rut depth (mm or inch with 2 decimals)	5.00	5	4.50	6
Size and weight implications of changed fleet composition	4.60	5	4.67	6
Pavement damage (level of damage, damaged area, % of road km or miles)	4.40	5	4.50	6
Number of lanes and lane widths	3.80	5	5.00	5
Minimum bearing capacity on a road section (tonnes)	3.80	5	4.67	6

The respondents did not have suggestions for additional KPIs.

3.9 Costs

Once an automation application has moved out of prototyping, and into production, what is a reasonable estimate of the capital and operating cost for the technology? This is important for assessing the future business case for deployment and ultimate usage.

The average rates for the proposed KPIs are shown in Table 25. The averages were also calculated separately for different levels of automation (Table 26) and for passenger cars and mixed traffic (Table 27). The ratings were measured with a scale from 0 = 'not at all important' to 6 = 'extremely important'.

Table 25. Average ratings for the cost KPIs in descending order

KPI	Rating	N
Capital cost per vehicle for the deployed system (infrastructure, monetary value)	5.08	12
Cost of purchased automated vehicle (market price, monetary value)	5.00	13
Operating cost for the deployed system (per vehicle-hour or per vehicle-km or mile, monetary value)	4.92	13
Investment cost for digital infrastructure (per road km or mile, monetary value)	4.83	12
Operation and maintenance cost for physical infrastructure (per road km or mile, monetary value)	4.58	12
Cost per trip (for user, monetary value)	4.54	13
Investment cost for physical infrastructure (per road km or mile, monetary value)	4.46	13
Operation and maintenance cost for digital infrastructure (per road km or mile, monetary value)	4.46	13
Investment cost for connectivity network (per road km or mile, monetary value)	4.23	13
Operation and maintenance cost for connectivity network (per road km or mile, monetary value)	4.23	13
Cost of education per driver (monetary value)	3.75	12

Table 26. Average ratings for the cost KPIs for different level of automation

KPI	SAE 1-2		SAE 3		SAE 4-5	
	Rating	N	Rating	N	Rating	N
Capital cost per vehicle for the deployed system (infrastructure, monetary value)	6.00	4	4.83	6	4.00	2
Cost of purchased automated vehicle (market price, monetary value)	5.50	4	5.17	6	4.00	3
Operating cost for the deployed system (per vehicle-hour or per vehicle-km or mile, monetary value)	5.76	4	4.83	6	4.00	3
Investment cost for digital infrastructure (per road km or mile, monetary value)	4.75	4	4.60	5	4.33	3
Operation and maintenance cost for physical infrastructure (per road km or mile, monetary value)	5.50	4	4.00	5	4.33	3
Cost per trip (for user, monetary value)	5.25	4	3.83	6	5.00	3
Investment cost for physical infrastructure (per road km or mile, monetary value)	5.25	4	4.00	6	4.33	3
Operation and maintenance cost for digital infrastructure (per road km or mile, monetary value)	5.00	4	4.17	6	4.67	3
Investment cost for connectivity network (per road km or mile, monetary value)	5.00	4	3.50	6	4.67	3
Operation and maintenance cost for connectivity network (per road km or mile, monetary value)	4.50	4	3.67	6	5.00	3
Cost of education per driver (monetary value)	4.50	4	3.00	5	4.00	3

Table 27. Average ratings for the cost KPIs for passenger cars and mixed traffic

KPI	Automated passenger car		Mixed traffic	
	Rating	N	Rating	N
Capital cost per vehicle for the deployed system (infrastructure, monetary value)	4.50	2	5.00	8
Cost of purchased automated vehicle (market price, monetary value)	4.67	3	5.13	8
Operating cost for the deployed system (per vehicle-hour or per vehicle-km or mile, monetary value)	5.67	3	4.38	8
Investment cost for digital infrastructure (per road km or mile, monetary value)	5.00	3	4.57	7
Operation and maintenance cost for physical infrastructure (per road km or mile, monetary value)	4.00	3	4.57	7
Cost per trip (for user, monetary value)	5.33	3	4.00	8
Investment cost for physical infrastructure (per road km or mile, monetary value)	3.67	3	4.63	8
Operation and maintenance cost for digital infrastructure (per road km or mile, monetary value)	5.00	3	4.38	8
Investment cost for connectivity network (per road km or mile, monetary value)	4.67	3	4.00	8
Operation and maintenance cost for connectivity network (per road km or mile, monetary value)	5.00	3	4.13	8
Cost of education per driver (monetary value)	4.50	2	3.50	8

The respondents suggested the following additional KPIs:

- Cost for retro-fit kits
- Cost per mile

3.10 Public health

Automation may impact the health (physical and mental) of individuals and entire communities, via safety, air pollution, amount of walking and bicycling, as well as access to medical care, food, employment, education and recreation.

The average rates for the proposed KPIs are shown in Table 28. The averages were also calculated separately for different levels of automation (Table 29) and for passenger cars and mixed traffic (Table 30). The ratings were measured with a scale from 0 = 'not at all important' to 6 = 'extremely important'.

Table 28. Average ratings for the public health KPIs in descending order

KPI	Rating	N
Modal share (%) and total mileage travelled (kms) by active modes of transportation (walking and bicycle)	5.80	5
Number of fatalities and injuries per year per million inhabitants	5.40	5
Proportion of people with improved access to health services	5.00	5
Population exposure to air pollution	4.60	5
Quality-adjusted life years	4.40	5

Table 29. Average ratings for the public health KPIs for different level of automation

KPI	SAE 1-2		SAE 3		SAE 4-5	
	Rating	N	Rating	N	Rating	N
Modal share (%) and total mileage travelled (kms) by active modes of transportation (walking and bicycle)	6.00	2	5.50	2	6.00	1
Number of fatalities and injuries per year per million inhabitants	5.00	2	5.50	2	6.00	1
Proportion of people with improved access to health services	6.00	2	3.50	2	6.00	1
Population exposure to air pollution	4.00	2	4.50	2	6.00	1
Quality-adjusted life years	3.50	2	4.50	2	6.00	1

Table 30. Average ratings for the public health KPIs for passenger cars and mixed traffic

KPI	Automated passenger car		Mixed traffic	
	Rating	N	Rating	N
Modal share (%) and total mileage travelled (kms) by active modes of transportation (walking and bicycle)	5.67	3	6.00	1
Number of fatalities and injuries per year per million inhabitants	5.00	3	6.00	1
Proportion of people with improved access to health services	4.67	3	5.00	1
Population exposure to air pollution	4.67	3	5.00	1
Quality-adjusted life years	5.00	3	4.00	1

The respondents suggested the following additional KPI:

- Improved access to recreation and other services

3.11 Land use

Automation may affect the use of land for transport functions (e.g., parking, road geometry). Longer-term land-use changes may include community planning. The number of factors that contribute to long-term land use changes makes distinguishing those changes contributed by automation a particular challenge.

The average rates for the proposed KPIs are shown in Table 31. The averages were also calculated separately for different levels of automation (Table 32) and for passenger cars and mixed traffic (Table 33). The ratings were measured with a scale from 0 = 'not at all important' to 6 = 'extremely important'.

Table 31. Average ratings for the land use KPIs in descending order

KPI	Rating	N
Number of parking slots	5.00	11
Density of housing	4.91	11
Location of parking	4.91	11
Location of employment	4.55	11
Road network design	4.40	10
Location of recreation	3.91	11

Table 32. Average ratings for the land use KPIs for different level of automation

KPI	SAE 1-2		SAE 3		SAE 4-5	
	Rating	N	Rating	N	Rating	N
Number of parking slots	6.00	2	4.50	4	5.00	5
Density of housing	5.50	2	4.50	4	5.00	5
Location of parking	5.00	2	4.75	4	5.00	5
Location of employment	5.50	2	4.25	4	4.40	5
Road network design	4.50	2	4.00	4	4.75	4
Location of recreation	4.50	2	3.75	4	3.80	5

Table 33. Average ratings for the land use KPIs for passenger cars and mixed traffic

KPI	Automated passenger car		Mixed traffic	
	Rating	N	Rating	N
Number of parking slots	5.33	3	4.67	6
Density of housing	4.00	3	5.33	6
Location of parking	5.67	3	4.67	6
Location of employment	4.00	3	4.83	6
Road network design	4.33	3	4.20	5
Location of recreation	3.33	3	4.33	6

The respondents suggested the following additional KPIs:

- Density of employment and shopping
- Creation of new real estate developments or new towns with transportation infrastructure designed specifically for AV access
- Distance in time to employment

3.12 Economic impacts

Improved safety, use of time, freight movement, travel options (for motorists and non-motorists), public health, land use and effects of changed emissions (including climate change) will have longer-term economic impacts. Automation may also have substantial impact on labor markets and industries.

The average rates for the proposed KPIs are shown in Table 34. The averages were also calculated separately for different levels of automation (Table 35) and for passenger cars and mixed traffic (Table 36). The ratings were measured with a scale from 0 = 'not at all important' to 6 = 'extremely important'.

Table 34. Average ratings for the economic impact KPIs in descending order

KPI	Rating	N
Work time gained due to ability to multitask while traveling (hours per year, overall and per capita; monetary value)	4,95	19
Socio-economic cost benefit ratio	4,80	20
Work time lost from traffic crashes (hours per year, overall and per capita; monetary value)	4,75	20
Number of vanished/disappeared jobs	4,40	20
New established businesses / job creation	4,35	20
Total factor productivity / multi-factor productivity estimates	4,25	20
Labor force participation rate – overall and for non-drivers	4,22	18
Work time lost from illnesses related to air pollution [hours per year, overall and per capita; monetary value]	3,95	20
Gross Domestic Product (hours per year, overall and per capita; monetary value)	3,68	19

Table 35. Average ratings for the economic impact KPIs for different level of automation

KPI	SAE 1-2		SAE 3		SAE 4-5	
	Rating	N	Rating	N	Rating	N
Work time gained due to ability to multitask while traveling (hours per year, overall and per capita; monetary value)	4,80	5	4,33	6	5,50	8
Socio-economic cost benefit ratio	4,83	6	3,67	6	5,63	8
Work time lost from traffic crashes (hours per year, overall and per capita; monetary value)	4,60	5	4,17	6	5,22	9
Number of vanished/disappeared jobs	4,80	5	3,67	6	4,67	9
New established businesses / job creation	5,00	5	3,67	6	4,44	9
Total factor productivity / multi-factor productivity estimates	4,40	5	3,83	6	4,44	9
Labor force participation rate – overall and for non-drivers	4,75	4	3,67	6	4,38	8
Work time lost from illnesses related to air pollution [hours per year, overall and per capita; monetary value]	3,00	5	3,67	6	4,67	9
Gross Domestic Product (hours per year, overall and per capita; monetary value)	4,00	5	2,50	6	4,38	8

Table 36. Average ratings for the economic impact KPIs for passenger cars and mixed traffic

KPI	Automated passenger car		Mixed traffic	
	Rating	N	Rating	N
Work time gained due to ability to multitask while traveling (hours per year, overall and per capita; monetary value)	4,57	7	5,22	9
Socio-economic cost benefit ratio	5,50	8	4,67	9
Work time lost from traffic crashes (hours per year, overall and per capita; monetary value)	4,86	7	4,60	10
Number of vanished/disappeared jobs	4,14	7	4,20	10
New established businesses / job creation	4,57	7	4,00	10
Total factor productivity / multi-factor productivity estimates	4,57	7	4,20	10
Labor force participation rate – overall and for non-drivers	4,33	6	4,00	9
Work time lost from illnesses related to air pollution [hours per year, overall and per capita; monetary value]	4,00	7	4,10	10
Gross Domestic Product (hours per year, overall and per capita; monetary value)	3,86	7	3,56	9

The respondents suggested the following additional KPIs:

- Average annual maintenance costs of automated vehicles (currency/veh./year)
- Number of providers of AV-fleets in a local market
- Market share of trips in shared fleet and privately owned cars
- Portion of mobility expenditures of household income
- Total-factor productivity

4. Discussion

This report documents the survey, which was designed to investigate views on the importance of different KPIs for expressing the impacts of automated driving in different impact areas. It documents the results of ratings and other answers given by the 77 respondents in Europe, US and Japan who filled in the survey.

The results were analyzed as the average rating on scale from 0 = 'not at all important' to 6 = 'extremely important'. These average ratings were calculated for all responses. They were then broken out for different levels of automation (SAE 1-2, SAE 3 or SAE 4-5) in mind or specifically for automated passenger cars or for mixed traffic. The report lists additional KPIs that were proposed by the respondents.

None of the KPIs received very low ratings. This is most likely due to having a large expert group selecting the KPIs for the survey and dropping irrelevant KPIs during survey design. On the other hand, as the impacts of automation are still partly unknown, the experts are interested in many potential impacts.

In order not to have too long a list of alternative KPIs to rate, some KPIs were not precisely defined. Consequently, they will need additional work on making them unambiguous before use in practice.

The Trilateral Impact Assessment Subgroup of ART WG will utilize these results when deciding the recommendations for the KPIs to be used in the impact assessment studies. The recommendations and a full list of potential KPIs (a KPI repository) will be added to version 2.0 of their impact assessment framework (expected in April 2018).

References

Innamaa, S; Smith, S; Barnard, Y; Rainville, L; Rakoff, H; Horiguchi, R; & Gellerman, H (2017). Trilateral Impact Assessment Framework for Automation in Road Transportation. Draft Version 1.0, 4 January 2017. 34 p. https://connectedautomateddriving.eu/wp-content/uploads/2017/05/Trilateral_IA_Framework_Draft_v1.0.pdf

Smith, S; Bellone, J; Bransfield, S; Ingles, A; Noel, G; Reed, E; & Yanagisawa, M. (2015). Benefits Estimation Framework for Automated Vehicle Operations (No. FHWA-JPO-16-229).

ANNEX I: Distributions for ratings

Number of respondents per rating for each KPI

KPI (VEHICLE OPERATIONS)	Rating						
	0	1	2	3	4	5	6
Number of instances where the driver must take manual control / 1000 km or miles	0	0	0	0	1	7	21
Mean and maximum duration of the transfer of control between operator/driver and vehicle (when requested by the vehicle)	0	0	0	0	2	7	21
Mean and maximum duration of the transfer of control between operator/driver and vehicle (turning automated driving system on/off, manual overrule)	1	0	1	2	2	8	15
Number of emergency decelerations per 1000 km or miles	0	0	1	3	5	10	13
Mean and minimum time-headway to the vehicle in front in car following situations	1	0	1	2	7	10	11
Minimum accepted gap at intersections or in lane changes	0	1	2	2	2	16	7
Mean and minimum distance to the vehicle in front in car following situations (headway 5 s or less)	1	0	1	2	9	10	9
Mean and maximum longitudinal acceleration and deceleration	0	1	1	6	5	10	8
Lateral position variation (st. dev. of distance from the center of the lane) while travelling within a lane	0	0	2	6	9	7	8
Speed variation (st. dev. of speeds) while travelling at constant speed (on link section, single speed limit)	0	0	4	6	6	8	8
Variance of the time-headway to the vehicle in front in car following situations	0	0	3	3	13	6	6
Maximum jerk (rate of change in acceleration, longitudinal and lateral)	0	0	2	7	9	9	5
Proportion of correct use of turning indicator/signal	1	1	3	5	6	7	6
Mean lateral acceleration during lane change	0	1	5	6	11	4	5
Proportion of distance driven when speeding	1	1	4	6	8	3	6

KPI (USE OF AUTOMATED DRIVING)	Rating						
	0	1	2	3	4	5	6
Number of instances where the driver must take manual control / 1000 km or miles	0	0	0	1	3	5	22
Use of automated driving functions (% of km of maximum possible use)	0	0	1	1	3	8	18
Comprehensibility of user interface (expressed on a Likert scale, e.g. 1–9, low–high)	0	0	0	2	3	11	13
Feeling of safety (expressed on a Likert scale, e.g. 1–9, very dangerous – very safe)	0	0	0	2	6	6	14
Interaction with other road users (expressed on a Likert scale, e.g. 1–9, failure–perfect)	0	0	0	3	6	9	13
Inappropriate use of automated driving functions (number of events per 100 km or miles)	0	0	0	1	7	13	9
Requirement of attention and concentration (number of events per 100 km)	0	0	1	2	6	9	13
Trust (expressed on a Likert scale, e.g. 1–9, low–high)	0	0	0	5	4	9	12
Reliability (subjective perception, expressed on a Likert scale, e.g. 1–9, low–high)	0	0	1	4	4	11	9
Mental workload (expressed on a Likert scale, e.g. 1–9, low–high)	0	2	1	1	9	11	7
Feeling of being able to control the vehicle (expressed on a Likert scale, e.g. 1–9, failure-perfect)	1	0	1	6	7	7	7
Feeling of frustration (expressed on a Likert scale, e.g. 1–9, low–high)	0	2	3	2	9	7	7
Intended use (statement of interest, % of maximum possible use, by driver, identify relevant journey types)	0	2	2	5	5	14	3
Feeling of pressure because of many parallel tasks (number of events per 100 km)	0	1	4	5	11	4	6

KPI (SAFETY)	Rating						
	0	1	2	3	4	5	6
Number of crashes (distinguishing property damage, and crashes with injuries and fatalities), in total and per 100 million km or miles	0	0	0	2	2	1	35
Number of instances where the driver must take manual control / 1000 km or miles	0	0	1	2	4	7	25
Number of conflicts encountered where time-to-collision (TTC) is less than a pre-determined threshold / 100 million km or miles	0	1	0	2	5	7	25
Number of instances with hard braking (high deceleration) / 1000 km or miles	0	0	0	2	5	15	17
Number of false positives / 1000 km or miles, i.e. instances where the vehicle takes unnecessary collision avoidance action	0	0	2	0	8	10	19
Number of instances rated by a human as being of increased risk or not correctly handled by the automated vehicle / 1000 km or miles	0	0	0	2	8	12	16
Proportion of time when time-to-collision (TTC) is less than a pre-determined threshold	0	0	0	2	11	12	15
Distribution of TTC at brake onsets	0	0	0	3	11	11	13
Number of selected traffic violations / 1000 km or miles of driving	0	0	1	3	9	11	14

KPI (ENERGY OR ENVIRONMENT)	Rating						
	0	1	2	3	4	5	6
Energy consumption of a vehicle (liters/100km or miles per gallon or electric equivalent)	0	0	0	0	3	9	9
Tailpipe carbon dioxide (CO2) emissions in total per year and per vehicle-km or mile	0	2	0	1	1	6	11
Tailpipe criteria pollutant emissions (NOX, CO, PM10, PM2.5, VOC) in total per year and per vehicle-km or mile	0	1	1	0	3	6	10
Total fossil (gasoline, diesel, compressed and liquefied natural gas) energy consumption from highway transportation (tonnes/year)	0	0	0	3	4	8	5
Annual traffic CO2 emissions (tonnes/year) on a route or in a region	0	1	0	5	2	8	5
Energy consumption of a vehicle (kWh/year)	1	0	1	4	5	5	5
Personal energy consumption (annual average kWh/person-km and kWh/person)	0	0	1	2	14	3	1
Annual average of the proportion of time when noise level above threshold	0	1	2	5	5	2	5

KPI (PERSONAL MOBILITY)	Rating						
	0	1	2	3	4	5	6
Type and duration of in-vehicle activities when not operating the vehicle (high levels of automation)	0	0	1	0	5	15	12
User perceptions of travelling quality (expressed on a Likert scale, e.g. 1–9, low–high)	0	0	0	2	8	11	14
User perceptions of travelling reliability (expressed on a Likert scale, e.g. 1–9)	0	0	0	4	6	14	10
Mean distance traveled per day	0	0	2	3	7	11	12
User perceptions of travelling comfort (expressed on a Likert scale, e.g. 1–9)	0	0	1	3	12	7	12
Total time spent travelling per day per person	0	1	3	3	6	9	13
User perception of travel time savings (min per day)	1	0	1	4	6	12	10
Number of journeys made per day	0	1	2	7	3	13	9

KPI (TRAVEL BEHAVIOR)	Rating						
	0	1	2	3	4	5	6
Share of transport modes (modal split) per week (based on number of trips)	1	0	1	1	3	10	16
Number and type of trips per week (in total and per inhabitant)	0	0	1	3	7	10	11
Total duration of trips per week (in total and per inhabitant)	0	0	0	5	7	13	7
Total kilometers or miles travelled per week in a region	1	0	1	4	4	12	10
Network-level journey time per week	0	0	1	6	7	9	8
Share of used road types per week (based on km or miles travelled)	2	1	3	2	7	8	9

KPI (NETWORK EFFICIENCY)	Rating						
	0	1	2	3	4	5	6
Throughput i.e. number of vehicles per hour through a particular road section or intersection approach, normalized to number of lanes and proportion of green time (where relevant)	0	0	0	2	1	7	14
Maximum road capacity (for a given road section)	0	0	0	5	1	7	11
Peak period travel time along a route	0	0	0	4	3	9	7
Average travel time (minutes) per road-km or mile	0	0	0	4	5	7	8
Road capacity at design speed (for a given road section)	2	0	0	2	1	8	9
Lowest and highest 5th percentile speed (on a given road section) - addresses "worst case" reliability	0	0	0	3	9	7	5
Total travel time and distance travelled per road section or route	0	1	0	3	8	4	7
95th percentile travel time (minutes) per road-km or mile	0	0	1	5	3	11	4
Median speed (on a given road section)	0	0	2	5	3	9	5
Free flow speed (on a given road section)	0	1	2	3	6	8	4

KPI (ASSET MANAGEMENT)	Rating						
	0	1	2	3	4	5	6
V2I infrastructure for automation	0	1	0	0	0	4	6
Frequency of pothole occurrence (number of potholes per 100 km or miles)	0	0	0	0	4	4	3
Use of hard shoulder (for hard-shoulder running or as emergency stop area for mal-functioning automated vehicles)	0	0	0	1	3	2	4
Mean rut depth (mm or inch with 2 decimals)	0	0	0	0	6	2	3
Size and weight implications of changed fleet composition	0	0	0	1	5	2	3
Pavement damage (level of damage, damaged area, % of road km or miles)	0	0	0	2	4	3	2
Number of lanes and lane widths	0	1	0	3	1	0	5
Minimum bearing capacity on a road section (tonnes)	0	1	1	1	3	1	4

KPI (COSTS)	Rating						
	0	1	2	3	4	5	6
Capital cost per vehicle for the deployed system (infrastructure, monetary value)	0	0	0	2	2	1	7
Cost of purchased automated vehicle (market price, monetary value)	0	0	0	0	5	3	5
Operating cost for the deployed system (per vehicle-hour or per vehicle-km or mile, monetary value)	0	0	0	2	2	4	5
Investment cost for digital infrastructure (per road km or mile, monetary value)	0	0	1	0	2	6	3
Operation and maintenance cost for physical infrastructure (per road km or mile, monetary value)	0	0	1	2	1	5	3
Cost per trip (for user, monetary value)	0	0	1	2	2	5	3
Investment cost for physical infrastructure (per road km or mile, monetary value)	0	0	2	1	2	5	3
Operation and maintenance cost for digital infrastructure (per road km or mile, monetary value)	0	0	2	1	1	7	2
Investment cost for connectivity network (per road km or mile, monetary value)	1	0	1	0	4	5	2
Operation and maintenance cost for connectivity network (per road km or mile, monetary value)	1	0	2	0	2	5	3
Cost of education per driver (monetary value)	1	1	0	2	2	6	0

KPI (PUBLIC HEALTH)	Rating						
	0	1	2	3	4	5	6
Modal share (%) and total mileage travelled (kms) by active modes of transportation (walking and bicycle)	0	0	0	0	0	1	4
Number of fatalities and injuries per year per million inhabitants	0	0	0	0	1	1	3
Proportion of people with improved access to health services	0	0	1	0	0	1	3
Population exposure to air pollution	0	0	0	0	3	1	1
Quality-adjusted life years	0	0	0	1	2	1	1

KPI (LAND USE)	Rating						
	0	1	2	3	4	5	6
Number of parking slots	0	0	0	1	3	2	5
Density of housing	0	0	0	1	3	3	4
Location of parking	0	0	0	0	5	2	4
Location of employment	0	0	1	1	3	3	3
Road network design	0	0	1	0	4	4	1
Location of recreation	0	0	1	4	3	1	2

KPI (ECONOMIC IMPACTS)	Rating						
	0	1	2	3	4	5	6
Work time gained due to ability to multitask while traveling (hours per year, overall and per capita; monetary value)	0	1	1	1	2	4	10
Socio-economic cost benefit ratio	1	1	0	1	3	4	10
Work time lost from traffic crashes (hours per year, overall and per capita; monetary value)	0	1	0	0	5	10	4
Number of vanished/disappeared jobs	0	1	1	1	8	4	5
New established businesses / job creation	1	0	0	3	7	4	5
Total factor productivity / multi-factor productivity estimates	0	1	1	4	4	6	4
Labor force participation rate – overall and for non-drivers	1	0	1	3	4	5	4
Work time lost from illnesses related to air pollution [hours per year, overall and per capita; monetary value]	0	2	2	1	7	6	2
Gross Domestic Product (hours per year, overall and per capita; monetary value)	2	1	2	3	2	6	3