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The impact of data related aspects of vehicle automation on CO_2 emission

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Contents

List of Figures

List of Tables

Abstract

CO_2 emission of vehicles and its influence on climate change is a widely discussed topic already for many years. New CO_2 emission norms for vehicles have been defined based on the 2021 baseline: 15% reduction resulting in 0.09 kg/km for 2025, and 37.5% reduction resulting in 0.069 kg/km for 2030 [17]. Both norms are defined under the Worldwide harmonized Light-duty Test Procedure (WLTP) and apply to light-duty vehicles. In this study a new accurate measure is introduced to determine data related CO_2 emissions of vehicle automation. These data related emissions are used to compare to the norms, which are based on the propulsion of the vehicle.

The data related aspects in this study include: sensing components, the computing platform, disks inside the vehicle, wireless communication networks and data centers. The studies of Kemp et al. [21], Gawron et al. [14] and Taiebat et al. [37], expect the influence of the computing power consumption and data transmission to be significant with respect to the life-cycle CO_2 emission of vehicles. However, these studies do not cover the amount of data generated and transmitted, and their relation to additional CO_2 emission. The expected high amounts of data related to vehicle automation are also mentioned by various articles [5, 6]. This study contributes to these expectations by investigating the CO_2 emission of the these data related aspects for varying scenarios.

In this study, a single moving automated vehicle (AV) in its operational phase is considered, which is always connected while driving to enable data transmission outside of the vehicle. The instantaneous and spatial CO_2 emission rates of these data related aspects are determined for varying scenarios. The instantaneous CO_2 emission rate is defined as the kilogram CO_2 emission per unit time (kg CO_2-e/h), and the spatial CO_2 emission rate is defined as the kilogram CO_2 emission per kilometer travelled (kg CO_2-e/km). The instantaneous CO_2 emission rate is used to evaluate which data related aspects have the strongest influence on the CO_2 emission for each scenario and is independent of the travel speed. The spatial CO_2 emission rate is used to compare to the defined propulsion-based CO_2 norms of vehicles, and is dependent on travel speed.

To obtain the instantaneous CO_2 emission rate for each scenario, a computational model is developed based on literature and a survey. The survey consists of questions regarding the power consumption and the amount of data generated and transmitted by the data related aspects. Literature was used to define the different components and corresponding values of the data related aspects. The results from the survey are used to more specifically define the values corresponding to components, that have a range of values due to uncertainty of the exact values. The amount of data generated and transmitted is assumed to be independent of travel speed. Moreover, it is assumed that 30-50% of the data generated is sent to the data center.

Scenario analysis is applied to define six different scenarios. The scenarios differ based on two varying sensing compositions and three varying energy grids. The two sensing compositions correspond to a Tesla Model S (SAE level 2) and Waymo's Chrysler Pacifica (SAE level 4). The different energy grids correspond to the 2019 Climate Act targets for 2030 and 2050 to reduce CO_2 emission, and are referred to as fixed CO_2 emission rates in kg CO_2-e/Wh for varying scenarios. Sensitivity analysis of the instantaneous CO_2 emission rate is applied, to obtain the data related aspects that have the strongest influence on the resulting CO_2 emission in each scenario. The results of the instantaneous CO_2 emission rate are obtained for varying parameter sets. Based on these results, for each scenario three different situations are defined corresponding to the combination of values of each parameter that results in the highest, lowest and median instantaneous CO_2 emission rate. The instantaneous data related CO_2 emission rate, corresponding to the three different situations of each scenario, is translated to the driving cycle of the WLTP to obtain the spatial data related CO_2 emission rate. The spatial CO_2 emission rate for each scenario and situation are used to compare to the CO_2 norms of vehicles.

From the sensitivity analysis, it is concluded that the energy intensity of wireless communication networks and the data transmission rate from vehicle to data center, are the two data related aspects that have the strongest influence on the instantaneous CO_2 emission rate. From the spatial CO_2 emission rate of each scenario, it is concluded that the energy grid also significantly affects whether the norms can be met. Moreover, from the spatial CO_2 emission rate, it is concluded that the travel speed influences whether or not the CO_2 norms can be met for varying scenarios and situations. In general, it shows that the CO_2 emission is highest at low speed and decrease monotonically with increasing speed. The type of sensing composition does not significantly influence the resulting spatial CO_2 emission rate.

It is concluded that for high amounts of data transmission, the norms seem to be difficult to achieve in most scenarios and situations. Therefore, the energy consumption of wireless communication networks should be further optimized. Regarding the data transmission rate, further research should be obtained to gain more insights into the values of the data transmission rates dependent on the travel speed. Based on the assumptions made in this study (Appendix A), the CO_2 emission from the data related aspects seem to exceed the propulsion-based CO_2 norms of vehicles. Future work should investigate if data related aspects of vehicle automation need to be included in the CO_2 norms of vehicles.

1 Introduction

Often vehicle automation is mentioned to be promising towards reducing the amount of CO_2 emission from the transport sector, by introducing shared autonomous vehicles on the road. Vehicle automation corresponds to different Society of Automotive Engineers (SAE) levels of automation. SAE level 1 and 2 correspond to Advanced Driver Assistance Systems (ADAS), that support the driver in performing the dynamic driving task (DDT), but do not perform the complete DDT. SAE level 3 and 4 correspond to automated driving systems (ADS), where the driver operates the vehicle during a portion of a trip. For SAE level 5, the system can operate the full DDT [32]. Actually, there are some aspects related to the environmental effects of vehicle automation, for which an accurate measure seems to be missing, that might negatively influence CO_2 emission. These are the data related aspects necessary to enable vehicle automation, for which a distinction can be made between aspects inside the vehicle and outside of the vehicle.

Aspects inside the vehicle related to data are: the sensing components to gather data, the computing platform to process the data, and disks to enable storage within the vehicle [14, 21, 23]. Both the computing platform and the sensing components, are widely discussed aspects in current studies related to their power consumption. The studies of Gawron et al. [14] and Kemp et al. [21] execute a life-cycle assessment (LCA) of SAE level 4 sensing and computing subsystems integrated into internal combustion engine vehicle (ICEV) and battery electric vehicle (BEV) platforms. From the study of Kemp et al. [21], it is concluded that a low carbon intensity grid (CO_2 emission in kg/kWh) results in a decrease in life-cycle greenhouse-gas (GHG) emissions, and high computing power in an increase in GHG emissions. According to Gawron et al. [14], these two subsystems could increase the GHG emissions by 3-20%, resulting from increases in power consumption, drag, weight, and data transmission. Taiebat et al. [37] mentions communication and data processing requires significant computational resources and large-scale infrastructure. However, the amount of data generated by both the computing platform and sensing components, and their relation to the amount of additional CO_2 emission, is hardly covered in current studies. Various online articles expect high amounts of data related to vehicle automation [5, 6]. The generated data will either be stored within the vehicle, or transmitted outside the vehicle to enable data storage and high-definition (HD) maps [13, 24]. HD maps are road-maps with high accuracy and environmental fidelity, that contain information about infrastructure and other vehicles on the road. According to Gawron et al. [14], the wireless data transmission for HD maps is a significant contributor to life-cycle burdens. In contrast to the studies of Gawron et al. [14] and Kemp et al. [21], in this study the power consumption of data centers, data transmission and data storage at data centers is incorporated. Moreover, the reuse of data is incorporated and is assumed to be due to HD map generation, for which data is sent back to the vehicle from the data center [13].

Data related aspects outside of the vehicle are wireless communication networks and data centers to enable data storage and HD map generation [13, 24]. The wireless communication networks enable data transmission from the automated vehicle (AV) to a data center, and from a data center back to the AV. The amount of data transmitted has a high range of values due to uncertainty of the exact value. The other element is the data center, which is a high energy-consuming infrastructure [11]. Different studies evaluate the energy consumption of data centers [11, 34]. However, the energy consumption and corresponding CO_2 emission of a data center have not been related to the energy consumption of automated vehicles yet. All these aspects discussed might significantly contribute to CO_2 emission resulting from vehicle automation.

In this study, a single moving vehicle in its operational phase is considered, that is always connected while driving. In contrast to existing studies, no LCA is executed, but both the instantaneous and spatial CO_2 emission rates are determined for varying scenarios. The instantaneous CO_2 emission rate is defined as CO_2 emission per unit time (kg CO_2-e/h), and the spatial CO_2 emission rate is defined as CO_2 emission per kilometer travelled (kg CO_2-e/km). The instantaneous CO_2 emission rate is independent of travel speed, and is used to evaluate which data related aspects have the strongest influence on the resulting CO_2 emission. The spatial CO_2 emission rate is dependent on travel speed, and is used to evaluate whether future CO_2 norms for vehicles can be met for varying scenarios.

The future CO_2 norms of vehicles are based on the propulsion of vehicles, the CO_2 emission from data related aspects is not included in these norms [8, 17]. These norms correspond to CO_2 emission targets for light-duty vehicles in the European Union for 2025 and 2030, and are based on the Worldwide harmonized Light-Duty Test Procedure (WLTP). The WLTP driving cycle is used compared to the NEDC driving cycle, as the WLTP driving cycle is a more accurate testing method according to UNECE [41]. It better simulates real driving conditions, with more modern and realistic driving scenarios [41]. According to ICCT [18], the new car CO_2 emission has to be reduced by 15% by 2025 and by 37.5% by 2030 with respect to the 2021 baseline. The 2021 baseline refers to a CO_2 emission of 0.109 kg/km [17]. This translates into a CO_2 norm of 0.09 kg CO_2-e/km for 2025, and 0.069 kg CO_2-e/km for 2030 [17]. The norms are based on European fleet-wide targets for light-duty vehicles [8]. In this study no fleet is considered, but a single moving AV in its operational phase. However, these two norms are used as benchmark to compare to the data related spatial CO_2 emission, and evaluate how these propulsion-based norms relate to the CO_2 emission of data related aspects for varying scenarios. The scenarios for which the model is applied and evaluated are based on varying sensing compositions and energy grids. The sensing compositions correspond to a Tesla Model S (SAE level 2) and a Waymo's Chrysler Pacifica (SAE level 4) [14, 21]. The energy grid is based on the 2019 Climate Act targets for 2030 and 2050 to reduce CO_2 emission.

This study is a contribution to the expectations that computing power consumption, data processing and transmission significantly influence the CO_2 emission of vehicles, by investigating the CO_2 emission of the data related aspects for varying scenarios. The varying scenarios contribute to the expectation that a low carbon intensity grid results in a decrease in GHG emissions.

The main- and sub-research questions are presented below. In section 2, the research methods used to answer these sub-research questions are defined. Section 3, answers all 6 sub-research questions corresponding to its sub-sections respectively. In section 4, the results are discussed to answer the main research question. The influence of the data related aspects on the resulting instantaneous CO_2 emission rates is discussed in section 4.1. In section 4.2, the resulting spatial CO_2 emission rates are given for the varying scenarios, and compared to the CO_2 norms of vehicles for 2025 and 2030. A short overview of the main assumptions is given in section 3.7, a more detailed overview of the assumptions is given in Appendix A.

Can future CO_2 emission norms for vehicles be met, when investigating the spatial CO_2 emission rate from data related vehicle automation aspects for varying scenarios?

1. What are the components corresponding to the data related aspects of vehicle automation to determine the instantaneous CO_2 emission rate?
2. How is the instantaneous CO_2 emission rate of the data related aspects of vehicle automation determined?
3. What are the varying scenarios, for which the instantaneous and spatial CO_2 emission rates are determined?
4. What are the values corresponding to all components of the data related aspects for the varying scenarios?
5. How is the influence of data related aspects on the resulting instantaneous CO_2 emission for the varying scenarios evaluated?
6. How is the spatial CO_2 emission rate of the data related aspects of vehicle automation determined for the varying scenarios?

2 Research methods

In this section the different research methods used to answer the research questions, are discussed. In section 1, the main- and sub-research questions are defined. The sub-research questions are used to answer the main research question. Below, the research methods corresponding to the six different sub-research questions are discussed.

The first sub-research question is mainly answered using knowledge from existing literature. To obtain the instantaneous CO_2 emission rate, a computational model is developed containing different components. Literature is used to obtain a conceptual model of determining the power consumption of the different data related aspects. Each data related aspect includes different components to determine its power consumption. By combining the power consumption of the data related aspects in Watt with the CO_2 emission rate corresponding to the energy grid in kg CO_2-e/Wh, the resulting instantaneous CO_2 emission rate can be determined.

As already mentioned, to obtain the instantaneous CO_2 emission rate, a computational model is developed. This model measures the CO_2 emission costs of the data related aspects for a single moving AV in its operational phase per unit time in kg CO_2-e/h. It is an empirical model that is based on observed relations between independent and dependent variables. The model is applied in Matlab-Simulink to be able to simulate the model for a large number of values, corresponding to the different components. Moreover, this enables the introduction of dependent variables, and evaluation of the influence of variables on the end results. Variables related to the amount of data are defined in GB/h, and are assumed to be independent on the travel speed.

The third sub-research question is answered by scenario analysis, to define the different scenarios. This is the process of evaluating possible future events through the consideration of alternative plausible, though, not equally likely, states of the world [30]. The scenarios differ based on varying energy grids, and varying sensing compositions. The two different sensing compositions are based on sensing compositions used in the studies of Gawron et al. [14] and Kemp et al. [21], corresponding to a Tesla Model S (SAE level 2) and Waymo's Chrysler Pacifica (SAE level 4) respectively. One of the differences between Tesla and Waymo, is that Tesla is initially more focused on lower SAE levels of automation and non-shared automation, whereas Waymo is focused on higher SAE levels of automation and shared automation. Based on plausible future scenarios for the composition of the Dutch energy grid, different scenarios are sketched for the CO_2 emission rates (`E`) in kg CO_2-e/Wh. These CO_2 emission rates are based on the Dutch energy mix and differ based on the amount of renewable or non-renewable energy represented. Renewable energy seems to be a possible solution to reduce the carbon footprint of vehicle automation and data centers. A distinction is made between the base case, the case for 2030 and the case for 2050. These different cases correspond to the Dutch energy grid of 2018, and the 2019 Climate Act targets for 2030 and 2050 to reduce CO_2 emission.

The fourth sub-research question is about defining the values of the components corresponding to the data related aspects for each scenario. A distinction is made between aspects with fixed values, referred to as fixed components, and aspects with a range of values, referred to as variable components. The variable components have a range of values due to uncertainty of the exact value. The values of the fixed components are based on current literature. The range of values corresponding to the variable components are partly based on literature, and partly on results from the survey. A survey is obtained to get more insights about the energy consumption of data related aspects from the industry and university research departments. The survey questions and answers can be found in Appendix D. In total 19 different original equipment manufacturers (OEM's) were contacted to fill in the survey, five different suppliers, and four different research departments. The survey is conducted on an anonymous basis, because it might ask for business sensitive information. The results from the survey are used to obtain a more accurate range of values corresponding to the variable components.

The fifth sub-research question is answered by sensitivity analysis. Sensitivity analysis is used to evaluate which variable data related aspects have the strongest influence in each scenario. Sensitivity analysis is defined as the way uncertainty of the output of the model can be apportioned to different source of uncertainty in the model input factors [44]. This way insights are given with respect to the significance of aspects, such as data transmission and storage, on the overall instantaneous CO_2 emission rate resulting from data related aspects.

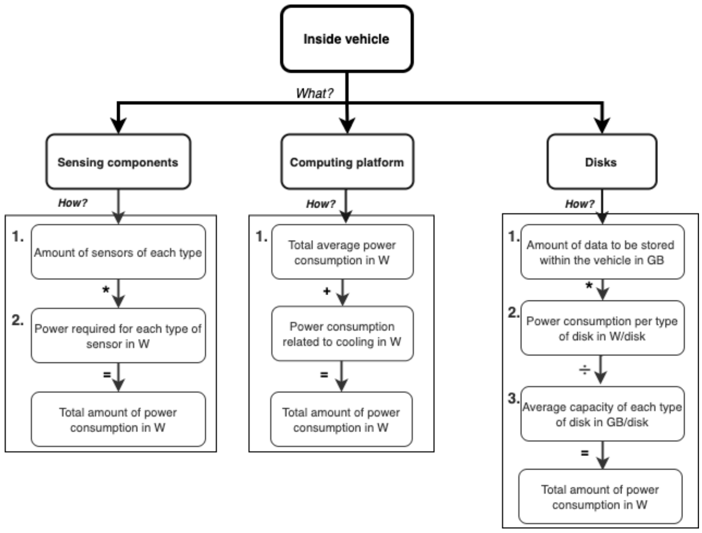
The sixth sub-research question is answered by translating the instantaneous CO_2 emission rates resulting from the computational model to the WLTP driving cycle. Based on the results of the instantaneous CO_2 emission rates, three different situations are defined for each scenario. These three different situations correspond to the combination of values that result in the highest, lowest and median instantaneous CO_2 emission rate. The spatial CO_2 emission rate is investigated for the three situations of each scenario, translated to the WLTP driving cycle. This way, it can be evaluated for which situations and scenarios the defined CO_2 norms of vehicles can be met.

3 Computational model and scenario design

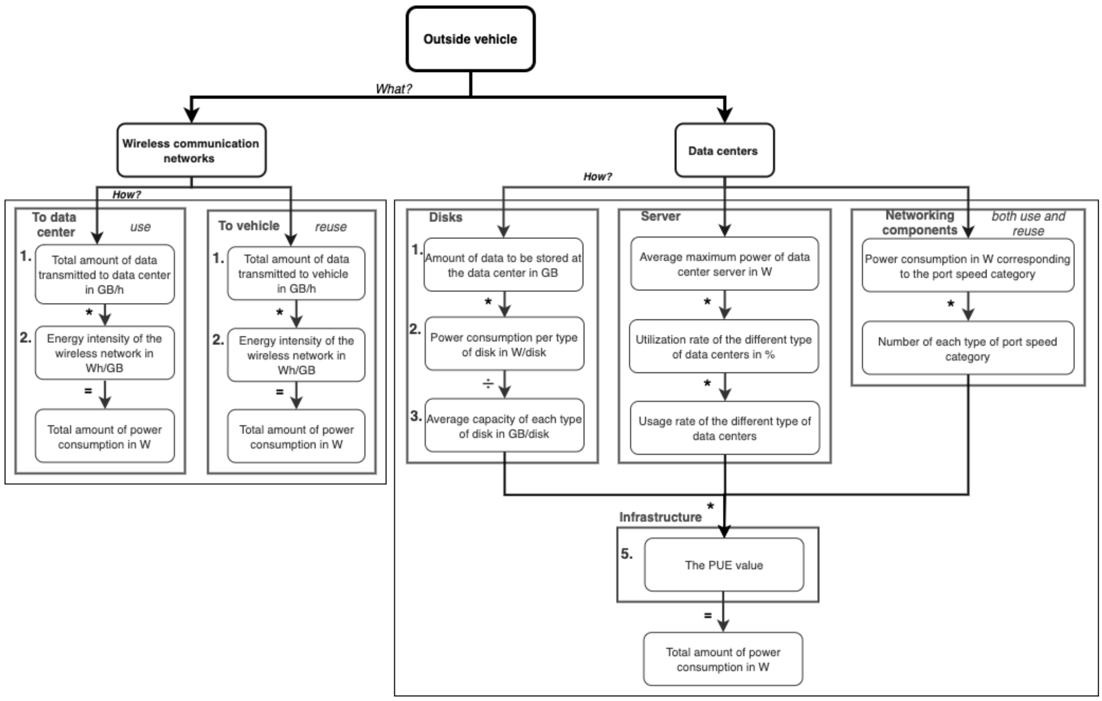
3.1 Conceptual structure of the model

In this section, the conceptual structure of the model and the main components are discussed. As already mentioned in section 1, the data related aspects are divided into aspects inside and outside the vehicle. A conceptual structure of determining the power consumption of both type of aspects, is given in figure 1. By combining the power consumption of the data related aspects with the CO_2 emission rates (E) in kg CO_2-e/Wh, the resulting instantaneous CO_2 emission rate in kg CO_2-e/h can be determined.

In table 1, an overview of the components used in the computational model is given, with corresponding possible values. A distinction is made between fixed components and variable components. The fixed components have a fixed value, and the variable components have a range of values. The conceptual structure, components and corresponding values are all based on literature and the survey. In section 3.2, a more elaborate evaluation of the varying components corresponding to the equations is given. In section 3.3, a more elaborate evaluation of the values corresponding to the components is given for different scenarios.



(a) Conceptual structure of data related aspects inside the vehicle



(b) Conceptual structure of data related aspects outside the vehicle

Figure 1: Conceptual structure of the model to determine the power consumption of the data related aspects

	Abb.:	Components:	Values	Source
Fixed:				
Sensing - amount:	n_C	Number of camera sensors	1-9	[14]
	n_R	Number of radar sensors	1-4	[14]
	n_X	Number of sonar sensors	0-12	[14]
	n_M	Number of small lidar sensors	0-4	[14]
	n_L	Number of large lidar sensors	0-1	[14]
	n_G	Number of GPS/GNSS sensors	1	[14]
Sensing - power:	P_C	Average power of a single camera sensor: Point Grey Dragonfly 2 [W]	2.1	[14]
	P_R	Average power of a single radar sensor: Bosch LRR3 [W]	4	[14]
	P_X	Average power of a single sonar sensor: Bosch Ultrasonic [W]	0.13	[14]
	P_M	Average power of a single small lidar sensor: Velodyne VLP-16 [W]	8	[14]
	P_L	Average power of a single large lidar sensor: Velodyne HDL-64E [W]	60	[14]
	P_G	Average power of a single GPS/GNSS sensor: NovAtel PwrPak7-E1 [W]	2	[14]
Computing platform:	m	Cooling rate to dissipate heat from computing platform [%]	77	[22]
Disks:	$A_{H,DC}$	Average capacity of HDD for data center [GB/disk]	10,000	[34]
	$A_{S,DC}$	Average capacity of SSD for data center [GB/disk]	5,000	[34]
	$A_{H,v}$	Average capacity of HDD inside vehicle [GB/disk]	1,000	[42]
	$A_{S,v}$	Average capacity of SSD inside vehicle [GB/disk]	250	[42]
	Z_H	Average power of HDD [W/disk]	6.5	[34]
	Z_S	Average power of SSD [W/disk]	6	[34]
Data center - server:	P_e	Average power of a 1S socket data center server [W]	118	[34]
	P_f	Average power of a 2S+ socket data center server [W]	365	[34]
	u_i	Average utilization rate of a server - internal data center [%]	15	[34]
	u_p	Average utilization rate of a server - service provider data center [%]	25	[34]
	u_h	Average utilization rate of a server - hyperscale data center [%]	50	[34]
	n_f	Number of 2S+ socket data center servers [-]	0-5	-
	n_e	Number of 1S socket data center servers [-]	0-5	-
	r_i	Usage rate of internal data centers [-]	0/1	-
	r_p	Usage rate of service provider data centers [-]	0/1	-
	r_h	Usage rate of hyperscale data centers [-]	0/1	-
Data center - networking component:	P_{p1}	Average power of speed port category: 100 MB [W]	0.6	[34, 35]
	P_{p2}	Average power of speed port category: 1000 MB [W]	1.0	[34, 35]
	P_{p3}	Average power of speed port category: 10 GB [W]	1.6	[34, 35]
	P_{p4}	Average power of speed port category: 40 GB [W]	2.7	[34, 35]
	J_{p1}	Port speed rate of category: 100 MB [GB/h]	360	[34]
	J_{p2}	Port speed rate of category: 1000 MB [GB/h]	3,600	[34]
	J_{p3}	Port speed rate of category: 10 GB [GB/h]	36,000	[34]
	J_{p4}	Port speed rate of category: 40 GB [GB/h]	144,000	[34]
	$r_{p1,DC}$	Number of speed ports for category: 100 MB, from vehicle to data center [-]	0/1	-
	$r_{p2,DC}$	Number of speed ports for category: 1000 MB, from vehicle to data center [-]	0/1	-
	$r_{p3,DC}$	Number of speed ports for category: 10 GB, from vehicle to data center [-]	0/1	-
	$r_{p4,DC}$	Number of speed ports for category: 40 GB, from vehicle to data center [-]	0/1	-
	$r_{p1,v}$	Number of speed ports for category: 100 MB, from data center to vehicle [-]	0/1	-
	$r_{p2,v}$	Number of speed ports for category: 1000 MB, from data center to vehicle [-]	0/1	-
	$r_{p3,v}$	Number of speed ports for category: 10 GB, from data center to vehicle [-]	0/1	-
	$r_{p4,v}$	Number of speed ports for category: 40 GB, from data center to vehicle [-]	0/1	-
Data center - infrastructure:	Q	Power usage effectiveness (PUE) [-]	1.51	[34, 35]
Energy grid variables:	E_a	CO_2 emission rate for the base case [kg CO_2-e/Wh]	0.00043	[19]
	E_b	CO_2 emission rate for the 2030 case [kg CO_2-e/Wh]	0.000258	[19]
	E_c	CO_2 emission rate for the 2050 case [kg CO_2-e/Wh]	0.0000253	[19]
Variable:				
Computing platform:	P_o	Average power consumption of the computing platform [W]	200-2,124	[14, 21, 23]
Storage inside vehicle:	O_v	Amount of data stored inside the vehicle [GB]	73-4,348	[14, 21, 29]
Wireless communication networks:	Y_{DC}	Data transmission rate from vehicle to the data center [GB/h]	21.9-2,174	[14, 21, 29]
	Y_v	Data transmission rate from the data center to the vehicle [GB/h]	0.00024-0.56	[13]
	I_w	Energy intensity of wireless network [Wh/GB]	4-100	[3, 33]
Data center - disks:	O_{DC}	Amount of data stored at the data center [GB]	21.9-2,174	[14, 21, 29]

Table 1: General overview of the data related aspects and possible corresponding values

3.2 Model specification of the instantaneous data related CO_2 emission rate

The computational model provides the instantaneous CO_2 emission rate of the data related aspects in kg CO_2-e/h. First, equations corresponding to the power consumption of the data related aspects are defined. Then, by using the CO_2 emission rates in kg CO_2-e/Wh, the total resulting instantaneous CO_2 emission rates for the data related aspects can be determined. An overview of the resulting computational model in Matlab-Simulink, is given in Appendix B.1.

Equations for the power consumption of the data related aspects

The first step of the computational model refers to the total power consumption of the varying data related aspects in Watt and is based on literature. Below each equation, a short description is given of the literature on which it is based. In the nomenclature, the abbreviations of components used in the equations are given. A general representation of the power consumption of the various aspects is given, such that it can be adjusted to many different situations.

The total power consumption of all aspects both inside and outside of the vehicle, is determined by equation 1.

$$P_{v,tot} = P_{v,in} + P_{v,out} \tag{1}$$

In general, the influence of AV's on the environment is divided into 5 levels of complexity [21, 37]: (1) society level, (2) urban system level, (3) transportation system level, (4) vehicle level, (5) sub-system level. The data related aspects for a single moving AV in operational mode result from urban, vehicle and sub-system level. The data related aspectss from vehicle and sub-system level are referred to as data related aspects inside the vehicle ($P_{v,in}$). To enable data storage and HD map generation for a single moving AV in operational mode, both wireless networking components and data centers from urban system level are incorporated. These aspects are referred to as data related aspects outside of the vehicle ($P_{v,out}$). The data related aspects inside and outside of the vehicle are mainly based on the study of Ulbrich et al. [40], where a functional system architecture of an AV is defined, that is independent of a specific implementation. This architecture entails different aspects; environment and perception, planning and control, localization, map provision, vehicle-to-X (V2X) communication, and interaction with human operators. A more detailed evaluation of the specific aspects inside and outside the vehicle, is given in the validation corresponding to equations 2 and 6.

Nomenclature

A	Average capacity	$GB/disk$
B	CO_2 emission per km	kg CO_2-e/km
C	Travel speed	km/h
E	CO_2 emission rate	$kg\ CO_2\text{-}e/Wh$
I	Energy intensity	Wh/GB
J	Port speed rate	GB/h
K	CO_2 emission per hour	$kg\ CO_2\text{-}e/h$
O	Amount of data stored	GB
P	Average power	W
Q	Power usage effectiveness	−
Y	Data transmission rate	GB/h
Z	Average power	$W/disk$
m	Cooling rate to dissipate heat	%
n	Number	−
r	Usage rate (0 or 1)	−
u	Average utilization rate	%

Subscripts

a	The base case
b	The case for 2030
c	The case for 2050
e	1S socket data center server
d	Disks
f	2S+ socket data center server
h	Hyperscale data center
i	Internal data center
o	Computing platform
p	Service provider data center
u	Utilization rate
v	Vehicle
w	Wireless communication network
C	Camera sensors
G	GPS sensors
H	Hard Disk Drive (HDD)
L	Large lidar sensors
M	Small lidar sensors
R	Radar sensors
S	Solid State Drive (SSD)
X	Sonar sensors
DC	Data center
$p1$	Port speed category: 100 MB
$p2$	Port speed category: 1000 MB
$p3$	Port speed category: 10 GB
$p4$	Port speed category: 40 GB
in	Inside
out	Outside
sen	Sensing components
ser	Server
tot	Total

Data related aspects inside the vehicle

`Inside vehicle - Total power consumption`

The total power consumption of the aspects inside the vehicle results from equation 2. This is a summation of the power consumption of the computing platform ($P_{v,o}$), the sensing components ($P_{v,sen}$) and the disks inside the vehicle ($P_{v,d}$).

$$P_{v,in} = P_{v,o} + P_{v,sen} + P_{v,d} \tag{2}$$

The studies of Gawron et al. [14], Kemp et al. [21], Liu et al. [23] and Baxter et al. [4], include sensing components and the computing platform in their vehicle automation system architecture. The sensing components and computing platform enable perception and mobility (planning and control, localization and map provision) of an AV, which are aspects of the functional system architecture according to Ulbrich et al. [40]. However, mobility of an AV is not only supported by sensing components and the computing platform, but also by aspects outside of the vehicle. Considering the aspects inside the vehicle, the study of Wang et al. [42] mentions the quickly growing amount of data to be stored, for which SSD's and HDD's are used inside the vehicle. Therefore, the total amount of power consumption resulting from the data related aspects inside the vehicle is considered to be a summation of the power consumption of the computing platform ($P_{v,o}$), the sensing components ($P_{v,sen}$) and the disks ($P_{v,d}$).

`Inside vehicle - Computing platform`

The first component of the data related aspects inside the vehicle is the computing platform. The total power consumption of the computing platform ($P_{v,o}$), can be determined by summing the power consumption of the computing platform (P_o) with the power consumption related to cooling. The latter is represented by the cooling rate (`m`) in order to dissipate the heat generated by the computing platform.

$$P_{v,o} = (1 + m) \cdot P_o \tag{3}$$

The computing platform and its influence on the energy consumption of AV's is evaluated by multiple studies [14, 21, 23]. These studies all mention the large range of values corresponding to the power consumption of the computing platform, which from all studies combined results to be between 200 and 6,000 Watt. In order to remove additional heat generated by the computing platform, the cooling rate to dissipate heat (m) should be incorporated according to Lin et al. [22]. A typical automotive air-conditioning system has a cooling rate of approximately 77% to dissipate heat [22].

`Inside vehicle - Sensing components`

The power consumption of the sensing components is determined by multiplying the number of each type of sensing component by the power consumption in Watt of the corresponding sensing component. A representation of the total power consumption of the sensing components is given in equation 4.

$$P_{v,sen} = (n_C \cdot P_C) + (n_R \cdot P_R) + (n_X \cdot P_X) + (n_M \cdot P_M) + (n_L \cdot P_L) + (n_G \cdot P_G) \tag{4}$$

Both the studies of Kemp et al. [21] and Gawron et al. [14], relate the power consumption of sensing components to the environmental effects of vehicle automation. Baxter et al. [4] also mentions the power consumption of sensing components. All studies determine the total power consumption, by multiplying the number of each type of sensing component by its corresponding power consumption. However, the studies use different sensing compositions. To ensure flexibility of the model, in equation 4, the power consumption of each single type of sensing component is incorporated. These type of sensing components incorporated, can be customized by defining the number of each type of sensing component used. In contrast to the study of Gawron et al. [14], in this study no DSRC sensor is considered. This is because over the years DSRC is been replaced by wireless communication networks [16], and 4G-LTE wireless communication is more preferred for traffic information, file download, or Internet accessing according to Xu et al. [43].

`Inside vehicle - Disks`

The power consumption of the disks inside the vehicle is determined by equation 5. The power consumption of the disks ($P_{v,d}$) can be determined by dividing the power consumption of both SSD (Z_S) and HDD (Z_H) in W/disk, by the capacity of SSD ($A_{S,v}$) and HDD ($A_{H,v}$) in GB/disk. By multiplying the power consumption in W/GB with the amount of data to be stored (O_v), the corresponding power consumption in Watt can be determined.

$$P_{v,d} = \frac{O_v \cdot (Z_H + Z_S)}{(A_{S,v} + A_{H,v})} \tag{5}$$

Disks inside the vehicle are necessary to ensure data storage within the vehicle [42]. The hard real-time processing applications, such as collision avoidance, are enabled by the computing platform [23, 42]. For soft real-time processing applications (such as map generation) and non time-critical applications, SSD's and HDD's are used respectively and can serve for permanent storage [42]. For long-time storage and HD map generation, the data processed by the vehicle is sent to the data center [13].

According to the study of Wang et al. [42], the capacity for both SSD's ($A_{S,v}$) and HDD's ($A_{H,v}$) inside vehicles are defined in GB/disk. According to the study of Shehabi et al. [34], the power consumption corresponding to SSD's (Z_S) and HDD's (Z_H) are defined in W/disk. Combining the two gives the power consumption per gigabyte in W/GB. By multiplying this by the amount of data to be stored (O_v) in GB, the resulting power consumption for the disks ($P_{v,d}$) can be determined.

Data related aspects outside the vehicle

`Outside vehicle - Total power consumption`

The equation corresponding to the aspects outside of the vehicle is given in equation 6. This equation is a summation of the power consumption of the wireless networking components (P_w) and the power consumption of the data center (P_{DC}).

$$P_{v,out} = P_w + P_{DC} \tag{6}$$

According to Ulbrich et al. [40], the aspects outside of the vehicle correspond to the connectivity aspects as part of the functional system architecture of an AV. Different studies mention the aspect of data centers and wireless communication networks in the functional system architecture of an AV to enable data storage [14, 23, 24, 37]. Moreover, these components correspond to the mobility of an AV by for example HD map generation, for which wireless communication networks and data centers are used to accumulate data from other vehicles [13, 24].

`Outside vehicle - Wireless networking components`

The power consumption of the wireless networking components, is determined by equation 7. For the power consumption of the wireless networking components, a distinction is made between the data transmission rate from the vehicle to the data center to enable data storage (Y_{DC}), and the data transmission rate from the data center to the vehicle to provide the vehicle with HD map information (Y_v). By multiplying the data transmission rate in GB/h by the network intensity (I_w) in Wh/GB, the power consumption in Watt is determined.

$$P_w = (Y_{DC} + Y_v) \cdot I_w \tag{7}$$

As already denoted in the validation of equation 6, mainly data transmission from the vehicle to the data center (Y_{DC}) to enable data storage, and data transmission from the data center to the vehicle (Y_v) to enable HD map generation, is considered. This is supported by the studies of Liu et al. [24] and Edwertz [13]. The amount of data generated and transmitted, is by various studies expressed in the amount of gigabyte corresponding to certain hours of driving [29, 31, 39]. Therefore, both the data transmission from vehicle to data center (Y_v) and the data transmission from data center to vehicle (Y_{DC}), are defined in GB/h. The energy intensity (I_w) is defined in Wh/GB, according to different studies [2, 3, 14, 21, 33].

`Outside vehicle - Data center`

Data center - Total power consumption

The second data related aspect outside of the vehicle is the data center. The total power consumption of a data center is based on the power consumption of: disks ($P_{DC,d}$), a server ($P_{DC,ser}$), and networking components ($P_{DC,w}$). The overall power consumption related to data centers can be determined by summing the power consumption of all separate aspects and multiplying this with the PUE value (`Q`). The corresponding equation is given by 8.

$$P_{DC} = (P_{DC,d} + P_{DC,ser} + P_{DC,w}) \cdot Q \tag{8}$$

Data centers contain multiple items; networking devices, storage, groups of servers, cooling systems, and power distribution units [11, 34]. Both the study of Dayarathna et al. [11] and Shehabi et al. [34] mention a distinction between data center IT equipment and the infrastructure.

The infrastructure of a data center refers to cooling and power conditioning systems [11, 34]. The infrastructural aspects are included in the energy consumption of a data center using the Power Usage Effectiveness (PUE) value [34]. This is the ratio between the power drawn by the infrastructure components and the power delivered to the servers, disks and networking devices. The power consumption of the IT equipment refers to the power consumption of servers ($P_{DC,ser}$) for data processing, disks for data storage ($P_{DC,d}$), and networking devices ($P_{DC,w}$) to ensure input/output of data [11, 34]. Therefore, the total power consumption of a data center is defined as a summation of the power consumption of the IT equipment, multiplied by the PUE value. To evaluate what the influence of a data center is on the energy consumption of a single AV in operational mode, the IT equipment components of a data center are related to the energy consumption of a single AV in the equations below.

Data center - Disks

The power consumption related to disks to enable storage is determined the same way as the energy consumption of the disks within the vehicle (equation 5). The capacity (`A`) for both the SSD and HDD disks differ for data centers compared to the disks within the vehicle.

$$P_{DC,d} = \frac{O_{DC} \cdot (Z_H + Z_S)}{(A_{H,DC} + A_{S,DC})} \tag{9}$$

The disks ensure storage of data at a data center. According to Shehabi et al. [34], two types of disks are used to ensure long-time storage at a data center; SSD's and HDD's. Same as explained in the validation of equation 5, both types of disks have a certain capacity ($A_{S,DC}$, $A_{H,DC}$), defined in GB/disk and power consumption (Z_S, Z_H), defined in W/disk [34, 42]. By multiplying the power in W/GB by the amount of data to be stored (O_{DC}) in GB, the resulting power consumption ($P_{DC,d}$) can be determined.

Data center - Server:

The power consumption related to the server of a data center is represented by equation 10. There is a distinction between a one processor socket volume server (1S) and a two or more processor socket volume server (2S+). The number of both type of servers (n_e, n_f) enables to customize the amount of 1S and/or 2S+ servers. The number of each type of server used, depends on the data transmission rate (Y_{DC}) and the bandwidth of the specific server. Utilization rates are used to distinguish different types of data centers: internal data center (u_i), service provider data center (u_p), hyperscale data center (u_h). These utilization rates are fixed variables based on the study of Shehabi et al. [34]. By including the usage rate (being 0 or 1) of all different types of data centers (r_i, r_p, r_h), it can be customized what type of data center is considered.

To determine the power consumption of the server (P_e, P_f), the number of each type of server should be multiplied by the corresponding power consumption. This can then be multiplied by the utilization rate including the usage rates, to obtain the total power consumption corresponding to the server.

$$P_{DC,ser} = (n_e \cdot P_e + n_f \cdot P_f) \cdot (r_i \cdot u_i + r_p \cdot u_p + r_h \cdot u_h) \tag{10}$$

where: $n_e + n_f >= 1$
$r_i + r_p + r_h >= 1$

According to Shehabi et al. [34], the average power usage of servers depends on the maximum power consumption and the utilization rate.

For the maximum power consumption, Shehabi et al. [34] use an average maximum over two types of disks, based on the Server Efficiency Rating Tool (SERT) database; the maximum power of a one processor socket volume server (P_e), and the maximum power of a two or more processor socket volume server (P_f). In order to customize, in equation 10 the number of each type of server (n_e, n_f) is multiplied by the corresponding power consumption. The number of each type of server depends on the specific bandwidth, and the amount of data to be processed by the data center server (Y_{DC}).

The other aspect that influences the power consumption of a server as mentioned by Shehabi et al. [34], is the utilization rate. The average utilization rate represents the per cent of computing ability used on average, and depends on the type of data center. According to Shehabi et al. [34], there are three types of data centers: (1) internal, (2) service provider, (3) hyperscale. Internal data centers is referred to as representing facilities for internal activities operated by an organization, such as financial activities, but are not directly involved with IT services. The service provider data centers are associated with the core product of a business and are used to provide communication services by companies such as Google, Microsoft and Amazon. Hyperscale sized data centers are referred to as warehouse scale data centers and are associated with service provider cloud data centers [34]. The utilization rates of each type of data center (u_i, u_p, u_h) are constants from the study of Shehabi et al. [34]. To customize for the type of data center used, the different type of utilization rates are multiplied by the usage rate of each type of data center (r_i, r_p, r_h), being 0 or 1.

Data center - Networking components

The power consumption of the networking components related to a data center, is represented by equation 11. Depending on the amount of data transmitted (Y_{DC} and Y_v), and the port speed rates (`J`) of each port category, it could be evaluated what the usage rate (r_{p1}, r_{p2}, r_{p3}, r_{p4}) of each port category is. By multiplying this with the corresponding power consumption of each port speed category (P_{p1}, P_{p2}, P_{p3}, P_{p4}), the power consumption related to the networking components of a data center can be determined in Watt.

$$P_{DC,w} = ((r_{p1,DC} + r_{p1,v}) \cdot P_{p1}) + ((r_{p2,DC} + r_{p2,v}) \cdot P_{p2}) + ((r_{p3,DC} + r_{p3,v}) \cdot P_{p3}) + ((r_{p4,DC} + r_{p4,v}) \cdot P_{p4})) \quad (11)$$

where: if $Y_{DC} <= J_{p1}$, then $r_{p1,DC} = 1$, $r_{p2,DC} = 0$, $r_{p3,DC} = 0$, $r_{p4,DC} = 0$
if $J_{p1} < Y_{DC} <= J_{p2}$, then $r_{p1,DC} = 0$, $r_{p2,DC} = 1$, $r_{p3,DC} = 0$, $r_{p4,DC} = 0$
if $J_{p2} < Y_{DC} <= J_{p3}$, then $r_{p1,DC} = 0$, $r_{p2,DC} = 0$, $r_{p3,DC} = 1$, $r_{p4,DC} = 0$
if $J_{p3} < Y_{DC} <= J_{p4}$, then $r_{p1,DC} = 0$, $r_{p2,DC} = 0$, $r_{p3,DC} = 0$, $r_{p4,DC} = 1$

where: if $Y_v <= J_{p1}$, then $r_{p1,v} = 1$, $r_{p2,v} = 0$, $r_{p3,v} = 0$, $r_{p4,v} = 0$
if $J_{p1} < Y_v <= J_{p2}$, then $r_{p1,v} = 0$, $r_{p2,v} = 1$, $r_{p3,v} = 0$, $r_{p4,v} = 0$
if $J_{p2} < Y_v <= J_{p3}$, then $r_{p,1v} = 0$, $r_{p2,v} = 0$, $r_{p3,v} = 1$, $r_{p4,v} = 0$
if $J_{p3} < Y_v <= J_{p4}$, then $r_{p1,v} = 0$, $r_{p2,v} = 0$, $r_{p3,v} = 0$, $r_{p4,v} = 1$

According to Shehabi et al. [34], the networking devices can be divided into four port speed categories; 100 MB, 1000 MB, 10 GB and 40 GB. All these different port speed categories have different power consumption defined in W/port [34]. Therefore, by multiplying the amount of ports of each category (r_{p1}, r_{p2}, r_{p3}, r_{p4}), by the power consumption of the specific port (P_{p1}, P_{p2}, P_{p3}, P_{p4}), the resulting power consumption of the networking components can be determined.

To relate the number of ports of each category to a single moving AV in operational mode, the data transmission rate in GB/h should be evaluated. So, the number of ports of each category is determined depending on the data transmission rate from the vehicle to the data center (Y_{DC}), and the data transmission rate from data center to the vehicle (Y_v). If the data transmission rate is within the port speed of a specific category (J_{p1}, J_{p2}, J_{p3}, J_{p4}), the corresponding number of that port speed category will become 1. For the usage rates of ports of each category, a distinction is made between data entering the data center from the vehicle ($r_{p1,DC}$, $r_{p2,DC}$, $r_{p3,DC}$, $r_{p4,DC}$), and data leaving the data center to the vehicle ($r_{p1,v}$, $r_{p2,v}$, $r_{p3,v}$, $r_{p4,v}$). As the largest port category (J_{p4}) can process 144 TB/h, and this exceeds the maximum considered amount of data to be transmitted, the maximum number of ports of each category is considered to be one.

Equation for the total instantaneous CO_2 emission rate of all data related aspects

The last step of the computational model is to determine the total instantaneous CO_2 emission rate of all data related aspects combined, defined by equation 12. To obtain this, the total power consumption in Watt for all aspects should be multiplied with the CO_2 emission rate in kg CO_2-e/Wh, corresponding to the different scenarios (E_a, E_b, E_c). In section 3.3, a more elaborate evaluation of the different CO_2 emission rates (E) corresponding to the energy grid is given.

$$K = P_{v,tot} \cdot E_{a/b/c} \quad (12)$$

3.3 Scenario design

In this section, the different scenarios are defined, for which the model is evaluated. As already explained in section 2, the scenarios differ based on two different sensing compositions and three different energy grids. Overall, this results in a total of six different scenarios: (1) base case composition 1, (2) case 2030 composition 1, (3) case 2050 composition 1, (4) base case composition 2, (5) case 2030 composition 2, (6) case 2050 composition 2.

Sensing composition 1 is related to a Tesla Model S (SAE level 2), and composition 2 is related to a Waymo's Chrysler Pacifica (SAE level 4) [14, 21]. One of the differences between Tesla and Waymo, is that Tesla is initially more focused on lower SAE levels of automation and non-shared automation, whereas Waymo is focused on higher SAE levels of automation and shared automation.

The base case is based on the Dutch energy grid of 2018. The total primary energy supply (TPES) consists for 90% out of non-renewable energy sources; 42% natural gas, 37% of oil, 11% of coal [19]. The rest of the 10% consists for 5% out of bio-fuels and waste, the other small share consists of solar, wind and other sources. This primary energy is converted to electricity, for which the efficiency of primary energy to electricity is 41% according to Kasliwal et al. [20]. According to CBS [7], the total CO_2 emission rate of the the electricity grid in 2018 (E_a) is 0.43 kg CO_2-e/kWh.

The case for 2030, is the desired scenario according to IEA [19]. IEA [19] states that the primary focus of the Dutch energy policy is obtaining a lower carbon energy system. The 2019 Climate Act sets targets to reduce CO_2 emission with 49% by 2030 compared to 1990 levels, and with 95% by 2050. Compared to 1990 levels, the GHG emissions were down with 15% in 2018 [19]. So, using 0.43 kg CO_2-e/kWh for 2018, the 1990 level has been 0.5059 kg CO_2-e/kWh. Including the 49% reduction for 2030, this results in 0.258 kg CO_2-e/kWh. In 2050, an even higher reduction of 95% of CO_2 emission with respect to 1990 is desired. The total CO_2 emission rate for the electricity grid of 2050 (E_c) is therefore decreased to 0.0253 kg CO_2-e/kWh. In table 2 below an overview of the CO_2 emission rates corresponding to the different scenarios is shown.

	Variable CO_2 emission rates:	**Values**
E_a	CO_2 emission rate for *the base case* [kg CO_2-e/kWh]	0.43
E_b	CO_2 emission rate for *the case for 2030* [kg CO_2-e/kWh]	0.258
E_c	CO_2 emission rate for *the case for 2050* [kg CO_2-e/kWh]	0.0253

Table 2: Overview of the energy grid CO_2 emission rates for the different scenarios [19]

An overview of all components and the corresponding values incorporated in these different scenarios, is given in table 3. A distinction is made between components that contain fixed values, and components that have variable values within a certain range. The values corresponding to the components in table 3 are based on literature and insights from the survey of Appendix D. In section 3.4, a more extensive description of the choice of component values is given based on literature and the survey.

	Scenarios:	**1.Base case composition 1**	**2.Case 2030 composition 1**	**3.Case 2050 composition 1**	**4.Base case composition 2**	**5.Case 2030 composition 2**	**6.Case 2050 composition 2**
Fixed:							
Sensing - amount:	n_C	8	8	8	9	9	9
	n_R	1	1	1	4	4	4
	n_X	12	12	12	0	0	0
	n_M	0	0	0	4	4	4
	n_L	0	0	0	1	1	1
	n_G	1	1	1	1	1	1
Sensing - power:	P_C	2.1	2.1	2.1	2.1	2.1	2.1
	P_R	4	4	4	4	4	4
	P_X	0.13	0.13	0.13	0.13	0.13	0.13
	P_M	8	8	8	8	8	8
	P_L	60	60	60	60	60	60
	P_G	2	2	2	2	2	2
Computing platform:	m	0.77	0.77	0.77	0.77	0.77	0.77
Disks:	$A_{H,DC}$	10,000	10,000	10,000	10,000	10,000	10,000
	$A_{S,DC}$	5,000	5,000	5,000	5,000	5,000	5,000
	$A_{H,v}$	1,000	1,000	1,000	1,000	1,000	1,000
	$A_{S,v}$	250	250	250	250	250	250
	Z_H	6.5	6.5	6.5	6.5	6.5	6.5
	Z_S	6	6	6	6	6	6
Data center - server:	P_e	118	118	118	118	118	118
	P_f	365	365	365	365	365	365
	u_i	0.15	0.15	0.15	0.15	0.15	0.15
	u_p	0.25	0.25	0.25	0.25	0.25	0.25
	u_h	0.50	0.50	0.50	0.50	0.50	0.50
	n_f	0	0	0	0	0	0
	n_e	1	1	1	1	1	1
	r_i	0	0	0	0	0	0
	r_p	0	0	0	0	0	0
	r_h	1	1	1	1	1	1
Data center - networking component:	P_{p1}	0.6	0.6	0.6	0.6	0.6	0.6
	P_{p2}	1.0	1.0	1.0	1.0	1.0	1.0
	P_{p3}	1.6	1.6	1.6	1.6	1.6	1.6
	P_{p4}	2.7	2.7	2.7	2.7	2.7	2.7
	J_{p1}	360	360	360	360	360	360
	J_{p2}	3,600	3,600	3,600	3,600	3,600	3,600
	J_{p3}	36,000	36,000	36,000	36,000	36,000	36,000
	J_{p4}	144,000	144,000	144,000	144,000	144,000	144,000
	$r_{p1,DC}$	0/1	0/1	0/1	0/1	0/1	0/1
	$r_{p2,DC}$	0/1	0/1	0/1	0/1	0/1	0/1
	$r_{p3,DC}$	0/1	0/1	0/1	0/1	0/1	0/1
	$r_{p4,DC}$	0/1	0/1	0/1	0/1	0/1	0/1
	$r_{p1,v}$	0/1	0/1	0/1	0/1	0/1	0/1
	$r_{p2,v}$	0/1	0/1	0/1	0/1	0/1	0/1
	$r_{p3,v}$	0/1	0/1	0/1	0/1	0/1	0/1
	$r_{p4,v}$	0/1	0/1	0/1	0/1	0/1	0/1
Data center - infrastructure:	Q	1.51	1.51	1.51	1.51	1.51	1.51
Energy grid variables:	E_a	0.00043	0	0	0.00043	0	0
	E_b	0	0.000258	0	0	0.000258	0
	E_c	0	0	0.0000253	0	0	0.0000253
Variable:							
Computing platform:	P_o	200-2,124	200-2,124	200-2,124	200-2,124	200-2,124	200-2,124
Storage within vehicle:	O_v	73-4,222	73-4,222	73-4,222	118-4,348	118-4,348	118-4,348
Wireless communication networks:	Y_{DC}	21.9-2,111	21.9-2,111	21.9-2,111	35.4-2,174	35.4-2,174	35.4-2,174
	Y_v	0.00024-0.56	0.00024-0.56	0.00024-0.56	0.00024-0.56	0.00024-0.56	0.00024-0.56
	I_w	4-100	4-100	4-100	4-100	4-100	4-100
Data center - disks:	O_{DC}	21.9-2,111	21.9-2,111	21.9-2,111	35.4-2,174	35.4-2,174	35.4-2,174

Table 3: Overview of the varying scenarios and corresponding values for all data related aspects

3.4 Choice of component values based on literature and the survey

In this section, the choice of the component values for each scenario is defined based on literature and the survey. The values corresponding to the fixed components are based on literature. The survey is used to more specifically define the range of values corresponding to the variable components. Based on the structure of table 3, the values corresponding to the different components are discussed below. An overview of the survey questions and answers can be found in Appendix D. There were 11 respondents to the survey. However, only 2 respondent answered the amount of data related questions. Therefore, in the evaluation below these two respondents are referred to specifically. `Respondent 1` is a pHd candidate from Eindhoven University of Technology, who represents a research vehicle in development phase. `Respondent 2` is a project manager from Eindhoven University of Technology, who represents a passenger car in the operational phase that has SAE level 4-5 automated driving.

Fixed components

Sensing components
The total power consumption of the sensing components depends on the number of each type of sensing component (n_C, n_R, n_X, n_M, n_L, n_G), and the power consumption of each type of sensing component (P_C, P_R, P_X, P_M, P_L, P_G). The number and power consumption of each type of sensing component is based on the study of Gawron et al. [14]. In contrast to the study of Gawron et al. [14], in this study no DSRC sensor is considered. This is because over the years DSRC is been replaced by wireless communication networks [16], and 4G-LTE wireless communication is more preferred for traffic information, file download, or Internet accessing according to Xu et al. [43]. According to Concox [10] an LTE terminal might be used as on-board device, and has a maximum power consumption of around 10 Watt. This is minor compared to for example the power consumption of the computing platform (P_o), and is therefore not included in this study.

Gawron et al. [14] distinguish the sensing subsystem architecture of a Tesla Model S and Waymo's Chrysler Pacifica. Tesla is initially more focused on lower SAE levels of automation and non-shared automation, whereas Waymo is focused on higher SAE levels of automation and shared automation. In this study, the same is distinguished corresponding to sensing composition 1 and 2, respectively. Composition 1 consists of: 8 camera's, 1 radar, 12 sonar, and 1 GPS. Composition 2 consists of: 9 camera's, 4 radar, 4 small lidars, 1 large lidar, and 1 GPS. For camera sensors a Point Grey Dragonfly 2 is assumed, with a power consumption of 2.1 Watt. For a radar sensor a Bosch LLR3 is assumed, with a power consumption of 4 Watt. For a sonar sensor a Bosch Ultrasonic is assumed, with a power consumption of 0.13 Watt. For a small lidar sensor, a Velodyne VLP-16 is assumed, with a power consumption of 8 Watt. For a large lidar sensor a Velodyne HDL-64E is assumed, with a power consumption of 60 Watt. For a GPS sensor a NovAtel PwrPak7-E1 is assumed, with a power consumption of 2 Watt.

Disks within the vehicle
To determine the power consumption of the disks within the vehicle, the capacity and power of each type of disk should be defined. The average capacity of both SSD's and HDD's are defined in GB/disk according to Wang et al. [42]. The average capacity of a HDD inside the vehicle ($A_{H,v}$) is 1,000 GB/disk [42]. The average capacity of a SSD inside the vehicle ($A_{S,v}$) is 250 GB/disk [42]. According to Shehabi et al. [34], the power consumption of HDD's is relatively fixed on a per disk level. Therefore, the power consumption per disk for HDD (Z_H) is assumed to be 6.5 W/disk for both the HDD within the vehicle and at a data center [34]. For SSD's, the power consumption is more related to the capacity, but is often still reported per disk level [34]. Therefore, the power consumption per disk of SSD (Z_S) is assumed to be 6.0 W/disk for both SSD within the vehicle and at a data center [34]. The amount of data to be stored (O) is a variable component with a large range of values. Validation of corresponding values are discussed at the variable components part.

Data center - server
The total power consumption of a data center server, depends on the average maximum power of a data center server (P_e, P_f) and the utilization rate of the type of data center (u_i, u_p, u_h) [34].

For the power consumption, a distinction is made based on the processor count; 1S socket server (P_e), 2S+ socket server (P_f). The power consumption of a 1S socket server is assumed to be 118 Watt, based on the study of Shehabi et al. [34], that uses the SERT database. For a 2S+ socket server, a power consumption of 365 Watt is assumed [34]. A 1S socket volume server has a total of 12 cores and a 2S socket volume server has a total of 24 cores [12]. The total amount of servers used from a data center for a single AV in operational mode, depends on the bandwidth of the data center server, and the amount of data to be processed by the data center server. Each core is assumed to have a bandwidth of 2.7 GHz [12]. So when a 1S socket server is used, a total bandwidth of 32.4 GHz is assumed. When a 2S socket server is used, a total bandwidth of 64.8 GHz is assumed. Considering these bandwidths, a 1S socket server should be sufficient to support the maximum expected data storage of 2,174 GB of a single moving AV in the operational phase. Therefore, the number of 1S socket servers (n_e) is assumed to be 1, and the number of 2S+ socket servers (n_f) is assumed to be 0 for all scenarios.

The average utilization rate represents the per cent of computing ability used on average and depends on the space types of data centers: 15% for internal (u_i), 25% for service provider (u_p), 50% for hyperscale (u_h) [34]. The utilization rates are constants provided by Shehabi et al. [34]. Internal data centers are referred to as representing facilities for internal activities operated by an organization, such as financial activities, but are not directly involved with IT services. The service provider data centers are associated with the core product of a business and are used to provide communication services by companies, such as Google, Microsoft and Amazon. Hyperscale sized data centers are referred to as warehouse scale data centers, and are associated with service provider cloud data centers [34]. Tesla for example mainly collects its data from AV's in-house according to various articles, with which the Tesla AV's will connect [15]. Therefore, a hyperscale data center is assumed in this study for all scenarios. This is realized by defining the usage rate of the hyperscale data center (r_h) to be 1, and the usage rate of the internal (r_i) and service provider (r_p) data centers to be 0.

Data center - disks
To determine the power consumption of the disks at a data center, the capacity and power of each type of disk should be defined. According to Shehabi et al. [34], the average capacity of a HDD at a data center ($A_{H,DC}$) is 10,000 GB/disk. For a SSD, the average capacity at a data center ($A_{S,DC}$) is 5,000 GB/disk [34]. The average power consumption per disk is assumed to be 6.5 W/disk for HDD (Z_H), and 6.0 W/disk for SSD (Z_S) [34].

Data center - networking components
The variables related to the networking components of a data center are: the power of different speed port categories (P_{p1}, P_{p2}, P_{p3}, P_{p4}), the port speed rate of each category (J_{p1}, J_{p2}, J_{p3}, J_{p4}), and the usage rate of speed ports for each category (r_{p1}, r_{p2}, r_{p3}, r_{p4}). According to Shehabi et al. [34], there are four port speed categories based on the amount of bytes; 100 MB, 1000 MB, 10 GB, 40 GB. These different categories all have different power consumption, which are 0.6 Watt/port, 1 Watt/port, 1.6 Watt/port and 2.7 Watt/port for 100 MB, 1000 MB, 10 GB and 40 GB, respectively [34, 35]. Moreover, these port speed categories have corresponding port speed rates, which are 360 GB/h, 3,600 GB/h, 36,000 GB/h, and 144,000 GB/h, respectively [34]. The usage rates for each category are introduced, to define which ports are used depending on the data transmission rate (Y) and the port speed rate of each category (J).

Data center - infrastructure
To cover the power consumption of the infrastructure aspect of data centers, the Power Usage Effectiveness (PUE) value is used according to Shehabi et al. [34]. It is the ratio between the power drawn by the infrastructure components and the power delivered to the servers, disks and networking devices. In general, the PUE ranges from 1.0 up to 3.0. A data center with a PUE of 1.0 would use no electricity other than the IT equipment. A PUE of 2.0 indicates that non-IT energy use is somewhat equal to the IT energy use in a data center [34]. In this study, an average PUE value of 1.51 for 2020 is assumed [35].

Variable components

Computing platform
The computing platform within vehicles has a high range of values in terms of power consumption. The study of Liu et al. [23] mention a total power consumption of 6,000 Watt for a NVIDIA PX2 platform as GPU based solution. Besides Liu et al. [23], the study of Gawron et al. [14] also incorporates a Nvidia Drive PX2 and mentions the overall computing platform could range from around 200 Watt up to 2,000 Watt for experimental and development vehicles. Kemp et al. [21] even mentions that industry professionals expect computing power requirements up to 4,000 Watt. From the obtained survey, respondent 1 expects the power consumption at peak level of the computing platform of a vehicle in development phase to be between 800 and 1,000 Watt. Respondent 2 expects the power consumption at peak level of a computing platform of a passenger car in operational phase to be higher than 1,000 Watt. So, the higher values within the range of the power consumption of the computing platform seem to be too high with respect to the expectations of the respondents to the survey. They seem to relate to a prototype or development vehicle. In this study, an AV in operational mode is considered. So this will result in a power consumption related to the computing platform, that probably ranges between 200 and 1,200 Watt.

However, next to the power consumption of the computing platform itself, also the power consumption to remove additional heat generated by the computing platform should be incorporated. This is referred to as cooling rate to dissipate heat, which according to Lin et al. [22] is 77% of the power consumption of the computing platform. Therefore, a total range for the power consumption between 200 and 2,124 Watt is assumed.

Storage within vehicle
The variable component corresponding to storage inside the vehicle, is the amount of data to be stored in GB (O_v). The amount of data stored depends on the amount of data generated by the sensing components and computing platform. According to Gawron et al. [14] and Kemp et al. [21], the data generated by a vehicle over its lifetime is assumed to be 220 GB and 248 GB respectively, which seems to be unrealistically low. Both studies assume no storage and reuse of data. Nelson [31] mentions, that Intel predicts the amount of data generated per day to be around 4,000 GB for just one hour of driving. Mellor [29] interviewed Christian Renaud (analyst at 451 Research), Robert Bielby (senior director of Automotive System Architecture at memory-maker Micron) and Thaddeus Fortenberry (has spent four years at Tesla working on an Autopilot architecture), about their predictions towards how much data AV's will generate per day in the operational phase. The prediction of 12-15 TB for AV's by Renaud, is based on 2 hours driving per day, which results in 6-7.5 TB/h. Bielby predicts 48 minutes of driving per day for personal-owned vehicles, which results in a prediction of 16-18.5 TB/h. It can be concluded, that all three predict the amount of data to be significantly high, but there still is significant difference between these predictions.

So, in general the amount of data generated varies between 220 GB/h up to 18.5 TB/h for AV's according to these different expectations. These expectations are compared to the amount of data generated for each type of sensor based on literature, and expectations from respondent 1 and 2 of the survey. According to Wang et al. [42], the amount of data generated by a camera varies between 20 and 60 megabits per second (Mbps), for a lidar this is 10 to 70 Mbps, for a sonar 10 to 100 kilobits per second (kbps), for a radar 10 kbps and for GPS 50 kbps. To relate this to the two different sensing compositions, in table 4 an overview of the amount of data generated per type of sensing component is evaluated for both scenarios. To translate from Mbps to GB/h, the fact that 1 Mbps is 0.125 MB/s is used. For sensing composition 1, this results in a total amount of data of 73-222 GB/h related to sensing components. For sensing composition 2, this is 118-348 GB/h related to sensing components. These numbers are not in line with the expectations obtained from respondent 1 of the survey, who expects the following; up to 4,000 GB/h for a camera, up to 10 GB/h for a radar, up to 10 GB/h for a lidar, up to 500 MB/h for a GPS. This results in a total of around 32.5 TB/h for sensing composition 1, and around 36.6 TB/h for sensing composition 2. Respondent 2 of the survey expects; up to 4,000 GB/h for a camera, up to 0.5 GB/h for a radar, up to 2,000 GB/h for a lidar, up to 0.1 GB/h for a GPS. However, these expectations seems to be too high, compared to literature. So, considering the amount of data generated by the sensing components, for sensing composition 1, 73-222 GB/h is assumed, and for sensing composition 2 118-348 GB/h is assumed.

Next to sensing components, the computing platform also generates certain amounts of data. According to respondent 1 of the survey, the data generated by a computing platform is up to 2,000 GB/h. Respondent 2 of the survey actually mentioned up to 4,000 GB/h for a SAE level 4-5 passenger car in operational mode. As a more conservative approach is chosen for the amount of data from the sensing components, in this case the less conservative approach of 4,000 GB/h for the computing platform is chosen. When adding the 4,000 GB/h to the total amount of data generated by both type of sensing components, this results in; (1) 73-4,222 GB/h for composition 1, (2) 118-4,348 GB/h for composition 2. These numbers are also more in line with the expectations of Christian Renaud and Robert Bielby.

Christian Renaud mentions that 78% of the OEM's is planning, that 50-70% of all data generated is analysed by the vehicle itself, and the rest is sent to data centers. Assuming all data generated within the vehicle is actually stored within the vehicle, the amount of data stored inside the vehicle (O_v) results to be; 36.5-2,955.4 GB/h for composition 1, 59-3,043.6 GB/h for composition 2.

	camera	radar	sonar	small lidar	large lidar	GPS	*Total:*
Amount of data generated *per sensor* [GB/h]	9-27	0.0045	0.0045-0.45	4.5-18.0	18.0-31.5	0.0225	-
Number of each type of sensor for *sensing composition 1* [-]	8	1	12	0	0	1	-
Number of each type of sensor for *sensing composition 2* [-]	9	4	0	4	1	1	-
Total amount of data generated for *sensing composition 1* [GB/h]	72-216	0.0045	0.054-5.4	0	0	0.0225	**73-222**
Total amount of data generated for *sensing composition 2* [GB/h]	81-244	0.018	0	18-72	18.0-31.5	0.0225	**118-348**

Table 4: Overview of the amount of data generated per type of sensing component for both scenarios

Wireless communication networks
The variable components corresponding to wireless communication networks are: the data transmission rate from vehicle to the data center (Y_{DC}), the data transmission rate from the data center to the vehicle (Y_v), and the energy intensity of the wireless network (I_w).

According to Christian Renaud (analyst at 451 Research), 30-50% of data generated is sent to data centers. In the validation of storage inside vehicles, already the amount of data generated is discussed for both sensing composition scenarios. This results in data transmission to data centers (Y_{DC}) of 21.9-2,111 GB/h for composition 1, and 35.4-2,174 GB/h for composition 2. Respondent 2 of the survey actually expects the amount of data transmitted to data centers to be smaller than 400 GB/h, but mentions it depends on the application type. However, the expectation of respondent 2 is also that the amount of data stored at the data center is higher than 4,000 GB/h. As the expectation of the amount of data stored at the data center exceeds the expectation corresponding to the data transmission rate, the latter expectation seems to be ambiguous.

Next to sending data to the data center, also data is sent back to the vehicle to provide HD maps. It is assumed that the amount of data that is sent back to the vehicle from the data center, is only related to real-time HD maps and not to data storage. This is because the stored data at data centers is accumulated with data from other cars, after which a more accurate map is sent back to the vehicle [13]. The required data transmission related to real-time HD maps varies between 0.00024 GB/h and 0.56 GB/h, according to Edwertz [13]. This is based on a range between 10 kB/km and 4 MB/km, for speeds between 24 and 140 km/hour [13]. So, the amount of data transmitted from data center to the vehicle (Y_v) ranges between 0.00024-0.56 GB/h for both type of sensing compositions.

The other aspect that influences the energy consumption of the wireless communication networks is the energy intensity. The primary energy intensity of data transmission over a LTE network is defined as 0.24 kWh/GB, as used in the study of Kemp et al. [21] based on Pihkola et al. [33]. Gawron et al. [14] use a primary energy intensity of 0.35 kWh/GB over the LTE network, which incorporates the base-station, tele-communication networks and data-centers. According to Pihkola et al. [33], the energy efficiency will improve over the years and is less than 0.1 kWh/GB in 2021. Aslan et al. [2] evaluated 14 different studies related to electricity intensity in data centers, and stated that the results for a transmission network system boundary varies from 7.3 kWh/GB based on a study of Taylor and Koomey [38], up to 0.004 kWh/GB from the study of Baliga et al. [3]. So there is a high range of values towards the energy intensity of wireless communication networks. Due to already high energy efficiency improvements over the years, in this study a range between 0.004 kWh/GB and 0.1 kWh/GB is used [3, 33].

Data center - disks
The variable component corresponding to the disks at a data center, is the amount of data stored at a data center (O_{DC}). It is assumed that all data, that is transmitted to the data center, is actually stored at the data center. Therefore, the amount of data stored (O_{DC}) is equal to the amount of data transmitted to the data center (Y_{DC}). So, the amount of data stored at the data center (O_{DC}) is 21.9-2,111 GB for composition 1, and 35.4-2,174 GB for composition 2. The expectation of respondent 2 are, that the amount of data stored at the data center is higher than 4,000 GB/h.

3.5 Sensitivity analysis design of instantaneous data related CO_2 emission rate

The variable components in table 3, all have a large range of values for the different scenarios. Sensitivity analysis is used to evaluate which variable data related aspects have the strongest influence in each scenario.

In this research, global sensitivity analysis is applied by using the sensitivity analyzer as part of the Simulink Design Optimization Toolbox. This tool in Simulink uses Monte Carlo simulations to evaluate design requirements at selected parameter values. The Monte Carlo simulation is a technique, used to study the response of a model to randomly generated inputs [27]. Considering the sensitivity analyzer, four main steps need to be taken: (1) sample and select parameters, (2) specify design requirements, (3) perform Monte Carlo simulation, (4) analyze and visualize model sensitivity to parameters [28].

The selected parameters are the variable components from table 3 that all have a large range of values: P_o, O_v, Y_{DC}, Y_v, I_w, O_{DC}. Considering the number of samples, it is stated that at least 10 times the number of variables should be used [26]. As 6 different parameters are selected, this results in a minimum number of samples of 60. The number of random samples created for each of these variables is chosen to be 100. For the random sampling, a uniform distribution is used for all selected variables. This is because all selected variables have a large range of values with equal likelihood, and there is no empirical evidence about the distribution. The design requirement is the minimization of the final signal `K` in kg CO_2-e/h.

For scenario 1 up to 3, parameter set one (table 7) is used of Appendix B.2. For scenario 4 up to 6, parameter set two (table 8) is used of Appendix B.2. The different parameter sets are explained by the different sensing compositions (composition 1 for scenario 1-3, composition 2 for scenario 4-6).

The results of the sensitivity analysis of the instantaneous CO_2 emission rate are visualized using scatter plots and tornado plots. The scatter plots show the evaluated cost function value as a function of each parameter in the parameter set [25]. Besides, the probability distribution of the evaluated cost function values is shown in the scatter plots. The tornado plots show the relation between the cost function evaluations and parameter samples. Three main methods are used to analyze this, which are all shown in the tornado plots; (1) correlation, (2) partial correlation, (3) linear regression. These methods are all provided by the sensitivity analyzer tool of Matlab. Below, the methods of obtaining these three different types of analyzes by the sensitivity analyzer, are described.

Correlation
Correlation analyzes how a model parameter and cost function output are correlated. A positive correlation means that variables increase together. A negative correlation means that when one variable increases, other variables will decrease. The correlation coefficient `R` is calculated by equation 13 [25].

$$R(i,j) = \frac{C(i,j)}{\sqrt{C(i,i)C(j,j)}} \tag{13}$$

where: C = cov(x,y) = E[(x-μ_x)($y - \mu_y$)]
$\mu_x = E[x]$
$\mu_y = E[y]$

x = contains N_s samples of N_p model parameters
y = contains N_s rows (each row corresponds to the cost function evaluation for a sample in x)

R ranges between [-1 1]

if: R(i,j) $>$ 0 $\rightarrow$ variables have positive correlation
R(i,j) $=$ 0 $\rightarrow$ variables have no correlation
R(i,j) $<$ 0 $\rightarrow$ variables have negative correlation

Partial correlation
Partial correlation analyzes how a model parameter and the cost function are correlated, removing the effects of the remaining parameters. The correlation coefficient `R` is in this case determined using `partialcorri` from the Statistics and Machine Learning Toolbox of Matlab [25].

linear regression
Linear regression is used when it is expected that the model parameters linearly influence the cost function. The regression coefficient `R` is determined by equation 14 [25].

$$R = b_x \frac{\sigma_x}{\sigma_y} \tag{14}$$

where: x = single sample
y = output corresponding to single sample
b = regression coefficient vector (calculated using least squares assuming a linear model)
σ = standard deviation

3.6 Specification of spatial data related CO_2 emission rate

To ensure comparison between the data related CO_2 emission resulting from all 6 different scenarios, and the propulsion-based CO_2 emission norms, the CO_2 emission of the data related aspects have to be obtained in terms of kg CO_2-e/km. To obtain the spatial CO_2 emission rate, the instantaneous CO_2 emission rate should be translated using the travel speed (`C`) in km/h, as denoted by equation 15 below.

$$B = K/C \tag{15}$$

For the travel speed (`C`), the WLTP driving cycle is used. Based on the results of the instantaneous CO_2 emission rate for each scenario, three different situations are defined. These situations correspond to the values of components, for which the resulting emission is lowest (`situation 1`), highest (`situation 2`) and median (`situation 3`). The instantaneous data related CO_2 emission rate is translated to the WLTP driving cycle, to obtain the spatial CO_2 emission rates of the three situations of each scenario. The speed profile of the WLTP driving cycles is used, defined as WLTC. In this driving cycle, a distinction is made between 3 driving cycles based on the type of driving ratio: class 1, class 2, class 3. Class 1 refers to urban driving, with lower speeds. Class 3 refers to extra-urban driving, with higher speeds. Class 2 refers to combined driving, with both lower and higher speeds [9]. A schematic overview of the speed profile corresponding to these classes of the WLTC is given in figure 2.

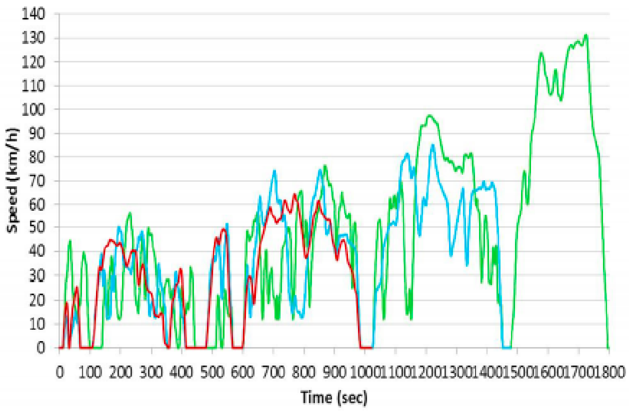


Figure 2: WLTC (red = class 1, blue = class 2, green = class 3) [9]

3.7 Main assumptions of the computational model and scenario design

The CO_2 emission of the data related aspects is compared to the future propulsion-based CO_2 norms of vehicles. The CO_2 norm for 2025 is assumed to be 0.09 kg CO_2-e/km based on a 15% reduction with respect to the baseline of 2021, which is defined as 0.109 kg CO_2-e/km. The CO_2 norm of 2030 is assumed to be 0.069 kg CO_2-e/km based on a 37.5% reduction with respect to 2021 [17]. The data related aspects are assumed to be: sensing components, the computing platform, disks inside the vehicle, wireless communication networks and data centers [13, 14, 21, 23, 24].

In this study an AV in its operational phase is assumed, that is always connected while driving. The amounts of data generated and transmitted by the AV in its operational phase, is assumed to be independent of travel speed. Moreover, it is assumed that 30-50% of the data generated is sent to a data center [29]. To ensure data transmission, wireless communication networks are used, for which the energy consumption is defined by energy intensity in Wh/GB [3, 33]. The energy intensity has a large range of values, for which already optimization over the last couple of years is assumed. Data centers are used to enable HD map generation, for which data from infrastructure and other vehicles is accumulated and sent back to the vehicle.

The scenarios differ based on type of sensing composition and the energy grid. A Tesla Model S is assumed for sensing composition 1, a Waymo's Chrysler Pacifica is assumed for sensing composition 2 [14, 21]. The Dutch energy grid of 2018 is assumed, defined by the CO_2 emission rate of 0.43 kg CO_2-e/kWh [7]. The cases for 2030 and 2050 are based on the targeted CO_2 emission reduction according to the 2019 Climate Act. A reduction of 49% by 2030 is assumed compared to 1990 levels, and a reduction of 95% by 2050 is assumed [19]. A more detailed overview of the assumptions can be found in Appendix A.

4 Results

In this section, the results are evaluated to answer the main research question described in section 1. First, the instantaneous CO_2 emission rates corresponding to the different scenarios are evaluated based on the sensitivity analysis. Then, the spatial CO_2 emission rates resulting from the data related aspects are compared to the propulsion-based CO_2 norms of vehicles for 2025 and 2030.

4.1 Sensitivity analysis of instantaneous data related CO_2 emission rate

Sensitivity analysis is obtained to evaluate which data related aspects have the strongest influence on the instantaneous CO_2 emission rate in kg CO_2-e/h. First, for all six scenarios the instantaneous CO_2 emission rate is evaluated, for which the parameter sets of the sensitivity analysis are used. The results of the instantaneous CO_2 emission corresponding to the parameter set are shown using scatter plots. A detailed overview of the resulting instantaneous CO_2 emission rate corresponding to the different parameters for each scenario can be found in Appendix C.1. The data related aspects, that have the strongest influence on the resulting instantaneous CO_2 emission rate, are discussed using tornado plots.

Scenarios 1, 2 and 3 differ from each other due to the varying CO_2 emission rates (`E`) in kg CO_2-e/Wh. Scenario 1 has the highest CO_2 emission rate (E_a), and therefore shows the highest instantaneous CO_2 emission in the scatter plot of figure 3a, with respect to scenario 2 (figure 4a) and 3 (figure 5a). Compared to scenario 1, the CO_2 emission is reduced in scenario 2, where the CO_2 emission rate corresponding to the energy grid of 2030 (E_b) is used. Besides, the probability of the CO_2 emission being a low number increases for scenario 2. A more significant drop in CO_2 emission with respect to scenario 2 seems to occur for scenario 3, where a CO_2 emission rate corresponding to the energy grid of 2050 (E_c) is used. The same relation occurs for scenarios 4, 5 and 6, where scenario 4 (figure 6a) shows the largest CO_2 emission, followed by scenario 5 (figure 7a), and 6 (figure 8a).

In tables 5 and 6 below, the extremes and medium of the instantaneous CO_2 emission rate of each scenario is given. With extremes, both the highest and lowest resulting instantaneous CO_2 emission rates are referred to for each scenario. `Situation 1` is referred to as the lowest resulting instantaneous CO_2 emission rate for each scenario. `Situation 2` is referred to as the highest resulting instantaneous CO_2 emission rate for each scenario. `Situation 3` refers to the median of the generated results of each scenario. Comparing the instantaneous CO_2 emission of scenarios 1, 2 and 3 (table 5) with 4, 5 and 6 (table 6), it seems that sensing composition 2 (scenarios 4, 5, 6) shows a slightly lower instantaneous CO_2 emission rate compared to sensing composition 1. From these two tables, it can also be concluded that based on the extremes, both scenarios 3 and 6 show the lowest instantaneous CO_2 emission rates. Between the instantaneous CO_2 emission rates of scenario 3 and 6, there only is a slight differences dependent on the type of situation. This might be due to the different parameter sets used corresponding to different sensing compositions. Although different parameter sets are used, the difference of the instantaneous CO_2 emission rates between sensing composition 1 and 2 seems to be small.

	Scenarios:	**1.Base case composition 1**			**2.Case 2030 composition 1**			**3.Case 2050 composition 1**		
		Situation 1	**Situation 2**	**Situation 3**	**Situation 1**	**Situation 2**	**Situation 3**	**Situation 1**	**Situation 2**	**Situation 3**
Fixed:	n_C [-]	8	8	8	8	8	8	8	8	8
	n_R [-]	1	1	1	1	1	1	1	1	1
	n_X [-]	12	12	12	12	12	12	12	12	12
	n_M [-]	0	0	0	0	0	0	0	0	0
	n_L [-]	0	0	0	0	0	0	0	0	0
	n_G [-]	1	1	1	1	1	1	1	1	1
	E_a [kg CO_2-e/Wh]	0.00043	0.00043	0.00043	0	0	0	0	0	0
	E_b [kg CO_2-e/Wh]	0	0	0	0.000258	0.000258	0.000258	0	0	0
	E_c [kg CO_2-e/Wh]	0	0	0	0	0	0	0.0000253	0.0000253	0.0000253
Variable:	P_o [W]	853.19	1619.64	1001.92	853.19	1619.64	1001.92	853.19	1619.64	1001.92
	O_v [GB]	2180.10	194.23	534.03	2180.10	194.23	534.03	2180.10	194.23	534.03
	Y_{DC} [GB/h]	163.94	1785.92	1123.15	163.94	1785.92	1123.15	163.94	1785.92	1123.15
	Y_v [GB/h]	0.00026	0.000250	0.000278	0.00026	0.000250	0.000278	0.00026	0.000250	0.000278
	I_w [Wh/GB]	7.31	80.34	41.65	7.31	80.34	41.65	7.31	80.34	41.65
	O_{DC} [GB]	324.74	1094.13	857.09	324.74	1094.13	857.09	324.74	1094.13	857.09
Results:	K [kg CO_2-e/h]	1.22	62.98	20.93	0.73	37.79	12.56	0.07	3.71	1.23

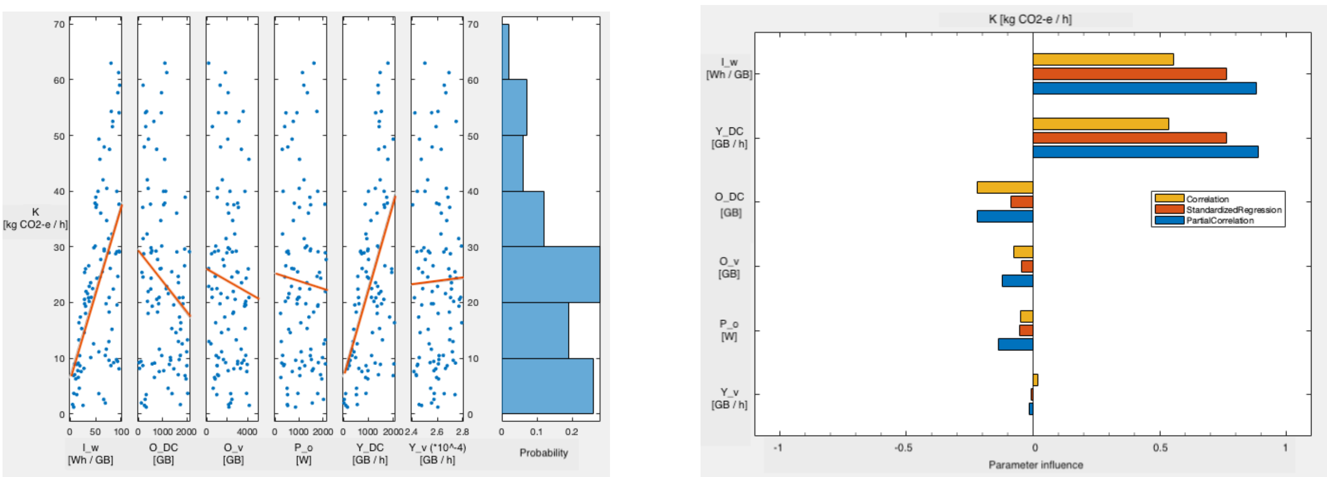
Table 5: Overview of the instantaneous CO_2 emission rates for the three situations of scenario 1, 2 and 3

	Scenarios:	4.Base case composition 2			5.Case 2030 composition 2			6.Case 2050 composition 2		
		Situation 1	**Situation 2**	**Situation 3**	**Situation 1**	**Situation 2**	**Situation 3**	**Situation 1**	**Situation 2**	**Situation 3**
Fixed:	n_C [-]	9	9	9	9	9	9	9	9	9
	n_R [-]	4	4	4	4	4	4	4	4	4
	n_X [-]	0	0	0	0	0	0	0	0	0
	n_M [-]	4	4	4	4	4	4	4	4	4
	n_L [-]	1	1	1	1	1	1	1	1	1
	n_G [-]	1	1	1	1	1	1	1	1	1
	E_a [kg CO_2-e/Wh]	0.00043	0.00043	0.00043	0	0	0	0	0	0
	E_b [kg CO_2-e/Wh]	0	0	0	0.000258	0.000258	0.000258	0	0	0
	E_c [kg CO_2-e/Wh]	0	0	0	0	0	0	0.0000253	0.0000253	0.0000253
Variable:	P_o [W]	973.80	695.99	547.74	973.80	695.99	547.74	973.80	695.99	547.74
	O_v [GB]	3286.83	3175.12	648.16	3286.83	3175.12	648.16	3286.83	3175.12	648.16
	Y_{DC} [GB/h]	89.15	2167.59	913.57	89.15	2167.59	913.57	89.15	2167.59	913.57
	Y_v [GB/h]	0.000268	0.000240	0.000270	0.000268	0.000240	0.000270	0.000268	0.000240	0.000270
	I_w [Wh/GB]	4.05	93.24	44.03	4.05	93.24	44.03	4.05	93.24	44.03
	O_{DC} [GB]	1956.90	779.37	758.46	1956.90	779.37	758.46	1956.90	779.37	758.46
Results:	K [kg CO_2-e/h]	1.01	87.55	17.81	0.60	52.53	10.69	0.06	5.15	1.05

Table 6: Overview of the instantaneous CO_2 emission rates for the three situations of scenario 4, 5 and 6

To evaluate which data related aspects have the strongest influence on the resulting instantaneous CO_2 emission rate, tornado plots are used. The tornado plots show which parameters have the strongest influence on the output, using correlation, partial correlation and linear regression. The specific methods and formulas behind these techniques are discussed in section 3.5. The tornado plots corresponding to each scenario are given in figures 3b, 4b, 5b, 6b, 7b, 8b below.

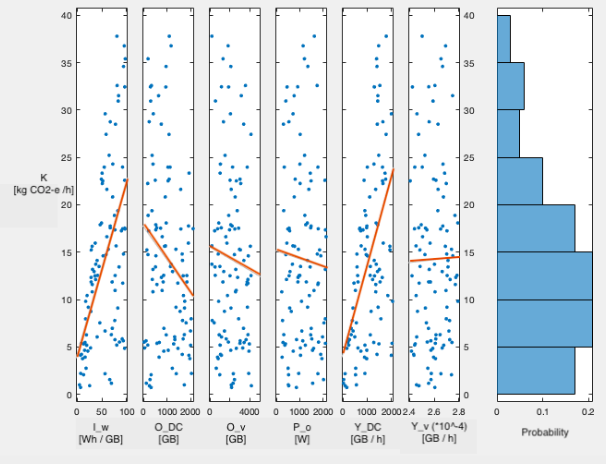
From the sensitivity analysis of all six scenarios, it can be concluded that in each scenario both the energy intensity of the wireless network (I_w), and the data transmission rate from the vehicle to the data center (Y_{DC}), have the strongest influence on the resulting instantaneous CO_2 emission rate. This can for example be concluded from figure 3b, by the largest positive correlation for these two variables. A positive correlation means, that if a value of a component increases, the resulting instantaneous CO_2 emission rate also increases. When looking at the partial correlation, where the effects of the remaining parameters is removed, this can also be concluded. For scenario 1, 2 and 3 (figures 3b, 4b, 5b), some variables (O_v, P_o, O_{DC}) have slightly negative partial correlation, which means that when the values of these three variables increase, the resulting instantaneous CO_2 emission rate will slightly decrease. For scenario 4, 5 and 6 (figures 6b, 7b, 8b), this only relates to O_v and P_o. It can be concluded, that independent of the type of sensing composition, both the energy intensity of the wireless network (I_w), and the data transmission rate from the vehicle to the data center (Y_{DC}), have the strongest influence on the resulting instantaneous CO_2 emission rate.



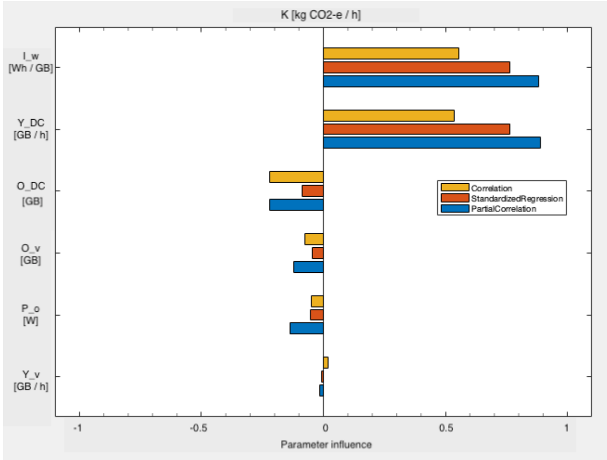
(a) Scatter plot of scenario 1

(b) Tornado plot of scenario 1

Figure 3: Results of sensitivity analysis for scenario 1

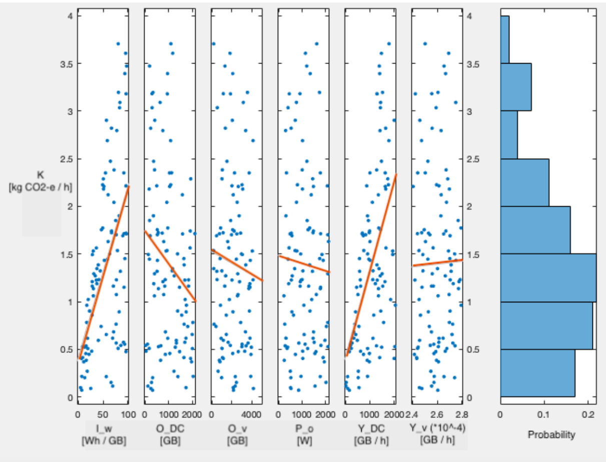


(a) Scatter plot of scenario 2

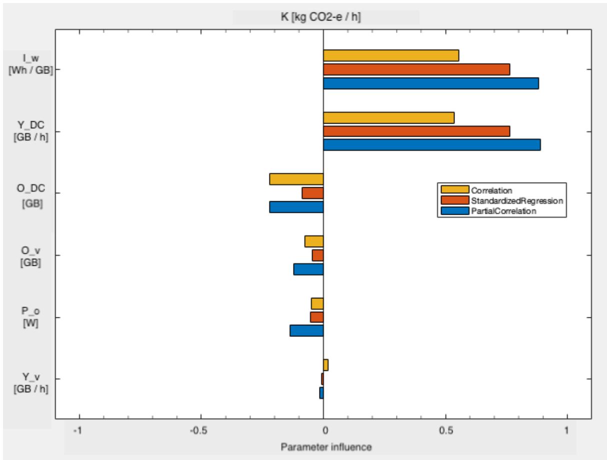


(b) Tornado plot of scenario 2

Figure 4: Results of sensitivity analysis for scenario 2

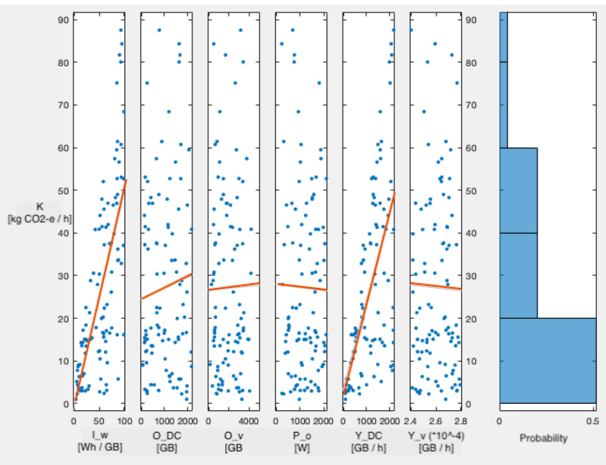


(a) Scatter plot of scenario 3

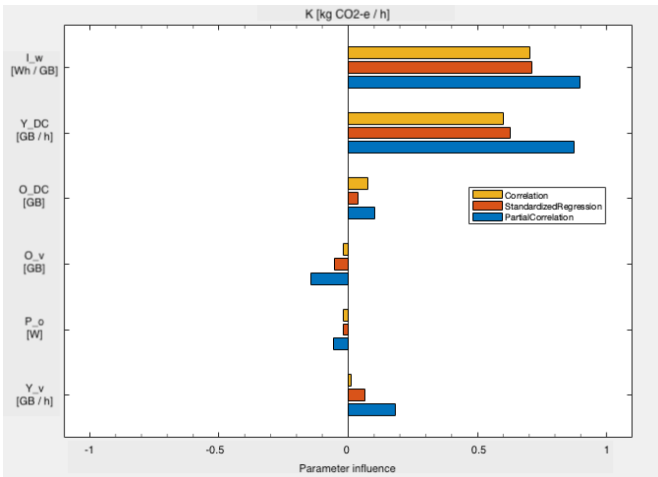


(b) Tornado plot of scenario 3

Figure 5: Results of sensitivity analysis for scenario 3

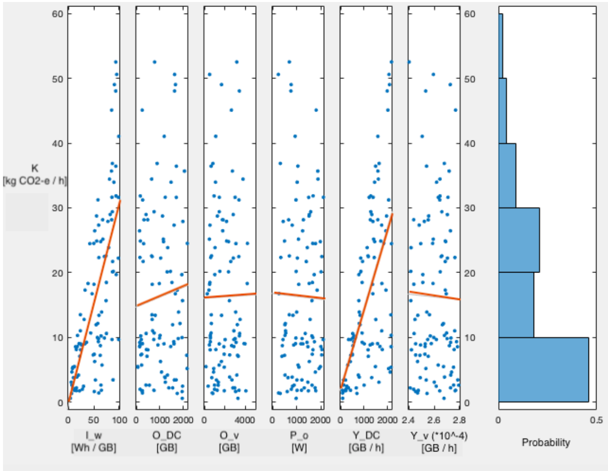


(a) Scatter plot of scenario 4

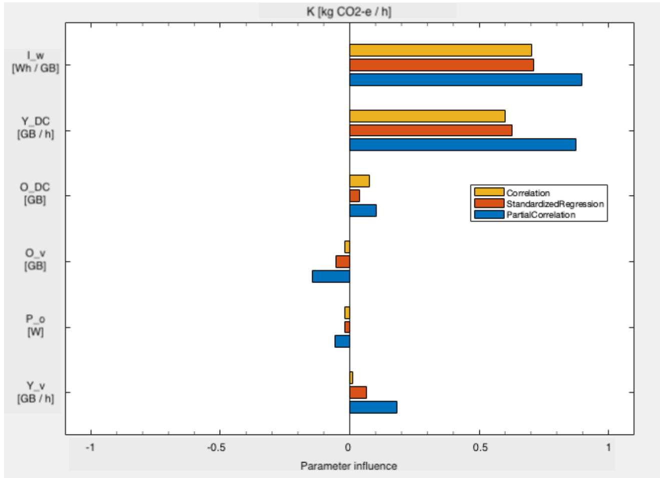


(b) Tornado plot of scenario 4

Figure 6: Results of sensitivity analysis for scenario 4

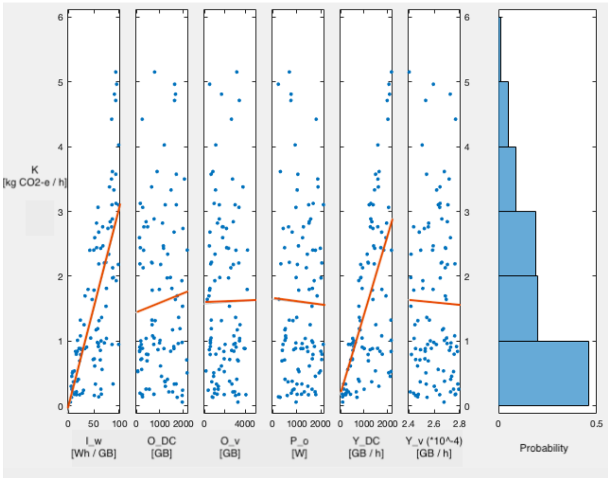


(a) Scatter plot of scenario 5

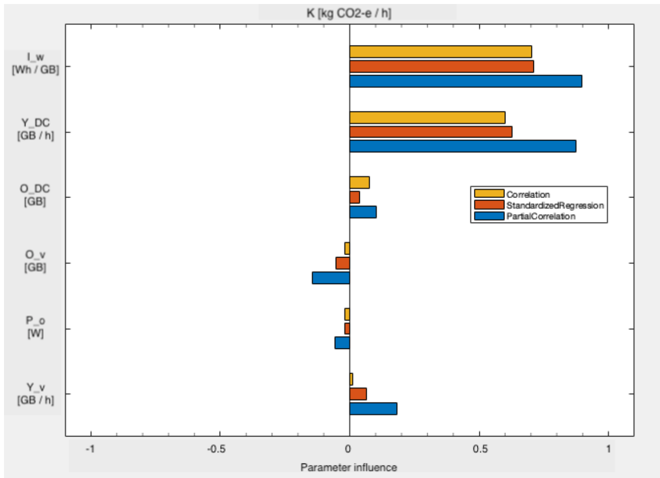


(b) Tornado plot of scenario 5

Figure 7: Results of sensitivity analysis for scenario 5



(a) Scatter plot of scenario 6



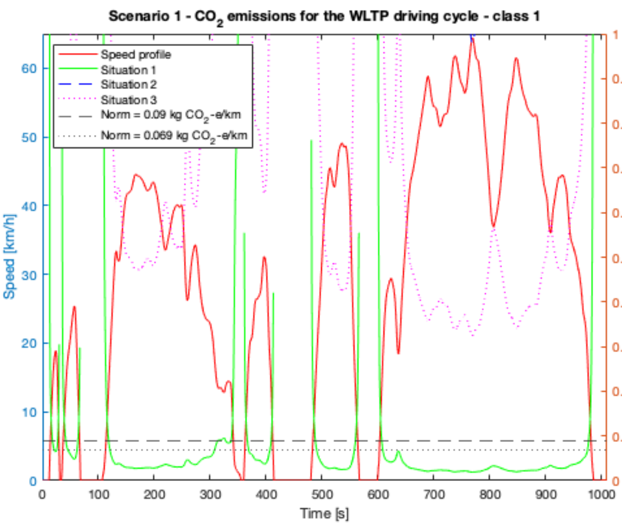
(b) Tornado plot of scenario 6

Figure 8: Results of sensitivity analysis for scenario 6

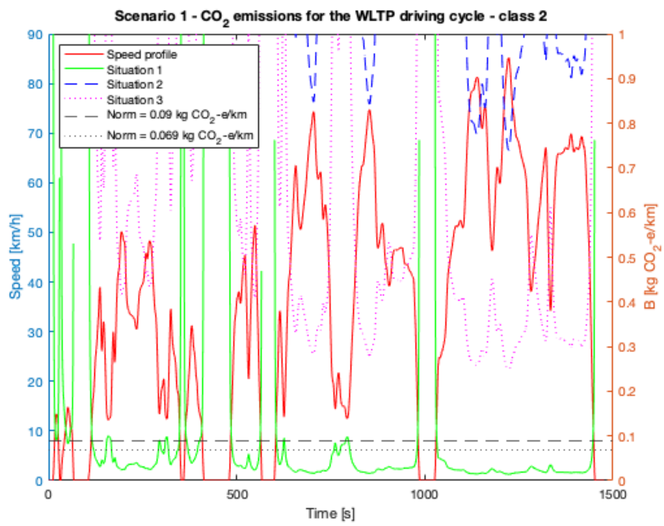
4.2 Comparison of spatial data related CO_2 emission rate to the CO_2 emission norms of vehicles

In 2021 a new CO_2-norm of 0.109 kg CO_2-e/km entered for car manufacturers. This norm has been targeted to be even further reduced by 2025 to 0.09 kg CO_2-e/km, and to 0.069 by 2030 for light-duty vehicles [17]. For the CO_2 norms of vehicles, the CO_2 emission resulting from the data related aspects are not incorporated. In this section, it is evaluated whether solely based on the CO_2 emission of the data related aspects of vehicle automation, the norms can be met for the varying scenarios and situations.

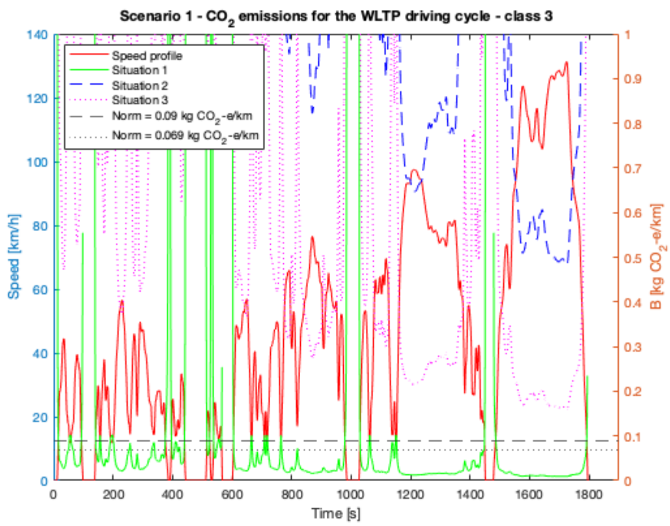
To evaluate for which situations of each scenario the norms can be met, the instantaneous CO_2 emission rates from tables 5 and 6 are translated to spatial CO_2 emission rates in kg CO_2-e/km, using the WLTP driving cycle. Figures 9, 10, 11, 12, 13 and 14 show the spatial CO_2 emission rate for each time step of the WLTP driving cycle. In each figure, the two different norms are denoted by the horizontal dotted lines. From these figures, it seems that for situation 2 the norms can only be met for scenario 3 and 6. For situation 1, both norms can be met in each scenario. For situation 3, both norms can be met for scenario 3 and 6. Whether or not the norms can be met for scenario 5 corresponding to situation 3 seems to be dependent on the travel speed. From figure 13, it seems that only for high travel speeds corresponding to WLTP class 3, the norm of 0.09 kg CO_2-e/km for 2025 can be met.



(a) Scenario 1, class 1



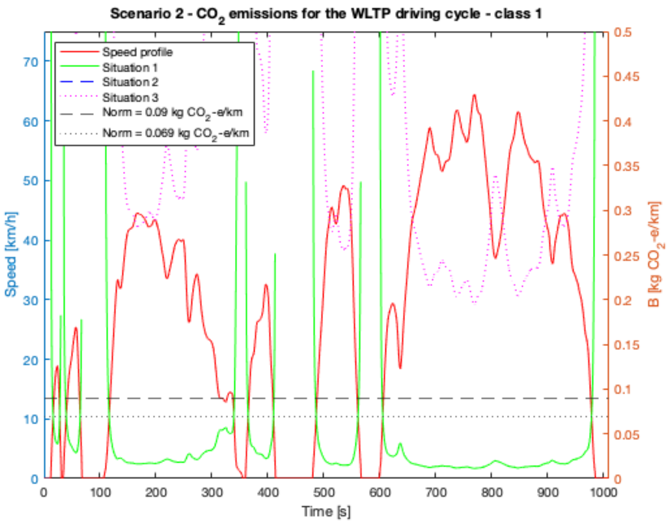
(b) Scenario 1, class 2



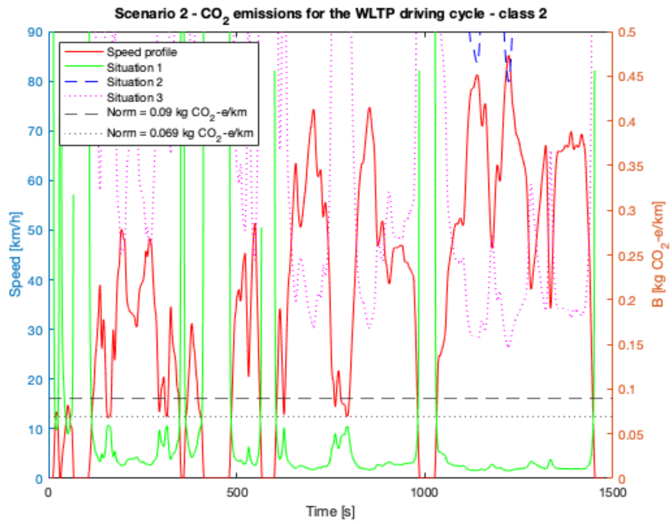
(c) Scenario 1, class 3

Figure 9: Spatial data related CO_2 emission translated to the WLTP driving cycle for scenario 1

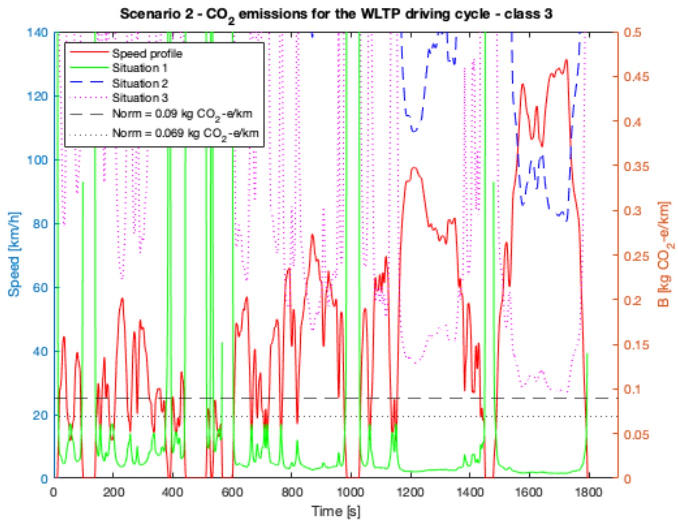
Based on figure 9, for scenario 1 both CO_2 norms can be reached for situation 1, based on solely on the CO_2 emission resulting from the data related aspects. When investigating situation 2 and 3, the norms cannot be achieved for scenario 1.



(a) Scenario 2, class 1



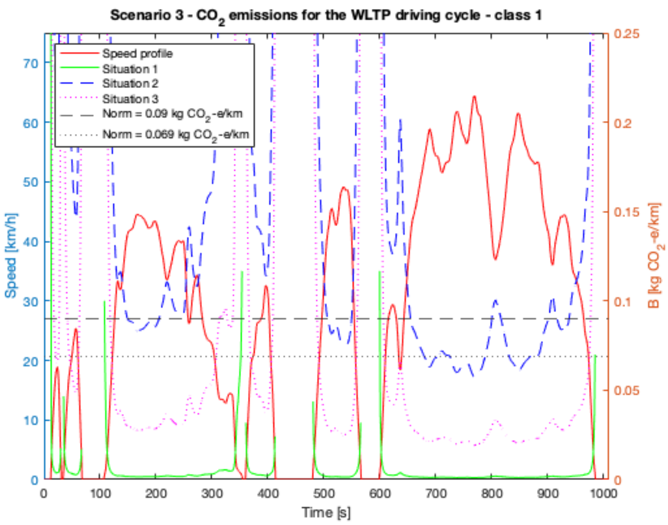
(b) Scenario 2, class 2



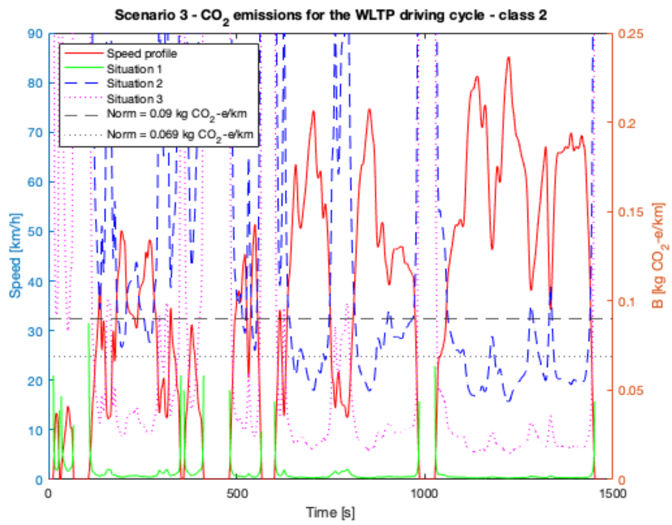
(c) Scenario 2, class 3

Figure 10: Spatial data related CO_2 emission translated to the WLTP driving cycle for scenario 2

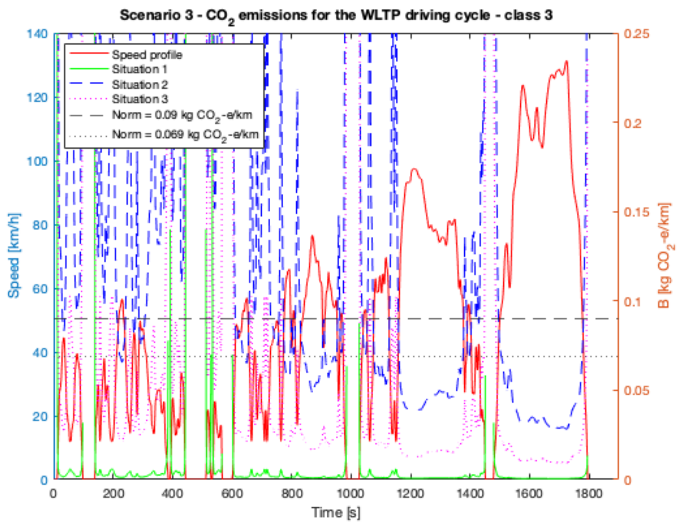
Based on figure 10, for scenario 2 both CO_2 norms can be reached for situation 1, based on solely on the CO_2 emission resulting from the data related aspects. When investigating situation 2 and 3, the norms cannot be achieved for scenario 2.



(a) Scenario 3, class 1



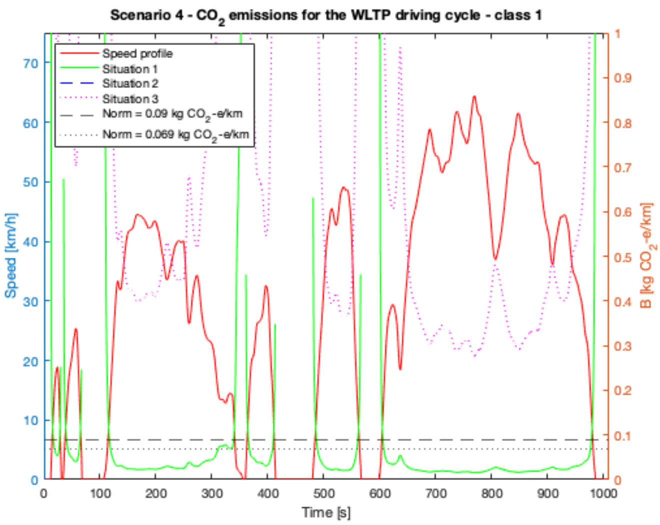
(b) Scenario 3, class 2



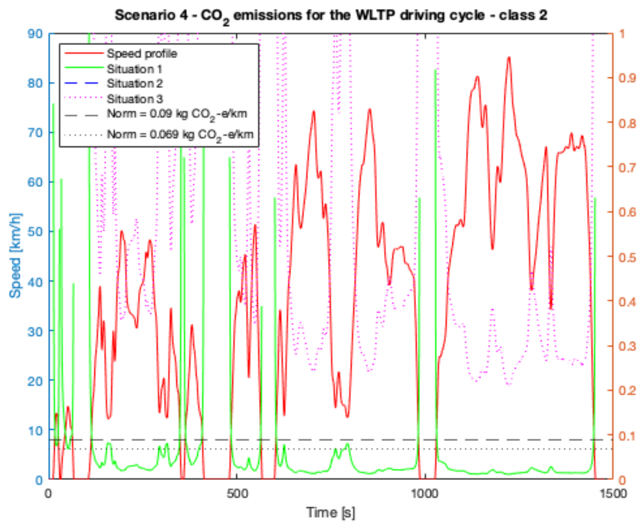
(c) Scenario 3, class 3

Figure 11: Spatial data related CO_2 emission translated to the WLTP driving cycle for scenario 3

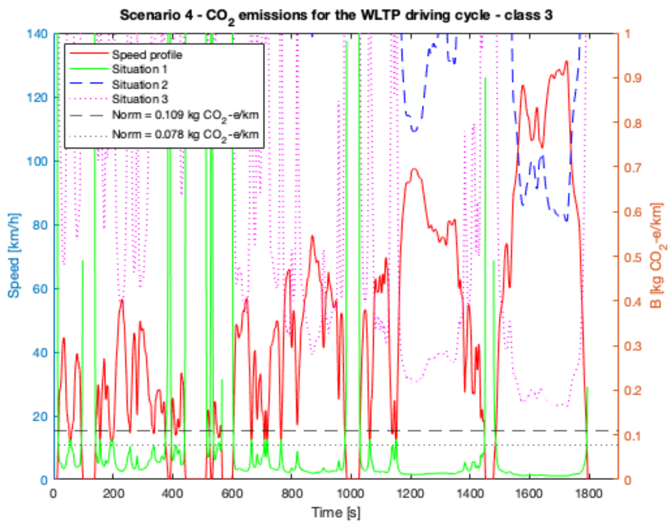
Based on figure 11, for scenario 3 both CO_2 norms can be reached for situation 1 and 3, based on solely on the CO_2 emission resulting from the data related aspects. When investigating situation 2, the norms can be achieved for scenario 3 dependent on the travel speed. For the higher travel speed corresponding to class 3 (figure 11c), both norms seem to be achievable for scenario 3.



(a) Scenario 4, class 1



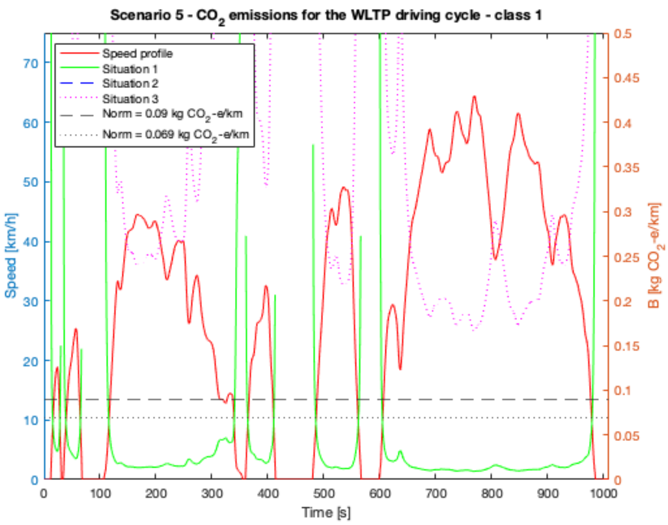
(b) Scenario 4, class 2



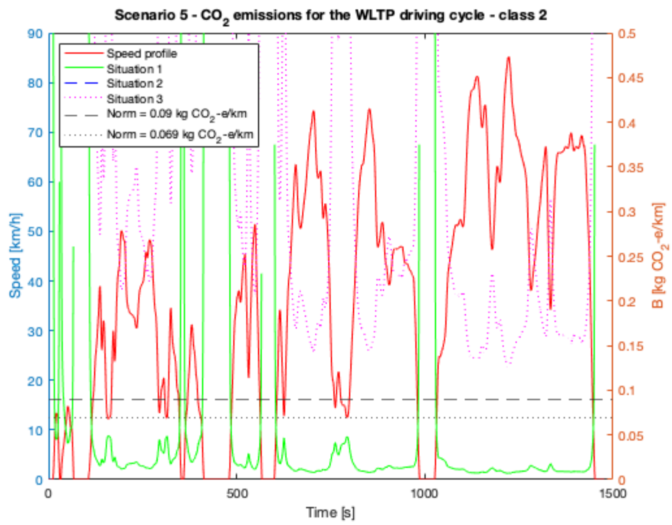
(c) Scenario 4, class 3

Figure 12: Spatial data related CO_2 emission translated to the WLTP driving cycle for scenario 4

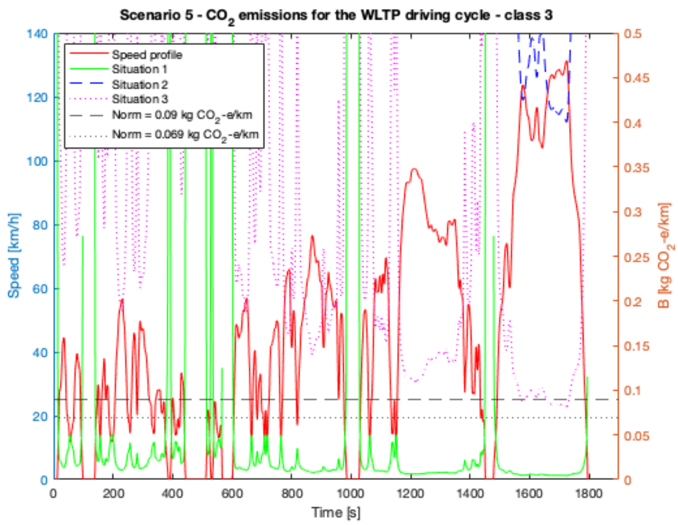
Based on figure 12, for scenario 4 both CO_2 norms can be reached for situation 1, based on solely on the CO_2 emission resulting from the data related aspects. When investigating situation 2 and 3, the norms cannot be achieved for scenario 4.



(a) Scenario 5, class 1



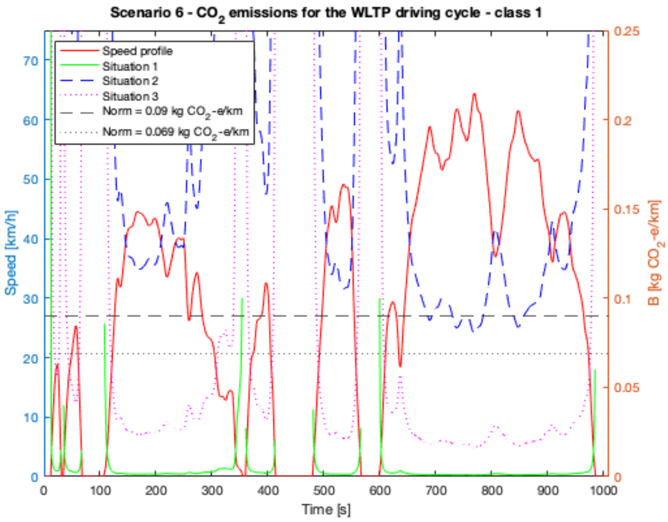
(b) Scenario 5, class 2



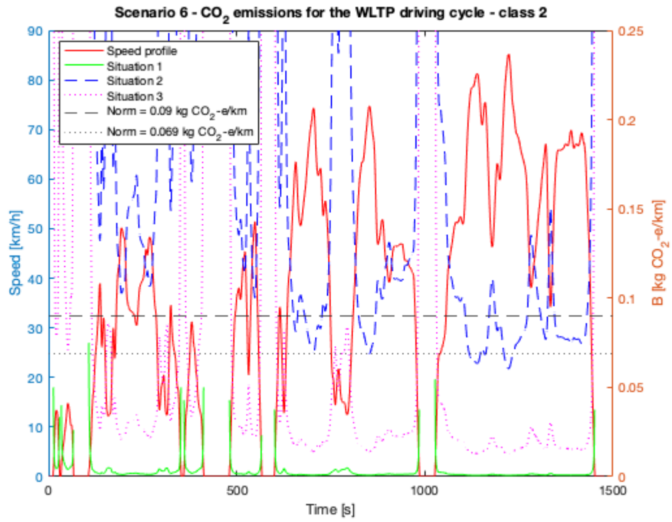
(c) Scenario 5, class 3

Figure 13: Spatial data related CO_2 emission translated to the WLTP driving cycle for scenario 5

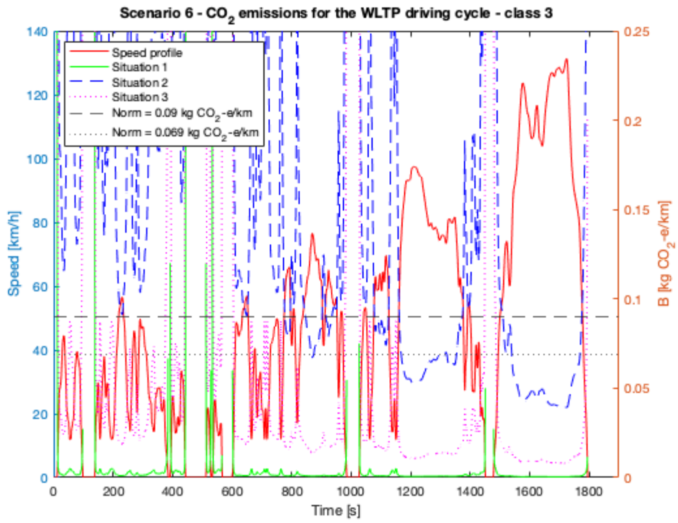
Based on figure 13, for scenario 5 both CO_2 norms can be reached for situation 1, based on solely on the CO_2 emission resulting from the data related aspects. When investigating situation 2 and 3, the norms cannot be achieved for scenario 5.



(a) Scenario 6, class 1



(b) Scenario 6, class 2



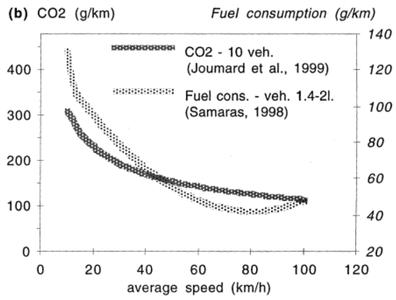
(c) Scenario 6, class 3

Figure 14: Spatial data related CO_2 emission translated to the WLTP driving cycle for scenario 6

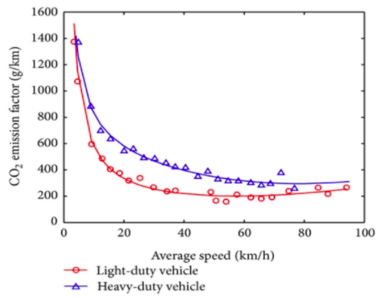
Based on figure 14, for scenario 6 both CO_2 norms can be reached for situation 1 and 3, based on solely on the CO_2 emission resulting from the data related aspects. When investigating situation 2, the norms can be achieved for scenario 6 dependent on the travel speed. For the higher travel speed corresponding to class 3 (figure 11c), the norm of 0.09 kg CO_2-e/km for 2025 seems to be achievable for scenario 6.

To better evaluate for which situations of each scenario the norms can be met corresponding to different travel speeds, the instantaneous CO_2 emission rates from tables 5 and 6 are translated to spatial CO_2 emission rates over a range of travel speeds (C). Figures 16 and 17 show a schematic overview of the spatial CO_2 emission rates corresponding to the three different situations for each scenario, over a range of velocities from 0-120 km/h. From these figures, it can be concluded that the CO_2 emission is highest at low speed and then decreases monotonically with increasing speed. This is line with the studies of André and Hammarström [1], where the CO_2 emission of a gasoline passenger car is evaluated (figure 15a), and Song et al. [36], where the CO emission of light and heavy duty vehicles is evaluated for varying speeds (figure 15b). According to both André and Hammarström [1] and Song et al. [36], the CO_2 emission is high at low speeds, decrease up to 60-80 km/h, and then slightly increase again.

From figures 16 and 17, it can be concluded that for situation 1, the norms can be met for all scenarios. However, the lowest possible speed for which the norms can be met differs for the varying scenarios. For situation 2, the norm of 0.09 kg CO_2-e/km can be met for scenario 3 at around 42 km/h, and for scenario 6 at around 58 km/h. For situation 2, the norm of 0.069 kg CO_2-e/km can be met for scenario 3 at around 58 km/h, and for scenario 6 at around 78 km/h. Considering situation 3, the norm of 0.09 kg CO_2-e/km can be met for scenario 3 at around 15 km/h, for scenario 5 at around 120 km/h, and for scenario 6 at around 15 km/h. For situation 3, the norm of 0.069 kg CO_2-e/km can be met for scenario 3 at around 19 km/h, and for scenario 6 at around 17 km/h.

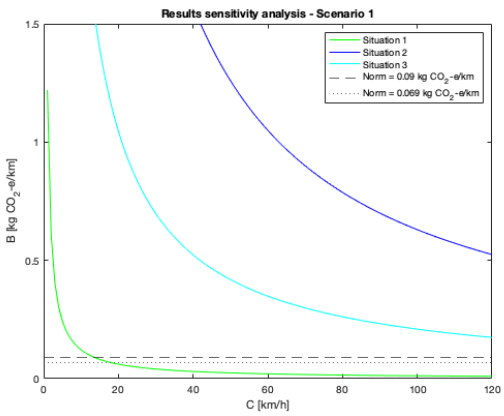


(a) For a gasoline passenger car according to André and Hammarström [1]

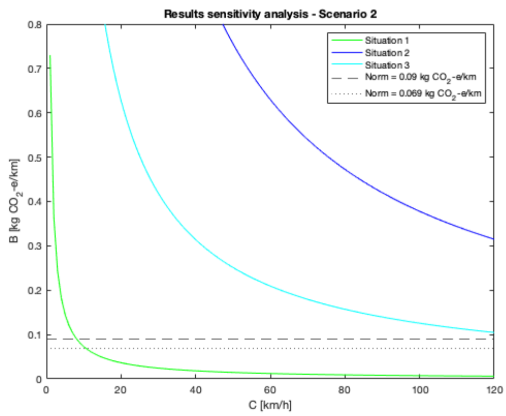


(b) For light- and heavy-duty vehicles according to Song et al. [36]

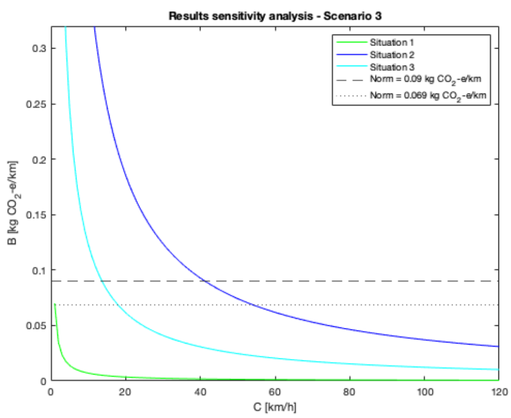
Figure 15: Spatial CO_2 emission over a range of driving speeds according to André and Hammarström [1] and Song et al. [36]



(a) Scenario 1

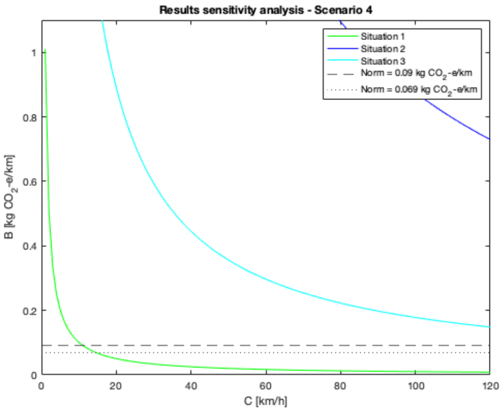


(b) Scenario 2

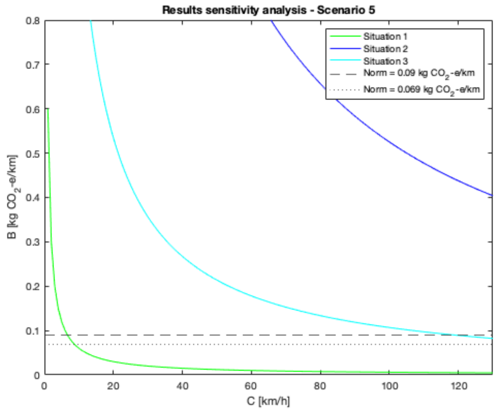


(c) Scenario 3

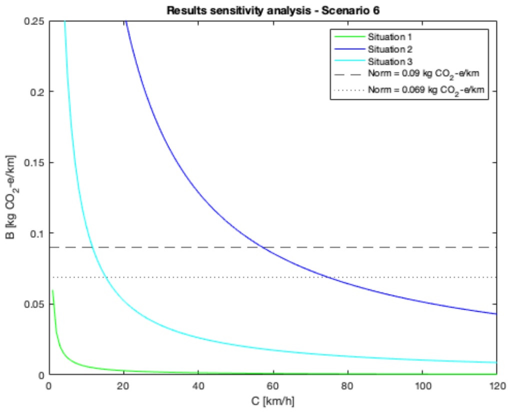
Figure 16: Spatial CO_2 emission rates for scenario 1-3 over a range of velocities



(a) Scenario 4



(b) Scenario 5



(c) Scenario 6

Figure 17: Spatial CO_2 emission rates for scenario 4-6 over a range of velocities

In general, situation 1 is feasible with respect to both norms for each situation. This is a logic result, as situation 1 refers to the combination of values of the varying parameters that resulted in the lowest instantaneous CO_2 emission rate. Situation 2, which refers to the combination of values of the varying parameters that resulted in the highest instantaneous CO_2 emission rate, is only feasible with respect to the norms for scenario 3 and 6. This might be due to the high values of both Y_{DC} and I_w, which are the two data related aspects that have the strongest influence on the resulting CO_2 emission. Besides, both scenarios 3 and 6 correspond to the desired and lowest energy grid for 2050.

In summary, whether or not the norms can be met mainly depends on the values corresponding to the data transmission rate from the vehicle to the data center (Y_{DC}), the energy intensity of the wireless communication networks (I_w), and the CO_2 emission rate (E) in kg CO_2-e/Wh for the energy grid. Besides, also the travel speed seems to influence whether or not the norms can be met.

5 Discussion

This study is executed to investigate whether future propulsion-based CO_2 emission norms can be met, on basis of the CO_2 emission for the data related aspects of vehicle automation. The outcomes show that for most scenarios and situations, the CO_2 emission from the data related aspects are higher than the propulsion-based CO_2 norms of vehicles. The future CO_2 norm of 2025 is based on a 15% reduction in CO_2 emission with respect to the norm of 2021. The norm of 2030 is based on 37.5% reduction in CO_2 emission with respect to the norm of 2021. Changing these future norms may affect the conclusions from this study. Moreover, the norms are based on European fleet-wide targets, where in this study the same norms are assumed for a single moving AV in its operational mode. Therefore, these results should be seen in the light of the assumptions (Appendix A) and figures used.

Based on literature and a survey, the data related aspects of vehicle automation are assumed to be: sensing components, the computing platform, disks inside the vehicle, wireless communication networks, and data centers. However, there might be potential other data related aspects that are not included in this study. The CO_2 emission of these data related aspects is determined both per unit time (the instantaneous CO_2 emission rate), and per kilometer travelled (the spatial CO_2 emission rate). According to the sensitivity analysis, the resulting instantaneous CO_2 emission rate is mainly dependent on the data transmission rate from the vehicle to the data center in GB/h (Y_{DC}), and the energy intensity of wireless communication networks in Wh/GB (I_w).

The values for the data transmission rate from the vehicle to the data center are based on the assumption, that 30-50% of the data generated by the vehicle is sent to the data center. Actually, when a lower percentage of the generated data is sent to the data center, the resulting CO_2 emission rate is lower, and perhaps closer to the propulsion-based norms. The amount of data transmitted by the vehicle is still relatively uncertain or at least not reported by the industry. The background of this remark is the fact that there were 11 respondents to the survey, of which only two university research related respondents actually answered the data related questions. Maybe the industry is not willing to share this information due to for example competitive advantage.

The energy intensity of the wireless communication networks used in this study corresponds to a large range of values. Over the last couple of years, the energy intensity of wireless communication networks has been assumed to already be optimized significantly. However, even more optimization should be realized to enable high amounts of data transmission with limited CO_2 emission. Probably, the coming years more AV's will enter the road, which will result in even more amounts of data to be transmitted and stored.

According to the scenario analysis, it is concluded that the CO_2 emission rate ($\mathtt{E}$) in kg CO_2-e/Wh also has significant influence on the resulting CO_2 emission from the data related aspects. The CO_2 emission rate in kg CO_2-e/Wh is already targeted to be reduced by 2030, and even further by 2050 according to the 2019 Climate Act. These target CO_2 emission rates are in this study assumed to be fixed targets. However, there might be uncertainty regarding these exact targets, as over the years these targets might be changed by even more or even less reduction. This uncertainty is not included in this study, but might influence the future scenarios, when the CO_2 emission rate targets are changed. If the expansion of AV's leads to rapidly increasing energy consumption for data, the targets for 2030 and 2050 might be in danger, as the planned replacement of fossil energy by renewable energy is not sufficient enough to cover the extra energy consumption of data.

In this study, the amount of data generated and transmitted is assumed to be independent of the travel speed, due to already uncertainty about the amount of data. However, as the spatial CO_2 emission rate is dependent on the travel speed, the amount of data generated and transmitted might actually be influenced by the travel speed. Further research is needed to obtain more insights regarding the amount of data generated and transmitted by an AV, dependent on the travel speed. Besides, in this study a single moving AV in operational phase is considered, that is always connected while driving. However, another possibility is that the vehicle is also connected while non-driving. This might possibly increase the instantaneous and spatial CO_2 emission rates of the data related aspects of an AV, for which further research is necessary.

As there are different stakeholders involved, it seems that the CO_2 emission from the data related aspects cannot only be translated into the future CO_2 norms for OEM's, but are also highly dependent on the energy intensity of wireless communication networks and the energy grid. However, based on the results of this study it seems necessary to evaluate if and which data related aspects should be included in these future CO_2 norms of vehicles.

6 Conclusion

In this study the main question is answered, whether the future propulsion-based CO_2 norms for 2025 and 2030 of vehicles can be met, on the basis of the CO_2 emission from the data related vehicle automation aspects. The CO_2 norm for 2025 is based on a 15% reduction in CO_2 emission with respect to the norm of 2021 and is targeted to be 0.09 kg CO_2-e/km, the norm for 2030 is based on a 37.5% reduction and is targeted to be 0.069 kg CO_2-e/km. As the CO_2 norms are defined per kilometer travelled, the CO_2 emissions corresponding to the data related aspects are also obtained per kilometer travelled, defined as the spatial CO_2 emission rates.

The data related aspects of vehicle automation are assumed to be: sensing components, the computing platform, disks inside the vehicle, wireless communication networks, and data centers. To obtain the spatial CO_2 emission rate of these data related aspects, the CO_2 emission per unit time, defined as the instantaneous CO_2 emission rate, is translated to the WLTP driving cycle. A computational model is developed to obtain the instantaneous CO_2 emission rate of the data related aspects for varying scenarios. The components and its values corresponding to the data related aspects are defined using literature and a survey. The survey is obtained to better specify the range of values corresponding to variable components, for which the exact value is uncertain. The scenarios differ based on the two sensing compositions, and three different future target energy grids. For each scenario, it is evaluated which data related aspects have the strongest influence on the resulting instantaneous CO_2 emission rate.

In summary, the spatial CO_2 emission of the data related aspect of vehicle automation, is in this study for most scenarios and situation higher than the future CO_2 norms for vehicles. From the sensitivity analysis, it can be concluded that compliance with the future CO_2 emission norms for vehicles, is mostly dependent on the data transmission rate from the vehicle to the data center, and the energy intensity of wireless communication networks. This is based on the assumption, that 30-50% of the data generated by the vehicle is sent to the data center. Moreover, it is assumed that the AV is only connected while driving, and the amounts of data generated and transmitted have been assumed to be independent of the travel speed. Another assumption is optimization of the energy intensity of wireless communication networks over the last couple of years, which translates to a smaller range of values. From the scenario analysis, it is concluded that the energy grid significantly influences whether the norms can be met. This is because, for both types of sensing compositions, the scenarios where the CO_2 emission rate corresponding to the energy grid of 2050 are used show the lowest resulting CO_2 emission. The Dutch energy grid is considered and fixed targets for the energy grid of 2030 and 2050 are assumed according to the 2019 Climate Act. Moreover, from the spatial CO_2 emission rate, it is concluded that the travel speed influences whether or not the CO_2 norms can be met for varying scenarios and situations. This is because, for all varying scenarios and situations, the lowest possible speed for which the norms can be met differs. In general, it shows that for scenarios and situations that resulted in the highest spatial CO_2 emission rates, the CO_2 norms of vehicles can only be met at higher speeds.

To conclude, further optimization of the energy consumption of wireless communication networks is necessary to ensure that high amounts of data transmission can be executed with less resulting CO_2 emission. Besides, reduction of the energy grid to the desired targets for 2030 and 2050 is important, as the CO_2 emission rate of the energy grid has a significant influence on the resulting CO_2 emission and expansion of AV's may lead to rapidly increasing energy consumption for data. Based on the scenarios corresponding to the two different sensing compositions, it can be concluded that the type of sensing composition does not significantly influence the resulting spatial CO_2 emission rate. Regarding the data transmission rate, it should be investigated whether the data transmission rate can be reduced. As the spatial CO_2 emission rates are dependent on speed, the amount of data generated and transmitted might also be influenced by the travel speed. Further research should be executed to gain more insight into the values of data transmission rates dependent on the travel speed. Moreover, further research is necessary to investigate data related CO_2 emissions of vehicles that are connected while non-driving, as this type of connected vehicles may result in different instantaneous and spatial CO_2 emission rates.

As it seems that the data related aspects of vehicle automation have a significant effect on the resulting CO_2 emission, it should be considered to include vehicle automation aspects into the CO_2 norms of vehicles. This is because, currently the future CO_2 norms of vehicles are only based on the propulsion of the vehicle, which are in most scenarios and situations below the resulting spatial CO_2 emission rates resulting from data related aspects of vehicle automation.

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A Assumptions and definitions

Data related aspects

- Aspects inside the vehicle related to data are assumed to be: the sensing components to gather data, the computing platform to process the data, and disks to enable storage within the vehicle [14, 21, 23].
- Aspects outside the vehicle related to data are assumed to be: wireless communication networks and data centers, both to enable data storage and high-definition (HD) map generation [13, 24].

Instantaneous CO_2 emission rate

- The instantaneous CO_2 emission rate is the CO_2 emission per unit time, defined in kg/h, and is independent of travel speed.
- The instantaneous CO_2 emission rate of the data related aspects is assumed to be determined by combining the power consumption of each data related aspect in Watt, with the CO_2 emission rate corresponding to the energy grid, defined in kg CO_2-e/Wh [19].

Spatial CO_2 emission rate

- The spatial CO_2 emission rate is the CO_2 emission per kilometer travelled, defined in kg/km, and is dependent of travel speed.
- The Worldwide harmonized Light-duty Test Procedure (WLTP) driving cycle is used to translate the instantaneous CO_2 emission rates to the spatial CO_2 emission rates, as the WLTP (compared to NEDC) is assumed to be a more accurate testing method [41].
- Situation 1 corresponds to the values of components, for which the resulting spatial CO_2 emission rate is lowest.
- Situation 2 corresponds to the values of components, for which the resulting spatial CO_2 emission rate is highest.
- Situation 3 corresponds to the values of components, for which the resulting spatial CO_2 emission rate is median.

Future CO_2 norms of vehicles

- The norms are based on European fleet-wide targets for light-duty vehicles, and are in this study assumed to be the future norms for a single moving AV in operational mode [8].
- The new car CO_2 emission is assumed to be reduced by 15% by 2025 and by 37.5% by 2030 with respect to the 2021 baseline, which refers to a CO_2 emission of 0.109 kg/km [17, 18].
- The future CO_2 norms of vehicles based on the WLTP driving cycle are: 0.09 kg CO_2-e/km for 2025, and 0.069 kg CO_2-e/km for 2030 [17].

Computational model

- The power consumption of the computing platform is assumed to be dependent on the power consumption of the computing platform itself, and the cooling rate to remove additional heat generated by the computing platform [22].
- The power consumption of the sensing components is assumed to be determined by multiplying the number of each type of sensing component used, with the power consumption of a single sensing component of the corresponding type in Watt [4, 14, 21].
- The power consumption of the disks inside the vehicle is assumed to be dependent on the power consumption per disk (defined in W/disk), the capacity per disk (defined in GB/disk) for both SSD and HDD type of disks, and the amount of data to be stored within the vehicle (defined in GB) [34, 42].
- The reuse of data is assumed to be only due to HD map generation, for which data is sent back to the vehicle from the data center [13].

- The power consumption of the wireless communication networks is assumed to be dependent on: the data transmission rate from the vehicle to the data center to enable data storage, the data transmission rate from the data center to the vehicle to provide the vehicle with HD map information, and the network intensity [13, 24].
- The data transmission rates are assumed to be expressed in GB/h [29, 31, 39].
- The energy intensity is assumed to be defined in Wh/GB [2, 3, 14, 21, 33].
- The power consumption of a data center related to a single moving AV in operational mode, is assumed to be dependent on both the power consumption of the data center IT equipment and the infrastructure [11, 34].
- The power consumption of the infrastructure of a data center is defined by the Power Usage Effectiveness (PUE) value, and refer refers to cooling and power conditioning systems [11, 34].
- The power consumption of the IT equipment is assumed to be dependent on the power consumption of servers for data processing, disks for data storage, and networking devices to ensure input/output of data [11, 34].
- The power consumption of the disks at the data center is assumed to be dependent on the power consumption per disk (defined in W/disk), the capacity per disk (defined in GB/disk) for both SSD and HDD type of disks, and the amount of data to be stored within the vehicle (defined in GB) [34, 42].
- The power consumption of a data center server is assumed to be dependent on the maximum power consumption and the utilization rate [34].
- It is assumed that the maximum power consumption of a data center server depends on the type of server, for which a distinction is made between a one processor socket volume server, and a two or more processor socket volume server [34].
- It is assumed that the utilization rate is a constant and depends on the type of data center used, for which there are three types: (1) internal, (2) service provider, (3) hyperscale [34].
- The power consumption of the networking components of a data center is assumed to be dependent on the power consumption of the different port speed categories, defined in W/port [34].
- The power consumption of the different port speed categories is assumed to be dependent on the data transmission rate both from the vehicle to the data center, and from the data center back to the vehicle.
- As the largest port category (J_{p4}) can process 144 TB/h, and this exceeds the maximum considered amount of data to be transmitted, the maximum number of ports of each category is assumed to be one.

Scenario design

- Sensing composition 1 corresponds to a Tesla Model S (SAE level 2), and composition 2 corresponds to a Waymo's Chrysler Pacifica (SAE level 4) [14, 21].
- The CO_2 emission rate of the energy grid is defined in kg CO_2-e/Wh, and is assumed to be currently 0.43 kg CO2-e/kWh for the Dutch energy grid [7].
- It is assumed that for the desired case of 2030, the CO_2 emission is reduced by 49% with respect to 1990 levels, according to the 2019 Climate Act [19].
- It is assumed that for the desired case of 2050, the CO_2 emission is reduced by 95% with respect to 1990 levels, according to the 2019 Climate Act [19].

Choice of component values

- Fixed values correspond to components of the data related aspects, that have a certain fixed value in each scenario.
- Variable values correspond to components of the data related aspects, that have a range of values due to uncertainty of the exact value.

- It is assumed that over the years DSRC is been replaced by wireless communication networks, and that 4G-LTE wireless communication is more preferred for traffic information, file download, or Internet accessing Gettman [16], Xu et al. [43].
- A LTE terminal might be used as on-board device to ensure 4G-LTE wireless communication. Its power consumption is minor compared to for example the computing platform, and is therefore not included in this study.
- The power consumption of HDD's is relatively fixed on a per disk level, and therefore assumed to be equal for both the HDD within the vehicle and at a data center in W/disk [34].
- The power consumption of SSD's is more related to the capacity, but is often still reported on per disk level, and therefore assumed to be equal for both the SDD within the vehicle and at a data center in W/disk [34].
- Based on the bandwidths of a 1S and 2S+ socket server, it is assumed that a 1S socket server should be sufficient to support the data transmission and storage of a single moving AV in its operational phase [12].
- A hyperscale data center is assumed for all scenarios, as hyperscale-sized data centers are referred to as warehouse scale data centers and are associated with service provider cloud data centers [34].
- It is assumed that the amount of data stored depends on the amount of data generated by the sensing components and the computing platform [14, 21]. The influence of travel speed on the amount of data generated and transmitted is not included in this study.
- It is assumed that 78% of the OEM's is planning, that 50-70% of all data generated is analysed within the vehicle itself, and the rest is sent to data centers [29]. So, it is also assumed that 30-50% of the generated data is sent to the data center.
- It is assumed that all data, that is transmitted to the data center, is actually stored at the data center.

B Computational model and scenario design

B.1 Model specification of instantaneous data related CO_2 emission rate

CO_2 emission in kg CO_2-e/h

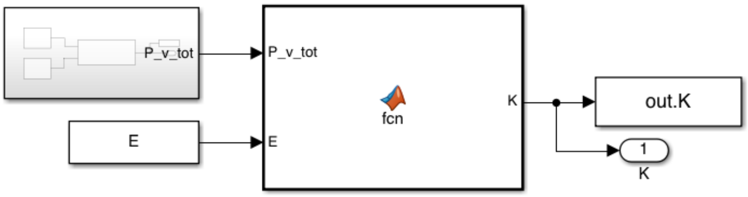


Figure 18: Resulting instantaneous CO_2 emission rate of the data related aspects

```
function K = fcn(P_v_tot, E)

K = P_v_tot * E;
```

Power consumption of the data related aspects in W

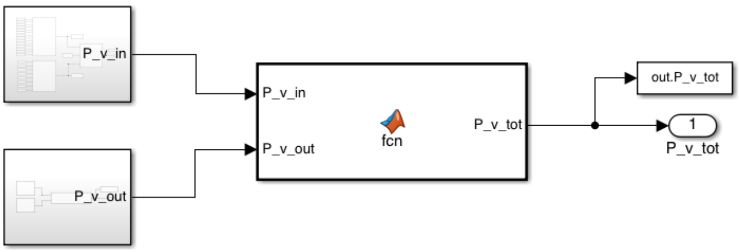


Figure 19: Resulting power consumption of the data related aspects in W

```
function P_v_tot = fcn(P_v_in, P_v_out)

P_v_tot = P_v_in + P_v_out;
```

Power consumption of the aspects inside the vehicle in W

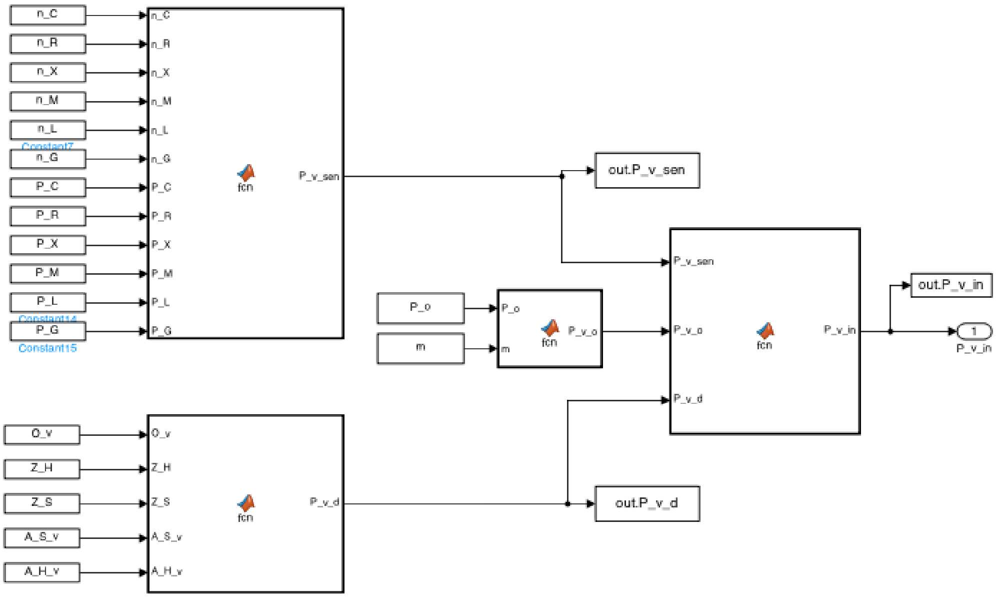


Figure 20: Resulting power consumption of the aspects inside of the vehicle in W

Total power consumption of aspects inside the vehicle

```
function P_v_in = fcn(P_v_sen, P_v_o, P_v_d)
P_v_in = P_v_sen + P_v_o + P_v_d;
```

Power consumption of the sensing components

```
function P_v_sen = fcn(n_C, n_R, n_X,n_M, n_L, n_G, P_C,...
    P_R, P_X, P_M, P_L, P_G)

P_v_sen = (n_C*P_C) + (n_R*P_R) + (n_X*P_X) + (n_M*P_M) + (n_L*P_L)...
    + (n_G*P_G);
```

Power consumption of the computing platform

```
function P_v_o = fcn(m, P_o)

P_v_o = (1 + m) * P_o;
```

Power consumption of disks within the vehicle

```
function P_v_d = fcn(O_v, Z_H, Z_S, A_S_v, A_H_v)

P_v_d = (O_v*(Z_H + Z_S))/(A_H_v + A_S_v);
```

Power consumption of the aspects outside of the vehicle in W

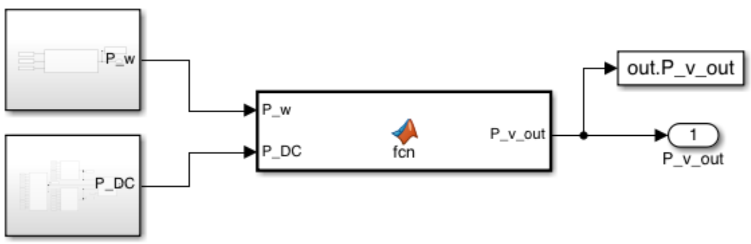


Figure 21: Resulting power consumption of the aspects outside of the vehicle in W

```
function P_v_out = fcn(P_w, P_DC)

P_v_out = P_w + P_DC;
```

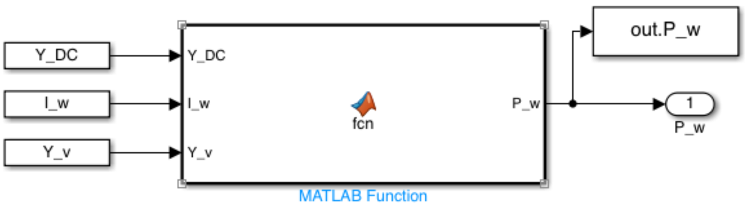


Figure 22: Resulting power consumption of the networking aspects outside of the vehicle in W

```
function P_w = fcn(Y_DC, I_w, Y_v)

P_w = (Y_DC + Y_v)* I_w;
```

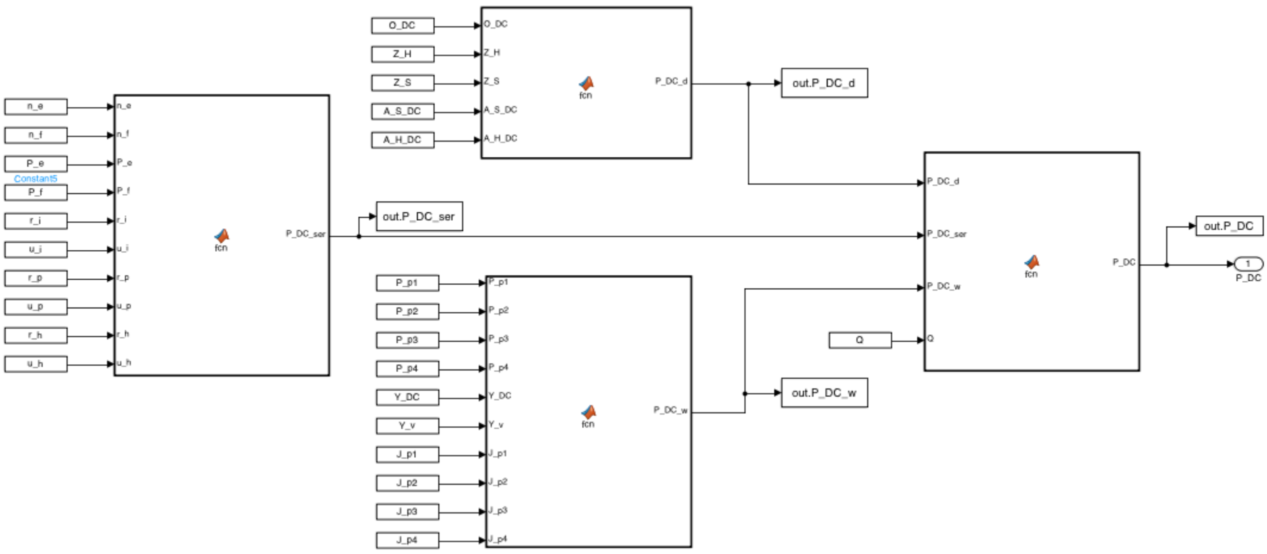


Figure 23: Resulting power consumption of the data center aspects outside of the vehicle in W

Total power consumption of the data center aspects

```
function P_DC = fcn(P_DC_d, P_DC_ser, P_DC_w, Q)

P_DC = (P_DC_d + P_DC_ser + P_DC_w)* Q;
```

Power consumption of the data center server

```
function P_DC_ser = fcn(n_e, n_f, P_e, P_f, r_i, u_i, r_p, u_p,...
    r_h, u_h)

P_DC_ser = (n_e*P_e + n_f*P_f) * (r_i*u_i + r_p*u_p + r_h*u_h);
```

Power consumption of the data center disks

```
function P_DC_d = fcn(O_DC, Z_H, Z_S, A_S_DC, A_H_DC)

P_DC_d = (O_DC*(Z_H + Z_S)) / (A_H_DC + A_S_DC);
```

Power consumption of the data center networking components

```
function P_DC_w = fcn(P_p1, P_p2, P_p3, P_p4, Y_DC, Y_v J_p1, J_p2,...
    J_p3, J_p4)

if Y_DC<= J_p1
    r_p1_DC = 1;
    r_p2_DC = 0;
    r_p3_DC = 0;
    r_p4_DC = 0;
else
    r_p1_DC = 0;
    r_p2_DC = 0;
    r_p3_DC = 0;
    r_p4_DC = 0;
end

if Y_DC > J_p1 && Y_DC <= J_p2
    r_p1_DC = 0;
    r_p2_DC = 1;
    r_p3_DC = 0;
    r_p4_DC = 0;
else
    r_p1_DC = 0;
    r_p2_DC = 0;
    r_p3_DC = 0;
    r_p4_DC = 0;
end

if Y_DC > J_p2 && Y_DC <= J_p3
    r_p1_DC = 0;
    r_p2_DC = 0;
    r_p3_DC = 1;
    r_p4_DC = 0;
else
    r_p1_DC = 0;
    r_p2_DC = 0;
    r_p3_DC = 0;
    r_p4_DC = 0;
end

if Y_DC > J_p3 && Y_DC <= J_p4
    r_p1_DC = 0;
    r_p2_DC = 0;
    r_p3_DC = 0;
    r_p4_DC = 1;
else
    r_p1_DC = 0;
    r_p2_DC = 0;
    r_p3_DC = 0;
    r_p4_DC = 0;
end


%%%%%%%

if Y_v<= J_p1
    r_p1_v = 1;
    r_p2_v = 0;
    r_p3_v = 0;
    r_p4_v = 0;
else
    r_p1_v = 0;
    r_p2_v = 0;
    r_p3_v = 0;
    r_p4_v = 0;
end

if Y_v > J_p1 && Y_v <= J_p2
    r_p1_v = 0;
    r_p2_v = 1;
    r_p3_v = 0;
    r_p4_v = 0;
else
    r_p1_v = 0;
    r_p2_v = 0;
    r_p3_v = 0;
    r_p4_v = 0;
end

if Y_v > J_p2 && Y_v <= J_p3
    r_p1_v = 0;
    r_p2_v = 0;
    r_p3_v = 1;
    r_p4_v = 0;
else
    r_p1_v = 0;
    r_p2_v = 0;
    r_p3_v = 0;
    r_p4_v = 0;
end

if Y_v > J_p3 && Y_v <= J_p4
    r_p1_v = 0;
    r_p2_v = 0;
    r_p3_v = 0;
    r_p4_v = 1;
else
    r_p1_v = 0;
    r_p2_v = 0;
    r_p3_v = 0;
    r_p4_v = 0;
end


P_DC_w = ((r_p1_DC + r_p1_v)*P_p1) + ((r_p2_DC + r_p2_v)*P_p2)...
    + ((r_p3_DC + r_p3_v)*P_p3) + ((r_p4_DC + r_p4_v)*P_p4);
```

B.2 Sensitivity analysis design of instantaneous data related CO_2 emission rate

Table 7: Overview parameter set scenario 1, 2, 3

	I_w [Wh/GB]	O_{DC} [GB]	O_v [GB]	P_o [W]	Y_{DC} [GB/h]	Y_v [GB/h]
1	82.21	360.72	2746.28	314.71	905.35	0.000263
2	90.96	1681.24	1643.85	1512.11	218.75	0.000261
3	16.19	672.06	3440.25	281.64	1272.28	0.000274
4	91.68	1126.06	2283.69	337.46	1005.71	0.000250
5	64.71	367.96	1528.17	1203.65	1475.81	0.000253
6	13.36	1279.50	3968.92	386.11	1484.04	0.000245
7	30.74	571.27	3707.29	1774.12	1355.85	0.000277
8	56.50	1388.34	2355.60	1772.96	92.10	0.000265
9	95.92	1461.74	2655.65	1589.97	165.64	0.000259
10	96.63	1584.86	2508.65	488.34	689.58	0.000265
11	19.13	963.13	934.92	1469.08	1130.93	0.000261
12	97.18	197.01	1322.87	1197.78	1389.10	0.000266
13	95.89	500.26	2026.86	2072.00	873.46	0.000261
14	50.60	1929.95	1029.30	1448.66	1734.92	0.000268
15	80.83	340.23	3576.04	1739.84	1522.62	0.000261
16	17.62	1747.11	881.08	1073.11	2045.51	0.000279
17	44.49	1146.55	1010.35	1031.92	1131.91	0.000249
18	91.91	2102.93	781.27	1787.90	701.16	0.000244
19	80.05	185.22	1017.58	360.60	242.57	0.000244
20	96.11	946.70	1880.71	456.22	1298.25	0.000243
21	66.95	244.71	1363.76	533.60	1648.90	0.000256
22	7.43	2031.40	3904.10	952.16	906.54	0.000258
23	85.52	31.58	1857.93	1799.57	211.64	0.000254
24	93.66	1640.77	839.80	1745.67	578.59	0.000270
25	69.16	1729.33	3827.35	316.35	342.90	0.000265
26	76.74	1836.69	4137.98	968.17	608.95	0.000270
27	75.34	198.29	1893.87	1213.71	941.28	0.000277
28	41.65	857.09	534.03	1001.92	1123.15	0.000278
29	66.93	564.80	1143.71	1463.80	977.51	0.000248
30	20.43	1693.32	1768.78	1408.22	1850.64	0.000245
31	71.78	923.17	2541.22	761.78	1104.16	0.000267
32	7.06	1924.33	1160.92	1030.50	1993.22	0.000244
33	30.58	401.80	2574.20	229.80	1354.14	0.000261
34	8.43	573.01	3023.83	2093.34	2022.62	0.000261
35	13.32	325.95	993.03	521.63	524.76	0.000274
36	83.05	306.16	560.17	404.36	1434.39	0.000259
37	70.70	1837.94	1303.91	916.52	625.78	0.000256
38	34.44	1232.96	1395.61	581.18	1425.37	0.000266
39	95.22	1170.61	1832.87	1142.16	1474.12	0.000269
40	7.31	324.73	2180.10	853.19	163.94	0.000260
41	46.12	1803.97	427.81	2030.94	554.18	0.000254
42	40.63	1321.44	1162.04	1970.72	489.94	0.000246
43	77.49	755.07	3396.41	301.35	1417.07	0.000263
44	80.34	1094.13	194.23	1619.64	1785.92	0.000250
45	21.94	861.32	3926.82	717.79	741.52	0.000242
46	51.02	180.60	3103.14	1013.54	1652.48	0.000270
47	46.78	523.11	2100.24	1254.10	1432.74	0.000250
48	66.05	279.53	2473.30	2013.83	35.93	0.000257
49	72.10	406.10	1057.49	1003.74	1279.89	0.000267
50	76.45	523.18	1976.76	2091.39	829.90	0.000254
51	30.50	893.61	4068.85	780.00	1935.50	0.000269
52	69.25	125.63	2341.70	1548.91	24.30	0.000256
53	66.89	1907.76	2235.19	1482.04	988.00	0.000267
54	19.61	1995.65	1033.89	1237.28	908.41	0.000268
55	15.42	1047.36	2101.44	1543.16	984.80	0.000257
56	51.84	1044.00	2662.23	1482.40	1630.84	0.000241
57	96.14	727.43	2890.73	542.73	695.58	0.000253
58	36.68	1902.20	1713.99	446.30	1661.30	0.000257
59	60.19	793.29	1597.49	2122.23	1006.61	0.000251
60	25.49	254.21	4172.14	529.24	96.61	0.000248
61	76.12	1651.92	229.58	262.72	389.32	0.000272
62	28.49	836.10	3745.56	1279.75	1529.72	0.000257
63	52.57	526.82	3862.23	1896.71	1011.06	0.000275
64	71.11	865.71	3376.37	1487.49	340.95	0.000255
65	89.53	223.40	482.56	566.39	734.54	0.000270
66	96.09	297.61	1159.50	909.80	1290.80	0.000256
67	56.53	1989.94	1464.40	1086.44	422.48	0.000272
68	17.31	2019.36	2893.19	2088.67	1564.55	0.000270
69	18.33	1223.57	639.56	500.92	529.24	0.000255
70	28.72	146.79	3065.37	1846.03	1938.49	0.000249
71	84.71	512.38	515.95	1440.53	584.00	0.000271
72	28.41	759.68	2785.44	923.95	1621.11	0.000277
73	82.17	1737.46	2123.33	567.34	416.03	0.000253
74	27.38	54.08	3305.29	1023.96	622.51	0.000266
75	93.21	111.78	3039.69	1127.41	212.25	0.000257
76	37.60	374.94	3822.54	432.06	1225.66	0.000273
77	22.87	1377.97	3769.44	1334.21	1449.51	0.000270
78	28.10	1550.54	1459.44	635.19	1163.79	0.000247
79	63.14	1375.11	2972.10	940.01	911.29	0.000274
80	49.44	963.92	893.71	1321.67	1368.21	0.000279
81	37.76	1164.66	199.71	684.47	1374.84	0.000260
82	83.76	640.94	3160.16	758.81	1440.43	0.000275
83	60.19	1577.64	2147.59	1387.28	1350.12	0.000263
84	56.77	416.65	2064.20	710.40	1996.46	0.000246
85	92.05	1456.64	3826.69	1786.10	458.39	0.000248
86	31.44	405.27	2603.34	2090.64	1503.66	0.000256
87	76.69	791.70	2635.70	1605.00	515.41	0.000269
88	76.36	1328.88	3638.83	861.62	271.33	0.000273
89	40.52	1651.87	3414.98	1323.75	1290.62	0.000271
90	58.51	191.38	2465.82	407.35	962.28	0.000253
91	11.28	1963.48	831.95	1943.74	980.22	0.000261
92	9.18	1642.44	1068.48	1892.45	1404.77	0.000244
93	54.96	1038.86	3751.14	1773.37	1631.10	0.000244
94	78.80	932.45	191.97	701.64	753.54	0.000245
95	93.67	955.28	2105.60	1343.54	1404.90	0.000267
96	16.47	661.89	769.73	243.31	891.30	0.000260
97	58.61	1084.23	4133.55	1018.20	1780.77	0.000247
98	49.06	1088.95	3029.97	801.67	1761.95	0.000260
99	5.14	1730.01	2149.46	510.70	557.63	0.000246
100	36.36	1682.38	2027.55	543.95	1303.48	0.000242

Table 8: Overview parameter set scenario 4, 5, 6

	$\mathbf{I}_w$ [Wh/GB]	$\mathbf{O}_{DC}$ [GB]	$\mathbf{O}_v$ [GB]	$\mathbf{P}_o$ [W]	$\mathbf{Y}_{DC}$ [GB/h]	$\mathbf{Y}_v$ [GB/h]
1	85.67	1230.95	3010.12	2100.79	1385.26	0.000271
2	57.81	1861.98	676.71	527.91	794.76	0.000267
3	93.24	779.37	3175.12	695.99	2167.59	0.000240
4	70.88	989.27	584.80	963.44	514.81	0.000273
5	59.95	151.40	614.99	342.37	1430.73	0.000276
6	82.28	414.16	2828.24	1516.20	1329.23	0.000270
7	88.39	1452.88	1508.88	974.20	863.56	0.000242
8	98.94	742.91	2883.62	2090.97	339.48	0.000255
9	4.05	1956.90	3286.83	973.80	89.15	0.000268
10	87.08	288.09	2584.88	1394.17	935.99	0.000269
11	62.81	2149.23	3248.34	497.01	429.12	0.000249
12	99.04	1190.21	1111.32	933.71	1587.54	0.000251
13	54.66	1547.21	3226.87	510.02	827.46	0.000267
14	50.03	2172.91	4223.63	1658.61	1835.16	0.000259
15	80.93	650.99	3785.12	1876.02	1605.62	0.000265
16	25.87	921.90	482.77	874.89	1256.60	0.000249
17	51.82	1029.51	1668.03	1518.97	413.62	0.000247
18	90.48	1669.20	1679.71	765.94	2082.86	0.000273
19	59.17	1785.21	3015.67	1220.93	602.82	0.000270
20	85.14	249.73	2647.29	1801.58	2012.71	0.000277
21	74.91	416.32	3457.01	1349.57	513.96	0.000244
22	60.25	804.52	1673.17	845.14	834.30	0.000247
23	27.69	156.67	989.50	775.71	222.53	0.000244
24	67.98	1151.50	484.60	1070.79	1404.35	0.000259
25	12.01	753.65	3383.28	1013.17	421.67	0.000248
26	64.09	411.09	988.00	891.88	131.75	0.000275
27	67.45	482.25	1760.39	1274.21	1581.98	0.000244
28	74.06	1971.16	2452.02	1628.66	778.43	0.000242
29	89.51	1479.79	1086.47	1016.42	1448.20	0.000262
30	98.30	1037.27	2833.41	1026.08	856.34	0.000270
31	77.83	1986.09	2167.35	440.26	1377.04	0.000252
32	59.82	257.84	760.31	247.01	81.70	0.000247
33	93.12	1629.82	3425.57	758.32	1982.74	0.000253
34	59.69	1609.98	543.56	810.91	1747.47	0.000248
35	5.63	1237.00	1361.90	1457.70	1630.47	0.000260
36	15.60	429.32	1122.09	2041.14	1774.32	0.000276
37	86.82	1312.60	2363.59	2000.35	855.14	0.000265
38	50.49	676.85	505.04	1080.97	1355.51	0.000244
39	85.11	322.24	1832.48	662.68	1266.15	0.000255
40	24.10	490.07	561.50	1669.74	1168.97	0.000242
41	57.02	1949.32	592.96	1660.95	623.66	0.000260
42	64.47	188.21	3436.13	1625.01	567.12	0.000257
43	7.07	553.98	1351.34	1630.86	1001.27	0.000279
44	63.01	150.36	2670.95	403.79	522.39	0.000272
45	38.79	980.07	4197.51	1511.32	1755.80	0.000259
46	8.76	63.81	1947.41	1091.31	2144.28	0.000275
47	51.00	1954.13	3056.80	608.20	99.54	0.000245
48	22.48	455.97	3324.76	389.55	1180.97	0.000255
49	15.82	235.08	1948.08	1784.56	221.62	0.000277
50	23.73	692.73	2890.76	536.72	1750.75	0.000276
51	18.07	1010.72	582.26	514.71	2150.79	0.000268
52	22.15	252.83	4067.80	1481.36	178.57	0.000264
53	8.09	2164.14	910.96	1920.81	2044.40	0.000254
54	64.98	745.61	1243.94	1193.86	74.27	0.000277
55	31.06	671.31	3492.82	1552.00	1497.86	0.000245
56	55.71	168.09	2180.56	495.51	1711.50	0.000269
57	70.74	673.22	3370.69	2034.45	1177.71	0.000265
58	51.92	134.53	1793.11	1240.66	1928.83	0.000273
59	55.44	1116.31	1272.53	1507.81	1958.01	0.000256
60	46.74	1663.79	275.50	270.35	1374.03	0.000270
61	15.90	1385.01	2966.04	1756.91	330.25	0.000273
62	51.07	227.64	1935.06	1640.34	501.19	0.000253
63	85.89	208.33	2028.86	431.24	424.93	0.000262
64	87.90	1697.61	2697.70	1210.19	124.84	0.000279
65	29.95	1971.12	369.28	826.90	264.11	0.000262
66	24.01	1176.92	1453.88	1251.37	1353.73	0.000253
67	58.24	268.84	3386.61	967.45	2044.96	0.000264
68	65.47	1801.47	3063.91	998.64	793.44	0.000254
69	44.03	758.46	648.16	547.74	913.57	0.000270
70	23.77	664.09	668.54	691.36	2140.53	0.000256
71	95.00	1631.47	508.65	239.51	2057.62	0.000259
72	11.88	57.51	151.08	1977.15	1482.47	0.000267
73	14.15	139.01	1907.75	1457.72	2148.98	0.000278
74	17.64	1463.81	2891.07	1994.35	1675.35	0.000253
75	19.98	1325.98	3175.96	514.60	755.47	0.000273
76	63.61	1160.52	2365.02	1972.19	1451.97	0.000269
77	59.08	1595.96	578.30	1728.92	557.57	0.000278
78	9.00	1547.93	2790.37	1310.91	667.37	0.000241
79	93.40	1706.45	653.09	1046.63	1490.03	0.000254
80	73.95	651.27	686.10	695.65	1164.25	0.000266
81	74.83	1516.45	535.05	1646.74	915.63	0.000251
82	10.09	1225.89	718.78	639.96	1324.20	0.000249
83	86.60	883.40	829.70	323.50	1640.46	0.000268
84	93.70	167.12	948.13	1676.34	1283.34	0.000265
85	98.50	1703.88	1460.94	1491.39	1215.46	0.000263
86	86.46	757.36	1456.49	1576.07	1283.42	0.000266
87	79.41	1335.38	1038.29	1435.33	1129.98	0.000242
88	53.28	1620.65	1179.91	1006.25	212.03	0.000254
89	21.05	259.55	3895.06	951.83	1574.27	0.000258
90	42.26	308.90	3092.63	1770.25	2165.78	0.000249
91	16.86	1210.65	2468.77	810.73	793.61	0.000268
92	6.97	1073.11	898.15	1767.17	2112.53	0.000274
93	94.16	1939.77	1014.89	1718.18	776.32	0.000251
94	32.93	1744.06	445.18	1839.76	1931.36	0.000269
95	32.37	1605.86	3983.38	1172.84	1007.81	0.000245
96	35.96	145.18	3107.41	1423.01	919.56	0.000273
97	48.84	191.27	2477.45	2029.52	501.04	0.000245
98	66.23	224.72	1443.80	1054.19	304.12	0.000263
99	6.42	1742.75	821.04	315.48	696.04	0.000254
100	84.85	2052.12	2751.16	1867.63	1588.25	0.000272

C Results

C.1 Sensitivity analysis of instantaneous data related CO_2 emission rate

Scenario 1

Table 9: Instantaneous CO_2 emission rates from the sensitivity analysis for scenario 1

	I_w	O_{DC}	O_v	P_o	Y_{DC}	Y_v	K [kg CO_2-e/h]
1	82.21	360.72	2746.28	314.71	905.35	0.000263	32.31
2	90.96	1681.24	1643.85	1512.11	218.75	0.000261	9.76
3	16.19	672.06	3440.25	281.64	1272.28	0.000274	9.14
4	91.68	1126.06	2283.69	337.46	1005.71	0.000250	39.97
5	64.71	367.96	1528.17	1203.65	1475.81	0.000253	42.03
6	13.36	1279.50	3968.92	386.11	1484.04	0.000245	8.89
7	30.74	571.27	3707.29	1774.12	1355.85	0.000277	19.33
8	56.50	1388.34	2355.60	1772.96	92.10	0.000265	3.65
9	95.92	1461.74	2655.65	1589.97	165.64	0.000259	8.10
10	96.63	1584.86	2508.65	488.34	689.58	0.000265	29.08
11	19.13	963.13	934.92	1469.08	1130.93	0.000261	10.47
12	97.18	197.01	1322.87	1197.78	1389.10	0.000266	59.01
13	95.89	500.26	2026.86	2072.00	873.46	0.000261	37.65
14	50.60	1929.95	1029.30	1448.66	1734.92	0.000268	38.90
15	80.83	340.23	3576.04	1739.84	1522.62	0.000261	54.31
16	17.62	1747.11	881.08	1073.11	2045.51	0.000279	16.37
17	44.49	1146.55	1010.35	1031.92	1131.91	0.000249	22.49
18	91.91	2102.93	781.27	1787.90	701.16	0.000244	29.13
19	80.05	185.22	1017.58	360.60	242.57	0.000244	8.68
20	96.11	946.70	1880.71	456.22	1298.25	0.000243	54.06
21	66.95	244.71	1363.76	533.60	1648.90	0.000256	47.93
22	7.43	2031.40	3904.10	952.16	906.54	0.000258	3.69
23	85.52	31.58	1857.93	1799.57	211.64	0.000254	9.21
24	93.66	1640.77	839.80	1745.67	578.59	0.000270	24.68
25	69.16	1729.33	3827.35	316.35	342.90	0.000265	10.50
26	76.74	1836.69	4137.98	968.17	608.95	0.000270	20.90
27	75.34	198.29	1893.87	1213.71	941.28	0.000277	31.48
28	41.65	857.09	534.03	1001.92	1123.15	0.000278	20.93
29	66.93	564.80	1143.71	1463.80	977.51	0.000248	29.30
30	20.43	1693.32	1768.78	1408.22	1850.64	0.000245	17.39
31	71.78	923.17	2541.22	761.78	1104.16	0.000267	34.72
32	7.06	1924.33	1160.92	1030.50	1993.22	0.000244	6.89
33	30.58	401.80	2574.20	229.80	1354.14	0.000261	18.04
34	8.43	573.01	3023.83	2093.34	2022.62	0.000261	8.99
35	13.32	325.95	993.03	521.63	524.76	0.000274	3.46
36	83.05	306.16	560.17	404.36	1434.39	0.000259	51.58
37	70.70	1837.94	1303.91	916.52	625.78	0.000256	19.78
38	34.44	1232.96	1395.61	581.18	1425.37	0.000266	21.61
39	95.22	1170.61	1832.87	1142.16	1474.12	0.000269	61.28
40	7.31	324.73	2180.10	853.19	163.94	0.000260	1.22
41	46.12	1803.97	427.81	2030.94	554.18	0.000254	12.59
42	40.63	1321.44	1162.04	1970.72	489.94	0.000246	10.11
43	77.49	755.07	3396.41	301.35	1417.07	0.000263	47.51
44	80.34	1094.13	194.23	1619.64	1785.92	0.000250	62.98
45	21.94	861.32	3926.82	717.79	741.52	0.000242	7.61
46	51.02	180.60	3103.14	1013.54	1652.48	0.000270	37.08
47	46.78	523.11	2100.24	1254.10	1432.74	0.000250	29.83
48	66.05	279.53	2473.30	2013.83	35.93	0.000257	2.61
49	72.10	406.10	1057.49	1003.74	1279.89	0.000267	40.50
50	76.45	523.18	1976.76	2091.39	829.90	0.000254	28.93
51	30.50	893.61	4068.85	780.00	1935.50	0.000269	26.04
52	69.25	125.63	2341.70	1548.91	24.30	0.000256	1.96
53	66.89	1907.76	2235.19	1482.04	988.00	0.000267	29.60
54	19.61	1995.65	1033.89	1237.28	908.41	0.000268	8.66
55	15.42	1047.36	2101.44	1543.16	984.80	0.000257	7.76
56	51.84	1044.00	2662.23	1482.40	1630.84	0.000241	37.54
57	96.14	727.43	2890.73	542.73	695.58	0.000253	29.23
58	36.68	1902.20	1713.99	446.30	1661.30	0.000257	26.60
59	60.19	793.29	1597.49	2122.23	1006.61	0.000251	27.72
60	25.49	254.21	4172.14	529.24	96.61	0.000248	1.53
61	76.12	1651.92	229.58	262.72	389.32	0.000272	12.99
62	28.49	836.10	3745.56	1279.75	1529.72	0.000257	19.78
63	52.57	526.82	3862.23	1896.71	1011.06	0.000275	24.37
64	71.11	865.71	3376.37	1487.49	340.95	0.000255	11.62
65	89.53	223.40	482.56	566.39	734.54	0.000270	28.76
66	96.09	297.61	1159.50	909.80	1290.80	0.000256	54.08
67	56.53	1989.94	1464.40	1086.44	422.48	0.000272	11.15
68	17.31	2019.36	2893.19	2088.67	1564.55	0.000270	13.30
69	18.33	1223.57	639.56	500.92	529.24	0.000255	4.61
70	28.72	146.79	3065.37	1846.03	1938.49	0.000249	25.41
71	84.71	512.38	515.95	1440.53	584.00	0.000271	22.42
72	28.41	759.68	2785.44	923.95	1621.11	0.000277	20.57
73	82.17	1737.46	2123.33	567.34	416.03	0.000253	15.19
74	27.38	54.08	3305.29	1023.96	622.51	0.000266	8.17
75	93.21	111.78	3039.69	1127.41	212.25	0.000257	9.43
76	37.60	374.94	3822.54	432.06	1225.66	0.000273	20.21
77	22.87	1377.97	3769.44	1334.21	1449.51	0.000270	15.34
78	28.10	1550.54	1459.44	635.19	1163.79	0.000247	14.60
79	63.14	1375.11	2972.10	940.01	911.29	0.000274	25.52
80	49.44	963.92	893.71	1321.67	1368.21	0.000279	30.14
81	37.76	1164.66	199.71	684.47	1374.84	0.000260	22.89
82	83.76	640.94	3160.16	758.81	1440.43	0.000275	52.52
83	60.19	1577.64	2147.59	1387.28	1350.12	0.000263	36.06
84	56.77	416.65	2064.20	710.40	1996.46	0.000246	49.34
85	92.05	1456.64	3826.69	1786.10	458.39	0.000248	19.57
86	31.44	405.27	2603.34	2090.64	1503.66	0.000256	21.98
87	76.69	791.70	2635.70	1605.00	515.41	0.000269	18.28
88	76.36	1328.88	3638.83	861.62	271.33	0.000273	9.63
89	40.52	1651.87	3414.98	1323.75	1290.62	0.000271	23.56
90	58.51	191.38	2465.82	407.35	962.28	0.000253	24.58
91	11.28	1963.48	831.95	1943.74	980.22	0.000261	6.29
92	9.18	1642.44	1068.48	1892.45	1404.77	0.000244	7.04
93	54.96	1038.86	3751.14	1773.37	1631.10	0.000244	39.96
94	78.80	932.45	191.97	701.64	753.54	0.000245	26.12
95	93.67	955.28	2105.60	1343.54	1404.90	0.000267	57.66
96	16.47	661.89	769.73	243.31	891.30	0.000260	6.55
97	58.61	1084.23	4133.55	1018.20	1780.77	0.000247	45.72
98	49.06	1088.95	3029.97	801.67	1761.95	0.000260	37.84
99	5.14	1730.01	2149.46	510.70	557.63	0.000246	1.68
100	36.36	1682.38	2027.55	543.95	1303.48	0.000242	20.85

Scenario 2

Table 10: Instantaneous CO_2 emission rates from the sensitivity analysis for scenario 2

	I_w	O_{DC}	O_v	P_o	Y_{DC}	Y_v	K [kg CO_2-e/h]
1	82.21	360.72	2746.28	314.71	905.35	0.000263	19.38
2	90.96	1681.24	1643.85	1512.11	218.75	0.000261	5.86
3	16.19	672.06	3440.25	281.64	1272.28	0.000274	5.48
4	91.68	1126.06	2283.69	337.46	1005.71	0.000250	23.98
5	64.71	367.96	1528.17	1203.65	1475.81	0.000253	25.22
6	13.36	1279.50	3968.92	386.11	1484.04	0.000245	5.33
7	30.74	571.27	3707.29	1774.12	1355.85	0.000277	11.60
8	56.50	1388.34	2355.60	1772.96	92.10	0.000265	2.19
9	95.92	1461.74	2655.65	1589.97	165.64	0.000259	4.86
10	96.63	1584.86	2508.65	488.34	689.58	0.000265	17.45
11	19.13	963.13	934.92	1469.08	1130.93	0.000261	6.28
12	97.18	197.01	1322.87	1197.78	1389.10	0.000266	35.41
13	95.89	500.26	2026.86	2072.00	873.46	0.000261	22.59
14	50.60	1929.95	1029.30	1448.66	1734.92	0.000268	23.34
15	80.83	340.23	3576.04	1739.84	1522.62	0.000261	32.58
16	17.62	1747.11	881.08	1073.11	2045.51	0.000279	9.82
17	44.49	1146.55	1010.35	1031.92	1131.91	0.000249	13.50
18	91.91	2102.93	781.27	1787.90	701.16	0.000244	17.48
19	80.05	185.22	1017.58	360.60	242.57	0.000244	5.21
20	96.11	946.70	1880.71	456.22	1298.25	0.000243	32.44
21	66.95	244.71	1363.76	533.60	1648.90	0.000256	28.76
22	7.43	2031.40	3904.10	952.16	906.54	0.000258	2.21
23	85.52	31.58	1857.93	1799.57	211.64	0.000254	5.53
24	93.66	1640.77	839.80	1745.67	578.59	0.000270	14.81
25	69.16	1729.33	3827.35	316.35	342.90	0.000265	6.30
26	76.74	1836.69	4137.98	968.17	608.95	0.000270	12.54
27	75.34	198.29	1893.87	1213.71	941.28	0.000277	18.89
28	41.65	857.09	534.03	1001.92	1123.15	0.000278	12.56
29	66.93	564.80	1143.71	1463.80	977.51	0.000248	17.58
30	20.43	1693.32	1768.78	1408.22	1850.64	0.000245	10.43
31	71.78	923.17	2541.22	761.78	1104.16	0.000267	20.83
32	7.06	1924.33	1160.92	1030.50	1993.22	0.000244	4.13
33	30.58	401.80	2574.20	229.80	1354.14	0.000261	10.83
34	8.43	573.01	3023.83	2093.34	2022.62	0.000261	5.39
35	13.32	325.95	993.03	521.63	524.76	0.000274	2.07
36	83.05	306.16	560.17	404.36	1434.39	0.000259	30.95
37	70.70	1837.94	1303.91	916.52	625.78	0.000256	11.87
38	34.44	1232.96	1395.61	581.18	1425.37	0.000266	12.96
39	95.22	1170.61	1832.87	1142.16	1474.12	0.000269	36.77
40	7.31	324.73	2180.10	853.19	163.94	0.000260	0.73
41	46.12	1803.97	427.81	2030.94	554.18	0.000254	7.55
42	40.63	1321.44	1162.04	1970.72	489.94	0.000246	6.07
43	77.49	755.07	3396.41	301.35	1417.07	0.000263	28.51
44	80.34	1094.13	194.23	1619.64	1785.92	0.000250	37.79
45	21.94	861.32	3926.82	717.79	741.52	0.000242	4.56
46	51.02	180.60	3103.14	1013.54	1652.48	0.000270	22.25
47	46.78	523.11	2100.24	1254.10	1432.74	0.000250	17.90
48	66.05	279.53	2473.30	2013.83	35.93	0.000257	1.57
49	72.10	406.10	1057.49	1003.74	1279.89	0.000267	24.30
50	76.45	523.18	1976.76	2091.39	829.90	0.000254	17.36
51	30.50	893.61	4068.85	780.00	1935.50	0.000269	15.63
52	69.25	125.63	2341.70	1548.91	24.30	0.000256	1.18
53	66.89	1907.76	2235.19	1482.04	988.00	0.000267	17.76
54	19.61	1995.65	1033.89	1237.28	908.41	0.000268	5.19
55	15.42	1047.36	2101.44	1543.16	984.80	0.000257	4.66
56	51.84	1044.00	2662.23	1482.40	1630.84	0.000241	22.53
57	96.14	727.43	2890.73	542.73	695.58	0.000253	17.54
58	36.68	1902.20	1713.99	446.30	1661.30	0.000257	15.96
59	60.19	793.29	1597.49	2122.23	1006.61	0.000251	16.63
60	25.49	254.21	4172.14	529.24	96.61	0.000248	0.92
61	76.12	1651.92	229.58	262.72	389.32	0.000272	7.80
62	28.49	836.10	3745.56	1279.75	1529.72	0.000257	11.87
63	52.57	526.82	3862.23	1896.71	1011.06	0.000275	14.62
64	71.11	865.71	3376.37	1487.49	340.95	0.000255	6.97
65	89.53	223.40	482.56	566.39	734.54	0.000270	17.26
66	96.09	297.61	1159.50	909.80	1290.80	0.000256	32.45
67	56.53	1989.94	1464.40	1086.44	422.48	0.000272	6.69
68	17.31	2019.36	2893.19	2088.67	1564.55	0.000270	7.98
69	18.33	1223.57	639.56	500.92	529.24	0.000255	2.76
70	28.72	146.79	3065.37	1846.03	1938.49	0.000249	15.24
71	84.71	512.38	515.95	1440.53	584.00	0.000271	13.45
72	28.41	759.68	2785.44	923.95	1621.11	0.000277	12.34
73	82.17	1737.46	2123.33	567.34	416.03	0.000253	9.11
74	27.38	54.08	3305.29	1023.96	622.51	0.000266	4.90
75	93.21	111.78	3039.69	1127.41	212.25	0.000257	5.66
76	37.60	374.94	3822.54	432.06	1225.66	0.000273	12.13
77	22.87	1377.97	3769.44	1334.21	1449.51	0.000270	9.20
78	28.10	1550.54	1459.44	635.19	1163.79	0.000247	8.76
79	63.14	1375.11	2972.10	940.01	911.29	0.000274	15.31
80	49.44	963.92	893.71	1321.67	1368.21	0.000279	18.09
81	37.76	1164.66	199.71	684.47	1374.84	0.000260	13.74
82	83.76	640.94	3160.16	758.81	1440.43	0.000275	31.51
83	60.19	1577.64	2147.59	1387.28	1350.12	0.000263	21.63
84	56.77	416.65	2064.20	710.40	1996.46	0.000246	29.60
85	92.05	1456.64	3826.69	1786.10	458.39	0.000248	11.74
86	31.44	405.27	2603.34	2090.64	1503.66	0.000256	13.19
87	76.69	791.70	2635.70	1605.00	515.41	0.000269	10.97
88	76.36	1328.88	3638.83	861.62	271.33	0.000273	5.78
89	40.52	1651.87	3414.98	1323.75	1290.62	0.000271	14.14
90	58.51	191.38	2465.82	407.35	962.28	0.000253	14.75
91	11.28	1963.48	831.95	1943.74	980.22	0.000261	3.77
92	9.18	1642.44	1068.48	1892.45	1404.77	0.000244	4.22
93	54.96	1038.86	3751.14	1773.37	1631.10	0.000244	23.98
94	78.80	932.45	191.97	701.64	753.54	0.000245	15.67
95	93.67	955.28	2105.60	1343.54	1404.90	0.000267	34.60
96	16.47	661.89	769.73	243.31	891.30	0.000260	3.93
97	58.61	1084.23	4133.55	1018.20	1780.77	0.000247	27.43
98	49.06	1088.95	3029.97	801.67	1761.95	0.000260	22.71
99	5.14	1730.01	2149.46	510.70	557.63	0.000246	1.01
100	36.36	1682.38	2027.55	543.95	1303.48	0.000242	12.51

Scenario 3

Table 11: Instantaneous CO_2 emission rates from the sensitivity analysis for scenario 3

	$\mathbf{I}_w$	$\mathbf{O}_{DC}$	$\mathbf{O}_v$	$\mathbf{P}_o$	$\mathbf{Y}_{DC}$	$\mathbf{Y}_v$	**K [kg CO_2-e/h]**
1	82.21	360.72	2746.28	314.71	905.35	0.000263	1.90
2	90.96	1681.24	1643.85	1512.11	218.75	0.000261	0.57
3	16.19	672.06	3440.25	281.64	1272.28	0.000274	0.54
4	91.68	1126.06	2283.69	337.46	1005.71	0.000250	2.35
5	64.71	367.96	1528.17	1203.65	1475.81	0.000253	2.47
6	13.36	1279.50	3968.92	386.11	1484.04	0.000245	0.52
7	30.74	571.27	3707.29	1774.12	1355.85	0.000277	1.14
8	56.50	1388.34	2355.60	1772.96	92.10	0.000265	0.21
9	95.92	1461.74	2655.65	1589.97	165.64	0.000259	0.48
10	96.63	1584.86	2508.65	488.34	689.58	0.000265	1.71
11	19.13	963.13	934.92	1469.08	1130.93	0.000261	0.62
12	97.18	197.01	1322.87	1197.78	1389.10	0.000266	3.47
13	95.89	500.26	2026.86	2072.00	873.46	0.000261	2.22
14	50.60	1929.95	1029.30	1448.66	1734.92	0.000268	2.29
15	80.83	340.23	3576.04	1739.84	1522.62	0.000261	3.20
16	17.62	1747.11	881.08	1073.11	2045.51	0.000279	0.96
17	44.49	1146.55	1010.35	1031.92	1131.91	0.000249	1.32
18	91.91	2102.93	781.27	1787.90	701.16	0.000244	1.71
19	80.05	185.22	1017.58	360.60	242.57	0.000244	0.51
20	96.11	946.70	1880.71	456.22	1298.25	0.000243	3.18
21	66.95	244.71	1363.76	533.60	1648.90	0.000256	2.82
22	7.43	2031.40	3904.10	952.16	906.54	0.000258	0.22
23	85.52	31.58	1857.93	1799.57	211.64	0.000254	0.54
24	93.66	1640.77	839.80	1745.67	578.59	0.000270	1.45
25	69.16	1729.33	3827.35	316.35	342.90	0.000265	0.62
26	76.74	1836.69	4137.98	968.17	608.95	0.000270	1.23
27	75.34	198.29	1893.87	1213.71	941.28	0.000277	1.85
28	41.65	857.09	534.03	1001.92	1123.15	0.000278	1.23
29	66.93	564.80	1143.71	1463.80	977.51	0.000248	1.72
30	20.43	1693.32	1768.78	1408.22	1850.64	0.000245	1.02
31	71.78	923.17	2541.22	761.78	1104.16	0.000267	2.04
32	7.06	1924.33	1160.92	1030.50	1993.22	0.000244	0.41
33	30.58	401.80	2574.20	229.80	1354.14	0.000261	1.06
34	8.43	573.01	3023.83	2093.34	2022.62	0.000261	0.53
35	13.32	325.95	993.03	521.63	524.76	0.000274	0.20
36	83.05	306.16	560.17	404.36	1434.39	0.000259	3.04
37	70.70	1837.94	1303.91	916.52	625.78	0.000256	1.16
38	34.44	1232.96	1395.61	581.18	1425.37	0.000266	1.27
39	95.22	1170.61	1832.87	1142.16	1474.12	0.000269	3.61
40	7.31	324.73	2180.10	853.19	163.94	0.000260	0.07
41	46.12	1803.97	427.81	2030.94	554.18	0.000254	0.74
42	40.63	1321.44	1162.04	1970.72	489.94	0.000246	0.60
43	77.49	755.07	3396.41	301.35	1417.07	0.000263	2.80
44	80.34	1094.13	194.23	1619.64	1785.92	0.000250	3.71
45	21.94	861.32	3926.82	717.79	741.52	0.000242	0.45
46	51.02	180.60	3103.14	1013.54	1652.48	0.000270	2.18
47	46.78	523.11	2100.24	1254.10	1432.74	0.000250	1.76
48	66.05	279.53	2473.30	2013.83	35.93	0.000257	0.15
49	72.10	406.10	1057.49	1003.74	1279.89	0.000267	2.38
50	76.45	523.18	1976.76	2091.39	829.90	0.000254	1.70

	$\mathbf{I}_w$	$\mathbf{O}_{DC}$	$\mathbf{O}_v$	$\mathbf{P}_o$	$\mathbf{Y}_{DC}$	$\mathbf{Y}_v$	**K [kg CO_2-e/h]**
51	30.50	893.61	4068.85	780.00	1935.50	0.000269	1.53
52	69.25	125.63	2341.70	1548.91	24.30	0.000256	0.12
53	66.89	1907.76	2235.19	1482.04	988.00	0.000267	1.74
54	19.61	1995.65	1033.89	1237.28	908.41	0.000268	0.51
55	15.42	1047.36	2101.44	1543.16	984.80	0.000257	0.46
56	51.84	1044.00	2662.23	1482.40	1630.84	0.000241	2.21
57	96.14	727.43	2890.73	542.73	695.58	0.000253	1.72
58	36.68	1902.20	1713.99	446.30	1661.30	0.000257	1.56
59	60.19	793.29	1597.49	2122.23	1006.61	0.000251	1.63
60	25.49	254.21	4172.14	529.24	96.61	0.000248	0.09
61	76.12	1651.92	229.58	262.72	389.32	0.000272	0.76
62	28.49	836.10	3745.56	1279.75	1529.72	0.000257	1.16
63	52.57	526.82	3862.23	1896.71	1011.06	0.000275	1.43
64	71.11	865.71	3376.37	1487.49	340.95	0.000255	0.68
65	89.53	223.40	482.56	566.39	734.54	0.000270	1.69
66	96.09	297.61	1159.50	909.80	1290.80	0.000256	3.18
67	56.53	1989.94	1464.40	1086.44	422.48	0.000272	0.66
68	17.31	2019.36	2893.19	2088.67	1564.55	0.000270	0.78
69	18.33	1223.57	639.56	500.92	529.24	0.000255	0.27
70	28.72	146.79	3065.37	1846.03	1938.49	0.000249	1.49
71	84.71	512.38	515.95	1440.53	584.00	0.000271	1.32
72	28.41	759.68	2785.44	923.95	1621.11	0.000277	1.21
73	82.17	1737.46	2123.33	567.34	416.03	0.000253	0.89
74	27.38	54.08	3305.29	1023.96	622.51	0.000266	0.48
75	93.21	111.78	3039.69	1127.41	212.25	0.000257	0.55
76	37.60	374.94	3822.54	432.06	1225.66	0.000273	1.19
77	22.87	1377.97	3769.44	1334.21	1449.51	0.000270	0.90
78	28.10	1550.54	1459.44	635.19	1163.79	0.000247	0.86
79	63.14	1375.11	2972.10	940.01	911.29	0.000274	1.50
80	49.44	963.92	893.71	1321.67	1368.21	0.000279	1.77
81	37.76	1164.66	199.71	684.47	1374.84	0.000260	1.35
82	83.76	640.94	3160.16	758.81	1440.43	0.000275	3.09
83	60.19	1577.64	2147.59	1387.28	1350.12	0.000263	2.12
84	56.77	416.65	2064.20	710.40	1996.46	0.000246	2.90
85	92.05	1456.64	3826.69	1786.10	458.39	0.000248	1.15
86	31.44	405.27	2603.34	2090.64	1503.66	0.000256	1.29
87	76.69	791.70	2635.70	1605.00	515.41	0.000269	1.08
88	76.36	1328.88	3638.83	861.62	271.33	0.000273	0.57
89	40.52	1651.87	3414.98	1323.75	1290.62	0.000271	1.39
90	58.51	191.38	2465.82	407.35	962.28	0.000253	1.45
91	11.28	1963.48	831.95	1943.74	980.22	0.000261	0.37
92	9.18	1642.44	1068.48	1892.45	1404.77	0.000244	0.41
93	54.96	1038.86	3751.14	1773.37	1631.10	0.000244	2.35
94	78.80	932.45	191.97	701.64	753.54	0.000245	1.54
95	93.67	955.28	2105.60	1343.54	1404.90	0.000267	3.39
96	16.47	661.89	769.73	243.31	891.30	0.000260	0.39
97	58.61	1084.23	4133.55	1018.20	1780.77	0.000247	2.69
98	49.06	1088.95	3029.97	801.67	1761.95	0.000260	2.23
99	5.14	1730.01	2149.46	510.70	557.63	0.000246	0.10
100	36.36	1682.38	2027.55	543.95	1303.48	0.000242	1.23

Scenario 4

Table 12: Instantaneous CO_2 emission rates from the sensitivity analysis for scenario 4

	I_w	O_{DC}	O_v	P_o	Y_{DC}	Y_v	K [kg CO_2-e/h]
1	85.67	1230.95	3010.12	2100.79	1385.26	0.000271	52.74
2	57.81	1861.98	676.71	527.91	794.76	0.000267	20.26
3	93.24	779.37	3175.12	695.99	2167.59	0.000240	87.55
4	70.88	989.27	584.80	963.44	514.81	0.000273	16.52
5	59.95	151.40	614.99	342.37	1430.73	0.000276	37.24
6	82.28	414.16	2828.24	1516.20	1329.23	0.000270	48.29
7	88.39	1452.88	1508.88	974.20	863.56	0.000242	33.66
8	98.94	742.91	2883.62	2090.97	339.48	0.000255	16.14
9	4.05	1956.90	3286.83	973.80	89.15	0.000268	1.01
10	87.08	288.09	2584.88	1394.17	935.99	0.000269	36.21
11	62.81	2149.23	3248.34	497.01	429.12	0.000249	12.08
12	99.04	1190.21	1111.32	933.71	1587.54	0.000251	68.42
13	54.66	1547.21	3226.87	510.02	827.46	0.000267	19.94
14	50.03	2172.91	4223.63	1658.61	1835.16	0.000259	40.86
15	80.93	650.99	3785.12	1876.02	1605.62	0.000265	57.41
16	25.87	921.90	482.77	874.89	1256.60	0.000249	14.74
17	51.82	1029.51	1668.03	1518.97	413.62	0.000247	10.47
18	90.48	1669.20	1679.71	765.94	2082.86	0.000273	81.72
19	59.17	1785.21	3015.67	1220.93	602.82	0.000270	16.37
20	85.14	249.73	2647.29	1801.58	2012.71	0.000277	75.16
21	74.91	416.32	3457.01	1349.57	513.96	0.000244	17.69
22	60.25	804.52	1673.17	845.14	834.30	0.000247	22.36
23	27.69	156.67	989.50	775.71	222.53	0.000244	3.34
24	67.98	1151.50	484.60	1070.79	1404.35	0.000259	41.96
25	12.01	753.65	3383.28	1013.17	421.67	0.000248	3.06
26	64.09	411.09	988.00	891.88	131.75	0.000275	4.41
27	67.45	482.25	1760.39	1274.21	1581.98	0.000244	46.95
28	74.06	1971.16	2452.02	1628.66	778.43	0.000242	26.13
29	89.51	1479.79	1086.47	1016.42	1448.20	0.000262	56.61
30	98.30	1037.27	2833.41	1026.08	856.34	0.000270	37.08
31	77.83	1986.09	2167.35	440.26	1377.04	0.000252	46.52
32	59.82	257.84	760.31	247.01	81.70	0.000247	2.39
33	93.12	1629.82	3425.57	758.32	1982.74	0.000253	80.08
34	59.69	1609.98	543.56	810.91	1747.47	0.000248	45.57
35	5.63	1237.00	1361.90	1457.70	1630.47	0.000260	5.16
36	15.60	429.32	1122.09	2041.14	1774.32	0.000276	13.56
37	86.82	1312.60	2363.59	2000.35	855.14	0.000265	33.55
38	50.49	676.85	505.04	1080.97	1355.51	0.000244	30.35
39	85.11	322.24	1832.48	662.68	1266.15	0.000255	46.94
40	24.10	490.07	561.50	1669.74	1168.97	0.000242	13.48
41	57.02	1949.32	592.96	1660.95	623.66	0.000260	16.65
42	64.47	188.21	3436.13	1625.01	567.12	0.000257	17.07
43	7.07	553.98	1351.34	1630.86	1001.27	0.000279	4.39
44	63.01	150.36	2670.95	403.79	522.39	0.000272	14.57
45	38.79	980.07	4197.51	1511.32	1755.80	0.000259	30.55
46	8.76	63.81	1947.41	1091.31	2144.28	0.000275	9.01
47	51.00	1954.13	3056.80	608.20	99.54	0.000245	2.75
48	22.48	455.97	3324.76	389.55	1180.97	0.000255	11.82
49	15.82	235.08	1948.08	1784.56	221.62	0.000277	2.97
50	23.73	692.73	2890.76	536.72	1750.75	0.000276	18.38
51	18.07	1010.72	582.26	514.71	2150.79	0.000268	17.20
52	22.15	252.83	4067.80	1481.36	178.57	0.000264	2.94
53	8.09	2164.14	910.96	1920.81	2044.40	0.000254	8.68
54	64.98	745.61	1243.94	1193.86	74.27	0.000277	3.08
55	31.06	671.31	3492.82	1552.00	1497.86	0.000245	21.29
56	55.71	168.09	2180.56	495.51	1711.50	0.000269	41.48
57	70.74	673.22	3370.69	2034.45	1177.71	0.000265	37.48
58	51.92	134.53	1793.11	1240.66	1928.83	0.000273	44.10
59	55.44	1116.31	1272.53	1507.81	1958.01	0.000256	47.92
60	46.74	1663.79	275.50	270.35	1374.03	0.000270	27.92
61	15.90	1385.01	2966.04	1756.91	330.25	0.000273	3.70
62	51.07	227.64	1935.06	1640.34	501.19	0.000253	12.36
63	85.89	208.33	2028.86	431.24	424.93	0.000262	16.12
64	87.90	1697.61	2697.70	1210.19	124.84	0.000279	5.75
65	29.95	1971.12	369.28	826.90	264.11	0.000262	4.13
66	24.01	1176.92	1453.88	1251.37	1353.73	0.000253	15.03
67	58.24	268.84	3386.61	967.45	2044.96	0.000264	52.06
68	65.47	1801.47	3063.91	998.64	793.44	0.000254	23.20
69	44.03	758.46	648.16	547.74	913.57	0.000270	17.81
70	23.77	664.09	668.54	691.36	2140.53	0.000256	22.51
71	95.00	1631.47	508.65	239.51	2057.62	0.000259	84.33
72	11.88	57.51	151.08	1977.15	1482.47	0.000267	9.17
73	14.15	139.01	1907.75	1457.72	2148.98	0.000278	14.29
74	17.64	1463.81	2891.07	1994.35	1675.35	0.000253	14.33
75	19.98	1325.98	3175.96	514.60	755.47	0.000273	6.99
76	63.61	1160.52	2365.02	1972.19	1451.97	0.000269	41.32
77	59.08	1595.96	578.30	1728.92	557.57	0.000278	15.58
78	9.00	1547.93	2790.37	1310.91	667.37	0.000241	3.69
79	93.40	1706.45	653.09	1046.63	1490.03	0.000254	60.73
80	73.95	651.27	686.10	695.65	1164.25	0.000266	37.65
81	74.83	1516.45	535.05	1646.74	915.63	0.000251	30.81
82	10.09	1225.89	718.78	639.96	1324.20	0.000249	6.33
83	86.60	883.40	829.70	323.50	1640.46	0.000268	61.43
84	93.70	167.12	948.13	1676.34	1283.34	0.000265	53.08
85	98.50	1703.88	1460.94	1491.39	1215.46	0.000263	52.72
86	86.46	757.36	1456.49	1576.07	1283.42	0.000266	49.01
87	79.41	1335.38	1038.29	1435.33	1129.98	0.000242	39.78
88	53.28	1620.65	1179.91	1006.25	212.03	0.000254	5.72
89	21.05	259.55	3895.06	951.83	1574.27	0.000258	15.08
90	42.26	308.90	3092.63	1770.25	2165.78	0.000249	40.81
91	16.86	1210.65	2468.77	810.73	793.61	0.000268	6.47
92	6.97	1073.11	898.15	1767.17	2112.53	0.000274	7.77
93	94.16	1939.77	1014.89	1718.18	776.32	0.000251	32.84
94	32.93	1744.06	445.18	1839.76	1931.36	0.000269	28.84
95	32.37	1605.86	3983.38	1172.84	1007.81	0.000245	15.03
96	35.96	145.18	3107.41	1423.01	919.56	0.000273	15.41
97	48.84	191.27	2477.45	2029.52	501.04	0.000245	12.17
98	66.23	224.72	1443.80	1054.19	304.12	0.000263	9.56
99	6.42	1742.75	821.04	315.48	696.04	0.000254	2.26
100	84.85	2052.12	2751.16	1867.63	1588.25	0.000272	59.48

Scenario 5

Table 13: Instantaneous CO_2 emission rates from the sensitivity analysis for scenario 5

	I_w	O_{DC}	O_v	P_o	Y_{DC}	Y_v	K [kg CO_2-e/h]
1	85.67	1230.95	3010.12	2100.79	1385.26	0.000271	31.64
2	57.81	1861.98	676.71	527.91	794.76	0.000267	12.15
3	93.24	779.37	3175.12	695.99	2167.59	0.000240	52.53
4	70.88	989.27	584.80	963.44	514.81	0.000273	9.91
5	59.95	151.40	614.99	342.37	1430.73	0.000276	22.34
6	82.28	414.16	2828.24	1516.20	1329.23	0.000270	28.97
7	88.39	1452.88	1508.88	974.20	863.56	0.000242	20.20
8	98.94	742.91	2883.62	2090.97	339.48	0.000255	9.68
9	4.05	1956.90	3286.83	973.80	89.15	0.000268	0.60
10	87.08	288.09	2584.88	1394.17	935.99	0.000269	21.73
11	62.81	2149.23	3248.34	497.01	429.12	0.000249	7.25
12	99.04	1190.21	1111.32	933.71	1587.54	0.000251	41.05
13	54.66	1547.21	3226.87	510.02	827.46	0.000267	11.97
14	50.03	2172.91	4223.63	1658.61	1835.16	0.000259	24.52
15	80.93	650.99	3785.12	1876.02	1605.62	0.000265	34.45
16	25.87	921.90	482.77	874.89	1256.60	0.000249	8.85
17	51.82	1029.51	1668.03	1518.97	413.62	0.000247	6.28
18	90.48	1669.20	1679.71	765.94	2082.86	0.000273	49.03
19	59.17	1785.21	3015.67	1220.93	602.82	0.000270	9.82
20	85.14	249.73	2647.29	1801.58	2012.71	0.000277	45.10
21	74.91	416.32	3457.01	1349.57	513.96	0.000244	10.61
22	60.25	804.52	1673.17	845.14	834.30	0.000247	13.42
23	27.69	156.67	989.50	775.71	222.53	0.000244	2.00
24	67.98	1151.50	484.60	1070.79	1404.35	0.000259	25.18
25	12.01	753.65	3383.28	1013.17	421.67	0.000248	1.83
26	64.09	411.09	988.00	891.88	131.75	0.000275	2.64
27	67.45	482.25	1760.39	1274.21	1581.98	0.000244	28.17
28	74.06	1971.16	2452.02	1628.66	778.43	0.000242	15.68
29	89.51	1479.79	1086.47	1016.42	1448.20	0.000262	33.97
30	98.30	1037.27	2833.41	1026.08	856.34	0.000270	22.25
31	77.83	1986.09	2167.35	440.26	1377.04	0.000252	27.91
32	59.82	257.84	760.31	247.01	81.70	0.000247	1.43
33	93.12	1629.82	3425.57	758.32	1982.74	0.000253	48.05
34	59.69	1609.98	543.56	810.91	1747.47	0.000248	27.34
35	5.63	1237.00	1361.90	1457.70	1630.47	0.000260	3.09
36	15.60	429.32	1122.09	2041.14	1774.32	0.000276	8.13
37	86.82	1312.60	2363.59	2000.35	855.14	0.000265	20.13
38	50.49	676.85	505.04	1080.97	1355.51	0.000244	18.21
39	85.11	322.24	1832.48	662.68	1266.15	0.000255	28.17
40	24.10	490.07	561.50	1669.74	1168.97	0.000242	8.09
41	57.02	1949.32	592.96	1660.95	623.66	0.000260	9.99
42	64.47	188.21	3436.13	1625.01	567.12	0.000257	10.24
43	7.07	553.98	1351.34	1630.86	1001.27	0.000279	2.63
44	63.01	150.36	2670.95	403.79	522.39	0.000272	8.74
45	38.79	980.07	4197.51	1511.32	1755.80	0.000259	18.33
46	8.76	63.81	1947.41	1091.31	2144.28	0.000275	5.40
47	51.00	1954.13	3056.80	608.20	99.54	0.000245	1.65
48	22.48	455.97	3324.76	389.55	1180.97	0.000255	7.09
49	15.82	235.08	1948.08	1784.56	221.62	0.000277	1.78
50	23.73	692.73	2890.76	536.72	1750.75	0.000276	11.03
51	18.07	1010.72	582.26	514.71	2150.79	0.000268	10.32
52	22.15	252.83	4067.80	1481.36	178.57	0.000264	1.76
53	8.09	2164.14	910.96	1920.81	2044.40	0.000254	5.21
54	64.98	745.61	1243.94	1193.86	74.27	0.000277	1.85
55	31.06	671.31	3492.82	1552.00	1497.86	0.000245	12.78
56	55.71	168.09	2180.56	495.51	1711.50	0.000269	24.89
57	70.74	673.22	3370.69	2034.45	1177.71	0.000265	22.49
58	51.92	134.53	1793.11	1240.66	1928.83	0.000273	26.46
59	55.44	1116.31	1272.53	1507.81	1958.01	0.000256	28.75
60	46.74	1663.79	275.50	270.35	1374.03	0.000270	16.75
61	15.90	1385.01	2966.04	1756.91	330.25	0.000273	2.22
62	51.07	227.64	1935.06	1640.34	501.19	0.000253	7.41
63	85.89	208.33	2028.86	431.24	424.93	0.000262	9.67
64	87.90	1697.61	2697.70	1210.19	124.84	0.000279	3.45
65	29.95	1971.12	369.28	826.90	264.11	0.000262	2.48
66	24.01	1176.92	1453.88	1251.37	1353.73	0.000253	9.02
67	58.24	268.84	3386.61	967.45	2044.96	0.000264	31.23
68	65.47	1801.47	3063.91	998.64	793.44	0.000254	13.92
69	44.03	758.46	648.16	547.74	913.57	0.000270	10.69
70	23.77	664.09	668.54	691.36	2140.53	0.000256	13.50
71	95.00	1631.47	508.65	239.51	2057.62	0.000259	50.60
72	11.88	57.51	151.08	1977.15	1482.47	0.000267	5.50
73	14.15	139.01	1907.75	1457.72	2148.98	0.000278	8.57
74	17.64	1463.81	2891.07	1994.35	1675.35	0.000253	8.60
75	19.98	1325.98	3175.96	514.60	755.47	0.000273	4.19
76	63.61	1160.52	2365.02	1972.19	1451.97	0.000269	24.79
77	59.08	1595.96	578.30	1728.92	557.57	0.000278	9.35
78	9.00	1547.93	2790.37	1310.91	667.37	0.000241	2.21
79	93.40	1706.45	653.09	1046.63	1490.03	0.000254	36.44
80	73.95	651.27	686.10	695.65	1164.25	0.000266	22.59
81	74.83	1516.45	535.05	1646.74	915.63	0.000251	18.49
82	10.09	1225.89	718.78	639.96	1324.20	0.000249	3.80
83	86.60	883.40	829.70	323.50	1640.46	0.000268	36.86
84	93.70	167.12	948.13	1676.34	1283.34	0.000265	31.85
85	98.50	1703.88	1460.94	1491.39	1215.46	0.000263	31.63
86	86.46	757.36	1456.49	1576.07	1283.42	0.000266	29.41
87	79.41	1335.38	1038.29	1435.33	1129.98	0.000242	23.87
88	53.28	1620.65	1179.91	1006.25	212.03	0.000254	3.43
89	21.05	259.55	3895.06	951.83	1574.27	0.000258	9.05
90	42.26	308.90	3092.63	1770.25	2165.78	0.000249	24.49
91	16.86	1210.65	2468.77	810.73	793.61	0.000268	3.88
92	6.97	1073.11	898.15	1767.17	2112.53	0.000274	4.66
93	94.16	1939.77	1014.89	1718.18	776.32	0.000251	19.70
94	32.93	1744.06	445.18	1839.76	1931.36	0.000269	17.30
95	32.37	1605.86	3983.38	1172.84	1007.81	0.000245	9.02
96	35.96	145.18	3107.41	1423.01	919.56	0.000273	9.25
97	48.84	191.27	2477.45	2029.52	501.04	0.000245	7.30
98	66.23	224.72	1443.80	1054.19	304.12	0.000263	5.74
99	6.42	1742.75	821.04	315.48	696.04	0.000254	1.36
100	84.85	2052.12	2751.16	1867.63	1588.25	0.000272	35.69

Scenario 6

Table 14: Instantaneous CO_2 emission rates from the sensitivity analysis for scenario 6

	$\mathbf{I}_w$	$\mathbf{O}_{DC}$	$\mathbf{O}_v$	$\mathbf{P}_o$	$\mathbf{Y}_{DC}$	$\mathbf{Y}_v$	**K [kg CO_2-e/h]**
1	85.67	1230.95	3010.12	2100.79	1385.26	0.000271	3.10
2	57.81	1861.98	676.71	527.91	794.76	0.000267	1.19
3	93.24	779.37	3175.12	695.99	2167.59	0.000240	5.15
4	70.88	989.27	584.80	963.44	514.81	0.000273	0.97
5	59.95	151.40	614.99	342.37	1430.73	0.000276	2.19
6	82.28	414.16	2828.24	1516.20	1329.23	0.000270	2.84
7	88.39	1452.88	1508.88	974.20	863.56	0.000242	1.98
8	98.94	742.91	2883.62	2090.97	339.48	0.000255	0.95
9	4.05	1956.90	3286.83	973.80	89.15	0.000268	0.06
10	87.08	288.09	2584.88	1394.17	935.99	0.000269	2.13
11	62.81	2149.23	3248.34	497.01	429.12	0.000249	0.71
12	99.04	1190.21	1111.32	933.71	1587.54	0.000251	4.03
13	54.66	1547.21	3226.87	510.02	827.46	0.000267	1.17
14	50.03	2172.91	4223.63	1658.61	1835.16	0.000259	2.40
15	80.93	650.99	3785.12	1876.02	1605.62	0.000265	3.38
16	25.87	921.90	482.77	874.89	1256.60	0.000249	0.87
17	51.82	1029.51	1668.03	1518.97	413.62	0.000247	0.62
18	90.48	1669.20	1679.71	765.94	2082.86	0.000273	4.81
19	59.17	1785.21	3015.67	1220.93	602.82	0.000270	0.96
20	85.14	249.73	2647.29	1801.58	2012.71	0.000277	4.42
21	74.91	416.32	3457.01	1349.57	513.96	0.000244	1.04
22	60.25	804.52	1673.17	845.14	834.30	0.000247	1.32
23	27.69	156.67	989.50	775.71	222.53	0.000244	0.20
24	67.98	1151.50	484.60	1070.79	1404.35	0.000259	2.47
25	12.01	753.65	3383.28	1013.17	421.67	0.000248	0.18
26	64.09	411.09	988.00	891.88	131.75	0.000275	0.26
27	67.45	482.25	1760.39	1274.21	1581.98	0.000244	2.76
28	74.06	1971.16	2452.02	1628.66	778.43	0.000242	1.54
29	89.51	1479.79	1086.47	1016.42	1448.20	0.000262	3.33
30	98.30	1037.27	2833.41	1026.08	856.34	0.000270	2.18
31	77.83	1986.09	2167.35	440.26	1377.04	0.000252	2.74
32	59.82	257.84	760.31	247.01	81.70	0.000247	0.14
33	93.12	1629.82	3425.57	758.32	1982.74	0.000253	4.71
34	59.69	1609.98	543.56	810.91	1747.47	0.000248	2.68
35	5.63	1237.00	1361.90	1457.70	1630.47	0.000260	0.30
36	15.60	429.32	1122.09	2041.14	1774.32	0.000276	0.80
37	86.82	1312.60	2363.59	2000.35	855.14	0.000265	1.97
38	50.49	676.85	505.04	1080.97	1355.51	0.000244	1.79
39	85.11	322.24	1832.48	662.68	1266.15	0.000255	2.76
40	24.10	490.07	561.50	1669.74	1168.97	0.000242	0.79
41	57.02	1949.32	592.96	1660.95	623.66	0.000260	0.98
42	64.47	188.21	3436.13	1625.01	567.12	0.000257	1.00
43	7.07	553.98	1351.34	1630.86	1001.27	0.000279	0.26
44	63.01	150.36	2670.95	403.79	522.39	0.000272	0.86
45	38.79	980.07	4197.51	1511.32	1755.80	0.000259	1.80
46	8.76	63.81	1947.41	1091.31	2144.28	0.000275	0.53
47	51.00	1954.13	3056.80	608.20	99.54	0.000245	0.16
48	22.48	455.97	3324.76	389.55	1180.97	0.000255	0.70
49	15.82	235.08	1948.08	1784.56	221.62	0.000277	0.17
50	23.73	692.73	2890.76	536.72	1750.75	0.000276	1.08
51	18.07	1010.72	582.26	514.71	2150.79	0.000268	1.01
52	22.15	252.83	4067.80	1481.36	178.57	0.000264	0.17
53	8.09	2164.14	910.96	1920.81	2044.40	0.000254	0.51
54	64.98	745.61	1243.94	1193.86	74.27	0.000277	0.18
55	31.06	671.31	3492.82	1552.00	1497.86	0.000245	1.25
56	55.71	168.09	2180.56	495.51	1711.50	0.000269	2.44
57	70.74	673.22	3370.69	2034.45	1177.71	0.000265	2.21
58	51.92	134.53	1793.11	1240.66	1928.83	0.000273	2.59
59	55.44	1116.31	1272.53	1507.81	1958.01	0.000256	2.82
60	46.74	1663.79	275.50	270.35	1374.03	0.000270	1.64
61	15.90	1385.01	2966.04	1756.91	330.25	0.000273	0.22
62	51.07	227.64	1935.06	1640.34	501.19	0.000253	0.73
63	85.89	208.33	2028.86	431.24	424.93	0.000262	0.95
64	87.90	1697.61	2697.70	1210.19	124.84	0.000279	0.34
65	29.95	1971.12	369.28	826.90	264.11	0.000262	0.24
66	24.01	1176.92	1453.88	1251.37	1353.73	0.000253	0.88
67	58.24	268.84	3386.61	967.45	2044.96	0.000264	3.06
68	65.47	1801.47	3063.91	998.64	793.44	0.000254	1.37
69	44.03	758.46	648.16	547.74	913.57	0.000270	1.05
70	23.77	664.09	668.54	691.36	2140.53	0.000256	1.32
71	95.00	1631.47	508.65	239.51	2057.62	0.000259	4.96
72	11.88	57.51	151.08	1977.15	1482.47	0.000267	0.54
73	14.15	139.01	1907.75	1457.72	2148.98	0.000278	0.84
74	17.64	1463.81	2891.07	1994.35	1675.35	0.000253	0.84
75	19.98	1325.98	3175.96	514.60	755.47	0.000273	0.41
76	63.61	1160.52	2365.02	1972.19	1451.97	0.000269	2.43
77	59.08	1595.96	578.30	1728.92	557.57	0.000278	0.92
78	9.00	1547.93	2790.37	1310.91	667.37	0.000241	0.22
79	93.40	1706.45	653.09	1046.63	1490.03	0.000254	3.57
80	73.95	651.27	686.10	695.65	1164.25	0.000266	2.22
81	74.83	1516.45	535.05	1646.74	915.63	0.000251	1.81
82	10.09	1225.89	718.78	639.96	1324.20	0.000249	0.37
83	86.60	883.40	829.70	323.50	1640.46	0.000268	3.61
84	93.70	167.12	948.13	1676.34	1283.34	0.000265	3.12
85	98.50	1703.88	1460.94	1491.39	1215.46	0.000263	3.10
86	86.46	757.36	1456.49	1576.07	1283.42	0.000266	2.88
87	79.41	1335.38	1038.29	1435.33	1129.98	0.000242	2.34
88	53.28	1620.65	1179.91	1006.25	212.03	0.000254	0.34
89	21.05	259.55	3895.06	951.83	1574.27	0.000258	0.89
90	42.26	308.90	3092.63	1770.25	2165.78	0.000249	2.40
91	16.86	1210.65	2468.77	810.73	793.61	0.000268	0.38
92	6.97	1073.11	898.15	1767.17	2112.53	0.000274	0.46
93	94.16	1939.77	1014.89	1718.18	776.32	0.000251	1.93
94	32.93	1744.06	445.18	1839.76	1931.36	0.000269	1.70
95	32.37	1605.86	3983.38	1172.84	1007.81	0.000245	0.88
96	35.96	145.18	3107.41	1423.01	919.56	0.000273	0.91
97	48.84	191.27	2477.45	2029.52	501.04	0.000245	0.72
98	66.23	224.72	1443.80	1054.19	304.12	0.000263	0.56
99	6.42	1742.75	821.04	315.48	696.04	0.000254	0.13
100	84.85	2052.12	2751.16	1867.63	1588.25	0.000272	3.50

D Survey

D.1 Survey questions

Welcome to the survey

Thank you for participating in this survey. By means of completing this survey, you will contribute to research on the energy consumption of vehicle automation. The research is part of the MSc thesis of Rosalie van Oosterhout at the TU Delft, supervised by Meng Wang, Joost de Winter and Peter Striekwold.

The main purpose of this master thesis is to provide an accurate computational model of the energy consumption of vehicle automation. This survey aims to collect the input data to develop the model. We are willing to share the results of the survey with you. If you wish to receive the results, you can fill in your contact information at the end of the survey. This survey is fully anonymous, no IP addresses will be stored. The findings of this survey will be presented at group level, so no company names will be mentioned in the report unless you agree to this below. For the research, it would be useful to know what type of company you represent, which will be asked below.

The survey is divided into different topics; general specification of the functionalities of the vehicle, sensors, computing platform, connectivity and general questions. The main focus of the survey is on power consumption, data transmission and storage, which will be used for the computational model. This survey includes 33 questions and will take about 20 minutes.

If there are any further questions regarding the survey, you can always contact me using: R.vanOosterhout-1@student.tudelft.nl.

1. What type of company do you represent?
   - ◯ OEM
   - ◯ Suppliers

   Other: [ ]

2. What is your function within the company?

   [ ]

3. Are you willing to share the company name you work for, which can be used in the research? If so please fill in the company name below.

   [ ]

General specifications of the functionalities of the automated vehicle

The following questions are about the automated vehicle as applied by the company you represent. This way we are able to get a better understanding of functionalities of the automated vehicle. Preferably choose an automated vehicle that is in the operational phase. Please answer the rest of the survey from the perspective of the vehicle as described by you below while being in the use phase.

4. Please elaborate on the functionalities of the vehicle as represented by your company.
   - ☐ Adaptive cruise control
   - ☐ Automated lane keeping
   - ☐ Automated lane changing with driver initiating turning indicator
   - ☐ Automated lane changing without driver input
   - ☐ Driver has to prepare to take back control
   - ☐ Other: [ ]

5. Please elaborate on the phase (operational or development) the vehicle as represented by your company is at.

   [ ]

6. Is the automated vehicle a passenger car or a shuttle?
   - ◯ Passanger car
   - ◯ Shuttle
   - ◯ Other/more specifically: [ ]

Sensors

The following questions are related to the sensors implemented in the design of an automated vehicle.

7. What types of sensors are implemented in the design of the automated vehicle and how many of each?

	0	1	2	3	4	5	6	7	8	9	10	11	12	13
camera	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]														
radar	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]														
lidar	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]														
sonar	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]														
GPS/INS	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]														
IMU	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]														
Other	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]														

8. What is the power consumption by each type of sensor, assuming a single sensor of each type?

	0-10 Watt	10-20 Watt	20-30 Watt	30-40 Watt	40-50 Watt	50-60 Watt	60-70 Watt	70-80 Watt	80-90 Watt	90-100 Watt	100-110 Watt	100-120 Watt	>120 Watt
camera	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]													
radar	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]													
lidar	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]													
GPS/INS	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]													
IMU	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]													
Other	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯	◯
More specifically: [ ]													

9. What is the amount of data produced by each type of the sensors, assuming a single sensor of each type?

	0 kB/hour	up to 1000 kB/hour	up to 100 MB/hour	up to 500 MB/hour	up to 1000 MB/hour	up to 10 GB/hour	up to 50 GB/hour	up to 400 GB/hour	up to 2000 GB/hour	up to 4000 GB/hour	>4000 GB/hour
camera											
More specifically:											
radar											
More specifically:											
lidar											
More specifically:											
sonar											
More specifically:											
GPS/INS											
More specifically:											
IMU											
More specifically:											
Other											
More specifically:											

Computing platform

The following questions are about the computing platform.

10. What computing platform is incorporated in your analysis concerning automated vehicles?

11. What is the computing platform composed of and what is the amount of each element?

	0	1	2	3	4	5	6	7	8	9	10
I/O subsystem											
More specifically:											
GPUs											
More specifically:											
CPUs											
More specifically:											
DSP											
More specifically:											
FPGA											
More specifically:											
Shared memory											
More specifically:											
Other											
More specifically:											

12. What is the estimated power consumption at peak level for the overall computing platform?

0-100 Watt	100-500 Watt	500-800 Watt	800-1000 Watt	>1000 Watt

Other/more specifically:

13. What is the estimated power consumption at idle level for the overall computing platform?

0-100 Watt	100-500 Watt	500-800 Watt	800-1000 Watt	>1000 Watt

Other/more specifically:

14. What percentage of time is the overall computing platform running at its peak?

0-10%	10-30%	30-50%	50-70%	70-90%	>90%

Other/more specifically:

15. What is on average the amount of data generated by the computing platform?

0 kB/hour	up to 1000 kB/hour	up to 100 MB/hour	up to 500 MB/hour	up to 1000 MB/hour	up to 10 GB/hour	up to 50 GB/hour	up to 400 GB/hour	up to 2000 GB/hour	up to 4000 GB/hour	>4000 GB/hour

Other/more specifically:

16. What is on average the amount of data stored by the computing platform?

0 kB/hour	up to 1000 kB/hour	up to 100 MB/hour	up to 500 MB/hour	up to 1000 MB/hour	up to 10 GB/hour	up to 50 GB/hour	up to 400 GB/hour	up to 2000 GB/hour	up to 4000 GB/hour	>4000 GB/hour

Other/more specifically:

17. How long is the data in general stored at the computing platform?

- <1 hour
- 1-10 hours
- 24 hours
- 1-3 days
- 1-2 weeks
- 1-2 months
- Longer/more specifically:

18. What type of disks are used to enable storage within the vehicle?

- SSD
- HDD
- both SSD and HDD
- Other/more specifically:

Connectivity

The following questions are about the communication devices and networks to be used for an automated vehicle to ensure connectivity.

19. What type of connectivity is considered?

- ○ The automated vehicle is always connected, both when driving and non-driving.
- ○ The automated vehicle is only connected when non-driving and there is a certain upload of information at once.
- ○ The automated vehicle is only connected when driving.
- ○ Other, namely:

20. What type of communication is enabled to ensure connectivity?

- ○ V2V communication only
- ○ V2I communication only
- ○ Between vehicle and remote control center
- ○ Both V2V and V2I communication
- ○ Both V2V and remote control center
- ○ Both V2I and remote control center
- ○ V2V, V2I and remote control center
- ○ None
- ○ Other, namely:

21. What communication units are considered to be used to ensure connectivity?

- ☐ on-board DSRC units
- ☐ cellular: 4G
- ☐ cellular: 5G
- ☐ Other, namely:

22. What is the amount of data transmitted to data centers by a communication unit?

0 kB/hour	up to 1000 kB/hour	up to 100 MB/hour	up to 500 MB/hour	up to 1000 MB/hour	up to 10 GB/hour	up to 50 GB/hour	up to 400 GB/hour	up to 2000 GB/hour	up to 4000 GB/hour	>4000 GB/hour
○	○	○	○	○	○	○	○	○	○	○

Other/more specifically:

23. What is the average maximum power consumption of a server at a data center?

0-100 Watt	100-200 Watt	200-300 Watt	300-400 Watt	400-500 Watt
○	○	○	○	○

Other, more specifically

24. What is the average server utilization of a data center?

0-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	90-100%
○	○	○	○	○	○	○	○	○	○

Other/more specifically:

25. How long does a server at maximum power take to complete the workload expressed in amounts of data?

	<1 minute	1-10 minutes	10-20 minutes	20-30 minutes	30-40 minutes	40-50 minutes	50-60 minutes	1-2 hours	2-3 hours	3-4 hours	>4 hours
100 MB	○	○	○	○	○	○	○	○	○	○	○
1000 MB	○	○	○	○	○	○	○	○	○	○	○
10 GB	○	○	○	○	○	○	○	○	○	○	○
40 GB	○	○	○	○	○	○	○	○	○	○	○

Other, more specifically:

26. What is the amount of data stored at the data center as transmitted by a communication unit?

0 kB/hour	up to 1000 kB/hour	up to 100 MB/hour	up to 500 MB/hour	up to 1000 MB/hour	up to 10 GB/hour	up to 50 GB/hour	up to 400 GB/hour	up to 2000 GB/hour	up to 4000 GB/hour	>4000 GB/hour
○	○	○	○	○	○	○	○	○	○	○

Other/more specifically:

27. How long is the data as transmitted by the communication unit stored at the data center?

- ○ <1 hour
- ○ 1-10 hours
- ○ 24 hours
- ○ 1-3 days
- ○ 1-2 weeks
- ○ 1-2 months
- ○ Longer/more specifically:

28. What type of disks at data centers are used to enable storage?

- ○ SSD
- ○ HDD
- ○ both SSD and HDD
- ○ Other/more specifically:

General questions

29. What is your general estimation about the total amount of data that the vehicle as represented by your company generates?

- ○ <25 GB/hour
- ○ up to 25 GB/hour
- ○ up to 500 GB/hour
- ○ up to 4000 GB/hour
- ○ >4000 GB/hour

Other, namely:

30. Are HD maps applied by the vehicle as represented by your company? If so, please provide an estimation of the amount of data related to this.

- ○ Yes
- ○ No
- ○ Estimation of the amount of data related to HD maps:

31. Considering the different components discussed in this survey, which do you think consumes most energy to enable vehicle automation considering the different components discussed in this survey?

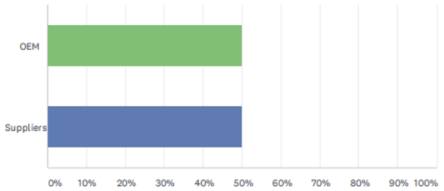
32. Are you willing to participate in a follow-up interview? If so, please provide your contact information below.

33. Would you like to receive the results of this survey? If so, please provide your contact details below.

D.2 Survey results

Q1 What type of company do you represent?

Answered: 4 Skipped: 7



ANSWER CHOICES	RESPONSES	
OEM	50.00%	2
Suppliers	50.00%	2
TOTAL		4

#	OTHER:	DATE
1	University	5/11/2021 8:33 AM
2	University	5/7/2021 2:49 PM
3	PhD Student working on autonomous vehicle	4/16/2021 8:00 PM
4	University	4/16/2021 1:20 PM
5	University	4/16/2021 1:06 PM
6	Software provider	3/1/2021 8:14 PM
7	lklajlajlho	2/8/2021 5:21 PM

Q2 What is your function within the company?

Answered: 10 Skipped: 1

#	RESPONSES	DATE
1	project manager EU projects	5/11/2021 8:33 AM
2	PhD candidate	5/7/2021 2:49 PM
3	PhD Student	4/16/2021 8:00 PM
4	phd student	4/16/2021 1:20 PM
5	Researcher	4/16/2021 1:06 PM
6	HMI project lead for automated driving	4/16/2021 1:05 PM
7	Management	3/1/2021 8:14 PM
8	Team Leader	2/26/2021 8:29 AM
9	Consultant Technical Vehicle Regulations for Type Approval	2/25/2021 6:22 PM
10	Regulations and Homologations	2/19/2021 5:54 AM

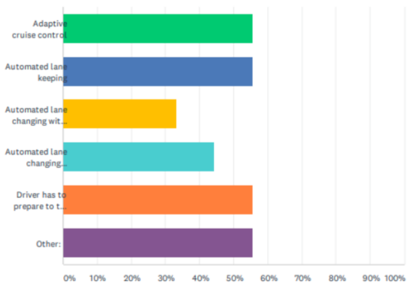
Q3 Are you willing to share the company name you work for, which can be used in the research? If so please fill in the company name below.

Answered: 7 Skipped: 4

#	RESPONSES	DATE
1	TU/e	5/11/2021 8:33 AM
2	Eindhoven University of Technology	5/7/2021 2:49 PM
3	TU Delft	4/16/2021 1:20 PM
4	TU Delft	4/16/2021 1:06 PM
5	RoadDB	3/1/2021 8:14 PM
6	No	2/26/2021 8:29 AM
7	Robert Bosch GmbH	2/25/2021 6:22 PM

Q4 Please elaborate on the functionalities of the vehicle as represented by your company.

Answered: 9 Skipped: 2



ANSWER CHOICES	RESPONSES	
Adaptive cruise control	55.56%	5
Automated lane keeping	55.56%	5
Automated lane changing with driver initiating turning indicator	33.33%	3
Automated lane changing without driver input	44.44%	4
Driver has to prepare to take back control	55.56%	5
Other:	55.56%	5
Total Respondents: 9		

#	OTHER:	DATE
1	level 4-5 automated driving	5/11/2021 8:33 AM
2	Autonomous driving research	5/7/2021 2:50 PM
3	Full autonomy	4/16/2021 1:21 PM
4	Level 3	4/16/2021 1:07 PM
5	None	3/1/2021 8:15 PM

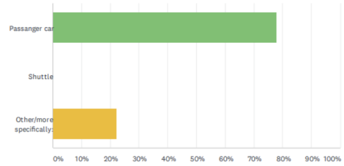
Q5 Please elaborate on the phase (operational or development) the vehicle as represented by your company is at.

Answered: 8 Skipped: 3

#	RESPONSES	DATE
1	operational	5/11/2021 8:33 AM
2	development	5/7/2021 2:50 PM
3	Development, but you could say by definition, as we are a university.	4/16/2021 1:21 PM
4	Level 1 & 2 is in operational phase Level 1 & 2 is in development phase	4/16/2021 1:07 PM
5	Field test	3/1/2021 8:15 PM
6	Developed and in series production	2/26/2021 8:30 AM
7	Development	2/25/2021 6:23 PM
8	development	2/19/2021 5:55 AM

Q6 Is the automated vehicle a passenger car or a shuttle?

Answered: 9 Skipped: 2

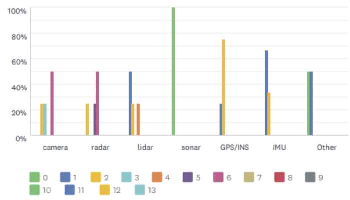


ANSWER CHOICES	RESPONSES	
Passanger car	77.78%	7
Shuttle	0.00%	0
Other/more specifically:	22.22%	2
TOTAL		9

#	OTHER/MORE SPECIFICALLY:	DATE
1	Research Vehicle	5/7/2021 2:50 PM
2	Both of 'em	2/19/2021 5:55 AM

Q7 What types of sensors are implemented in the design of the automated vehicle and how many of each?

Answered: 4 Skipped: 7



	0	1	2	3	4	5	6	7	8	9	10	11	12	13	TOTAL	WEIGHTED AVERAGE
camera	0.00% 0	0.00% 0	25.00% 1	25.00% 1	0.00% 0	0.00% 0	50.00% 2	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	4	4.25
radar	0.00% 0	0.00% 0	25.00% 1	0.00% 0	0.00% 0	25.00% 1	50.00% 2	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	4	4.75
lidar	0.00% 0	50.00% 2	25.00% 1	0.00% 0	25.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	4	2.50
sonar	100.00% 4	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	4	1.00
GPS/INS	0.00% 0	25.00% 1	75.00% 3	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	4	2.00
IMU	0.00% 0	66.67% 2	33.33% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	3	2.00
Other	50.00% 1	50.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	2	1.50

#	COMMENTS FOR "CAMERA"	DATE
	There are no responses.	

#	COMMENTS FOR "RADAR"	DATE
	There are no responses.	

#	COMMENTS FOR "LIDAR"	DATE
	There are no responses.	

#	COMMENTS FOR "SONAR"	DATE
	There are no responses.	

#	COMMENTS FOR "GPS/INS"	DATE
	There are no responses.	

#	COMMENTS FOR "IMU"	DATE
1	???	2/25/2021 6:32 PM

#	COMMENTS FOR "OTHER"	DATE
1	Thermal camera	5/7/2021 2:54 PM

Q8 What is the power consumption by each type of sensor, assuming a single sensor of each type?

Answered: 2 Skipped: 9

	0-10 WATT	10-20 WATT	20-30 WATT	30-40 WATT	40-50 WATT	50-60 WATT	60-70 WATT	70-80 WATT	80-90 WATT	90-100 WATT	100-110 WATT	100-120 WATT	>120 WATT	TOTAL	WEIGHTED AVERAGE
camera	100.00% 2	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	2	1.00
radar	100.00% 2	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	2	1.00
lidar	0.00% 0	50.00% 1	0.00% 0	50.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	2	3.00
GPS/INS	0.00% 0	50.00% 1	50.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	2	2.50
IMU	100.00% 2	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	2	1.00
Other	100.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	1	1.00

#	COMMENTS FOR "CAMERA"	DATE
1	Can't tell	2/25/2021 6:32 PM

#	COMMENTS FOR "RADAR"	DATE
	There are no responses.	

#	COMMENTS FOR "LIDAR"	DATE
1	Can't tell	2/25/2021 6:32 PM

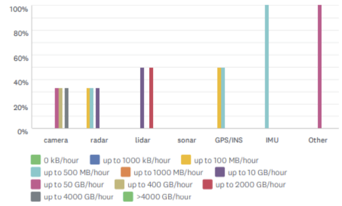
#	COMMENTS FOR "GPS/INS"	DATE
1	Can't tellHa	2/25/2021 6:32 PM

#	COMMENTS FOR "IMU"	DATE
	There are no responses.	

#	COMMENTS FOR "OTHER"	DATE
1	thermal camera	5/7/2021 2:54 PM

Q9 What is the amount of data produced by each type of the sensors, assuming a single sensor of each type?

Answered: 3 Skipped: 8



	0 KB/HOUR	UP TO 1000 KB/HOUR	UP TO 100 MB/HOUR	UP TO 500 MB/HOUR	UP TO 1000 MB/HOUR	UP TO 10 GB/HOUR	UP TO 50 GB/HOUR	UP TO 400 GB/HOUR	UP TO 2000 GB/HOUR	UP TO 4000 GB/HOUR	>4000 GB/HOUR	TOTAL	WEIGHTED AVERAGE
camera	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	33.33% 1	33.33% 1	0.00% 0	33.33% 1	0.00% 0	3	7.00
radar	0.00% 0	0.00% 0	33.33% 1	33.33% 1	0.00% 0	33.33% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	3	4.00
lidar	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	50.00% 1	0.00% 0	0.00% 0	50.00% 1	0.00% 0	0.00% 0	2	6.50
sonar	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0	0.00
GPS/INS	0.00% 0	0.00% 0	50.00% 1	50.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	2	3.50
IMU	0.00% 0	0.00% 0	0.00% 0	100.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	1	4.00
Other	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	100.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	1	6.00

#	COMMENTS FOR "CAMERA"	DATE
	There are no responses.	

#	COMMENTS FOR "RADAR"	DATE
	There are no responses.	

#	COMMENTS FOR "LIDAR"	DATE
1	Can't tell	2/25/2021 6:32 PM

#	COMMENTS FOR "SONAR"	DATE
	There are no responses.	

#	COMMENTS FOR "GPS/INS"	DATE
	There are no responses.	

#	COMMENTS FOR "IMU"	DATE
	There are no responses.	

#	COMMENTS FOR "OTHER"	DATE
	There are no responses.	

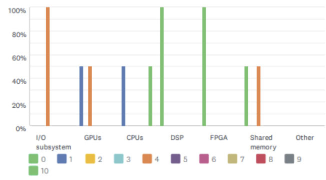
Q10 What computing platform is incorporated in your analysis concerning automated vehicles?

Answered: 2 Skipped: 9

#	RESPONSES	DATE
1	nvidia platforms (multiple)	5/11/2021 8:40 AM
2	X64_X86 pc	5/7/2021 3:00 PM

Q11 What is the computing platform composed of and what is the amount of each element?

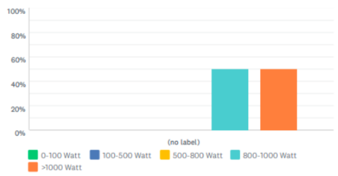
Answered: 2 Skipped: 9



	0	1	2	3	4	5	6	7	8	9	10	TOTAL	WEIGHTED AVERAGE
I/O subsystem	0.00% 0	0.00% 0	0.00% 0	0.00% 0	100.00% 2	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	2	4.00
GPUs	0.00% 0	50.00% 1	0.00% 0	0.00% 0	50.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	2	3.00
CPUs	0.00% 0	50.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	50.00% 1	2	6.00
DSP	100.00% 2	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	2	1.00
FPGA	100.00% 2	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	2	1.00
Shared memory	50.00% 1	0.00% 0	0.00% 0	0.00% 0	50.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	2	2.50
Other	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0	0.00

Q12 What is the estimated power consumption at peak level for the overall computing platform?

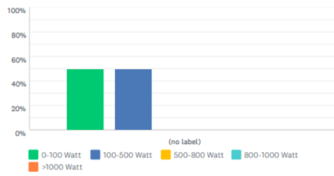
Answered: 2 Skipped: 9



	0-100 WATT	100-500 WATT	500-800 WATT	800-1000 WATT	>1000 WATT	TOTAL	WEIGHTED AVERAGE
(no label)	0.00% 0	0.00% 0	0.00% 0	50.00% 1	50.00% 1	2	4.50

Q13 What is the estimated power consumption at idle level for the overall computing platform?

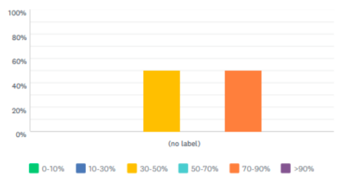
Answered: 2 Skipped: 9



	0-100 WATT	100-500 WATT	500-800 WATT	800-1000 WATT	>1000 WATT	TOTAL	WEIGHTED AVERAGE
(no label)	50.00% 1	50.00% 1	0.00% 0	0.00% 0	0.00% 0	2	1.50

Q14 What percentage of time is the overall computing platform running at its peak?

Answered: 2 Skipped: 9



	0-10%	10-30%	30-50%	50-70%	70-90%	>90%	TOTAL	WEIGHTED AVERAGE
(no label)	0.00% 0	0.00% 0	50.00% 1	0.00% 0	50.00% 1	0.00% 0	2	4.00

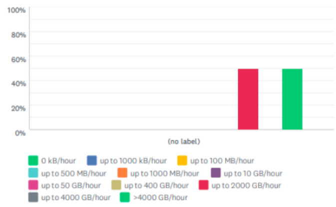
Q15 What is on average the amount of data generated by the computing platform?

Answered: 2 Skipped: 9

	0 KB/HOUR	UP TO 1000 KB/HOUR	UP TO 100 MB/HOUR	UP TO 500 MB/HOUR	UP TO 1000 MB/HOUR	UP TO 10 GB/HOUR	UP TO 50 GB/HOUR	UP TO 400 GB/HOUR	UP TO 2000 GB/HOUR	UP TO 4000 GB/HOUR	>4000 GB/HOUR	TOTAL	WEIGHTED AVERAGE
(no label)	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	50.00% 1	0.00% 0	50.00% 1	2	9.00

Q16 What is on average the amount of data stored by the computing platform?

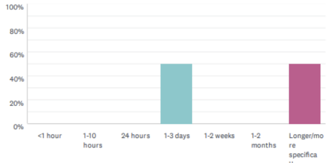
Answered: 2 Skipped: 9



	0 KB/HOUR	UP TO 1000 KB/HOUR	UP TO 100 MB/HOUR	UP TO 500 MB/HOUR	UP TO 1000 MB/HOUR	UP TO 10 GB/HOUR	UP TO 50 GB/HOUR	UP TO 400 GB/HOUR	UP TO 2000 GB/HOUR	UP TO 4000 GB/HOUR	>4000 GB/HOUR	TOTAL	WEIGHTED AVERAGE
(no label)	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	50.00% 1	0.00% 0	50.00% 1	2	6.50

Q17 How long is the data in general stored at the computing platform?

Answered: 2 Skipped: 9

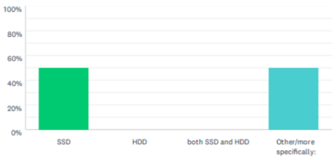


ANSWER CHOICES	RESPONSES	
<1 hour	0.00%	0
1-10 hours	0.00%	0
24 hours	0.00%	0
1-3 days	50.00%	1
1-2 weeks	0.00%	0
1-2 months	0.00%	0
Longer/more specifically:	50.00%	1
TOTAL		2

#	LONGER/MORE SPECIFICALLY:	DATE
1	depends on research	5/7/2021 3:00 PM

Q18 What type of disks are used to enable storage within the vehicle?

Answered: 2 Skipped: 9

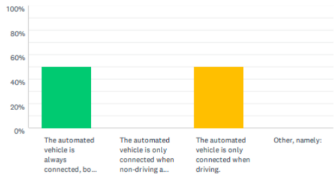


ANSWER CHOICES	RESPONSES	
SSD	50.00%	1
HDD	0.00%	0
both SSD and HDD	0.00%	0
Other/more specifically:	50.00%	1
TOTAL		2

#	OTHER/MORE SPECIFICALLY:	DATE
1	NVME SSD pcie gen4	5/7/2021 3:00 PM

Q19 What type of connectivity is considered?

Answered: 2 Skipped: 9

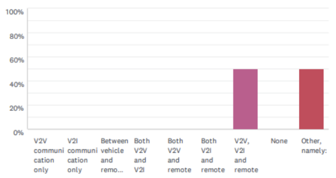


ANSWER CHOICES	RESPONSES	
The automated vehicle is always connected, both when driving and non-driving.	50.00%	1
The automated vehicle is only connected when non-driving and there is a certain upload of information at once.	0.00%	0
The automated vehicle is only connected when driving.	50.00%	1
Other, namely:	0.00%	0
TOTAL		2

#	OTHER, NAMELY:	DATE
	There are no responses.	

Q20 What type of communication is enabled to ensure connectivity?

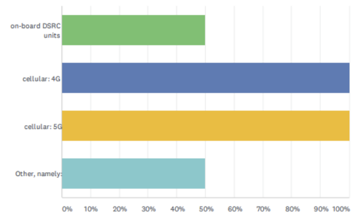
Answered: 2 Skipped: 9



ANSWER CHOICES	RESPONSES	
V2V communication only	0.00%	0
V2I communication only	0.00%	0
Between vehicle and remote control center	0.00%	0
Both V2V and V2I communication	0.00%	0
Both V2V and remote control center	0.00%	0
Both V2I and remote control center	0.00%	0
V2V, V2I and remote control center	50.00%	1
None	0.00%	0
Other, namely:	50.00%	1
TOTAL		2

Q21 What communication units are considered to be used to ensure connectivity?

Answered: 2 Skipped: 9



ANSWER CHOICES	RESPONSES	
on-board DSRC units	50.00%	1
cellular: 4G	100.00%	2
cellular: 5G	100.00%	2
Other, namely:	50.00%	1
Total Respondents: 2		

#	OTHER, NAMELY:	DATE
1	depends on research	5/7/2021 3:02 PM

Q22 What is the amount of data transmitted to data centers by a communication unit?

Answered: 0 Skipped: 11

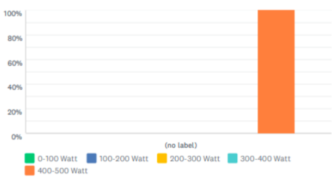
No matching responses.

	0 KB/HOUR	UP TO 1000 KB/HOUR	UP TO 100 MB/HOUR	UP TO 500 MB/HOUR	UP TO 1000 MB/HOUR	UP TO 10 GB/HOUR	UP TO 50 GB/HOUR	UP TO 400 GB/HOUR	UP TO 2000 GB/HOUR	UP TO 4000 GB/HOUR	>4000 GB/HOUR	TOTAL	WEIGHTED AVERAGE
(no label)	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0	0.00

#	OTHER/MORE SPECIFICALLY:	DATE
1	depends on the type of test: <400 GB/hour	5/11/2021 8:45 AM
2	depends on research	5/7/2021 3:02 PM

Q23 What is the average maximum power consumption of a server at a data center?

Answered: 1 Skipped: 10

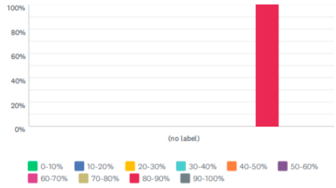


	0-100 WATT	100-200 WATT	200-300 WATT	300-400 WATT	400-500 WATT	TOTAL	WEIGHTED AVERAGE
(no label)	0.00% 0	0.00% 0	0.00% 0	0.00% 0	100.00% 1	1	5.00

#	OTHER, MORE SPECIFICALLY	DATE
1	not applicable	5/7/2021 3:02 PM

Q24 What is the average server utilization of a data center?

Answered: 1 Skipped: 10

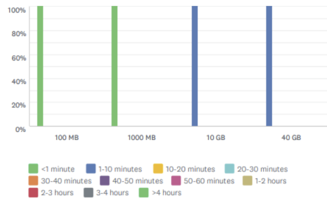


	0-10%	10-20%	20-30%	30-40%	40-50%	50-60%	60-70%	70-80%	80-90%	90-100%	TOTAL	WEIGHTED AVERAGE
(no label)	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	100.00% 1	0.00% 0	1	9.00

#	OTHER/MORE SPECIFICALLY:	DATE
1	not applicable	5/7/2021 3:02 PM

Q25 How long does a server at maximum power take to complete the workload expressed in amounts of data?

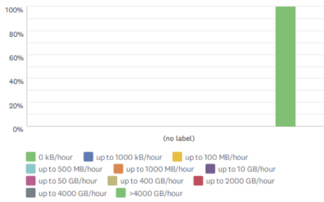
Answered: 1 Skipped: 10



	<1 MINUTE	1-10 MINUTES	10-20 MINUTES	20-30 MINUTES	30-40 MINUTES	40-50 MINUTES	50-60 MINUTES	1-2 HOURS	2-3 HOURS	3-4 HOURS	>4 HOURS	TOTAL	WEIGHTED AVERAGE
100 MB	100.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	1	2.00
1000 MB	100.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	1	2.00
10 GB	0.00% 0	100.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	1	2.00
40 GB	0.00% 0	100.00% 1	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	1	2.00

Q26 What is the amount of data stored at the data center as transmitted by a communication unit?

Answered: 1 Skipped: 10

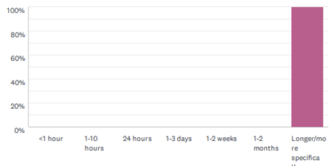


	0 KB/HOUR	UP TO 1000 KB/HOUR	UP TO 100 MB/HOUR	UP TO 500 MB/HOUR	UP TO 1000 MB/HOUR	UP TO 10 GB/HOUR	UP TO 50 GB/HOUR	UP TO 400 GB/HOUR	UP TO 2000 GB/HOUR	UP TO 4000 GB/HOUR	>4000 GB/HOUR	TOTAL	WEIGHTED AVERAGE
(no label)	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	100.00% 1	1	7.00

#	COMMENTS FOR "(NO LABEL)"	DATE
1	not applicable	5/7/2021 3:02 PM

Q27 How long is the data as transmitted by the communication unit stored at the data center?

Answered: 2 Skipped: 9

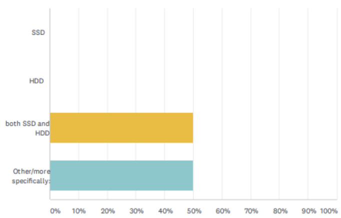


ANSWER CHOICES	RESPONSES	
<1 hour	0.00%	0
1-10 hours	0.00%	0
24 hours	0.00%	0
1-3 days	0.00%	0
1-2 weeks	0.00%	0
1-2 months	0.00%	0
Longer/more specifically:	100.00%	2
TOTAL		2

#	LONGER/MORE SPECIFICALLY:	DATE
1	as long as a research project requires (typically 3 years)	5/11/2021 8:45 AM
2	not applicable	5/7/2021 3:02 PM

Q28 What type of disks at data centers are used to enable storage?

Answered: 2 Skipped: 9



ANSWER CHOICES	RESPONSES	
SSD	0.00%	0
HDD	0.00%	0
both SSD and HDD	50.00%	1
Other/more specifically:	50.00%	1
TOTAL		2

#	OTHER/MORE SPECIFICALLY:	DATE
1	not applicable	5/7/2021 3:02 PM

Q29 What is your general estimation about the total amount of data that the vehicle as represented by your company generates?

Answered: 0 Skipped: 11

▲ No matching responses.

ANSWER CHOICES	RESPONSES	
<25 GB/hour	0.00%	0
up to 25 GB/hour	0.00%	0
up to 500 GB/hour	0.00%	0
up to 4000 GB/hour	0.00%	0
>4000 GB/hour	0.00%	0
TOTAL		0

#	OTHER, NAMELY:	DATE
1	not applicable	5/7/2021 3:04 PM