Issue 23(1), 2023, pp. 1-29
https://doi.org/10.18757/ejtir.2023.23.1.6553

TU Delft OPEN

EJTIR

ISSN: 1567-7141
http://ejtir.tudelft.nl/

Travel time, delay and CO_2 impacts of SAE L3 driving automation of passenger cars on the European motorway network

Elina Aittoniemi[1]
VTT Technical Research Centre of Finland Ltd., Espoo, Finland.

Teemu Itkonen[2]
VTT Technical Research Centre of Finland Ltd., Espoo, Finland.

Satu Innamaa[3]
VTT Technical Research Centre of Finland Ltd., Espoo, Finland.

Impacts of driving automation on traffic flow and emissions are usually studied with traffic simulations using only few speed limits and traffic volumes. Without considering the real-world prevalence of simulated scenarios, it is unknown how the results translate to real-world conditions, such as a regional motorway network. The present study assessed the potential impacts of conditionally automated driving, described by stable vehicle motion control and longer time gaps, on the European motorway network assuming no changes in other influential factors, such as travel demand or vehicle fleet. Traffic simulations provided estimates of the effect magnitude per vehicle kilometre travelled (VKT) in representative conditions, and results were scaled up using map-, traffic- and weather-related data, accounting for the VKT per condition. Overall, the impacts of automated vehicles (AVs) on the European motorway network are likely small. Travel times and delay are estimated to increase by 0.8% and 1.3% respectively at a 100% AV penetration rate among passenger cars, and CO2 emissions to drop by 0.5%. While large reductions of average travel time (up to 8.0–10.4%), delay (up to 17.5–34.8%) and emissions (up to 13.5–15.0%) were found at high traffic volumes, most (86%) of the VKT accumulate at low traffic volumes, with small estimated effects. Thus, although beneficial in some conditions, the AVs considered in this study are not likely to support Europe's sustainability goals. Findings advocate a comprehensive approach: Whereas impacts are likely greatest in heavy traffic, the prevalence of conditions must be considered in network level assessment.

Keywords: *driving automation, impact assessment, motorway network, traffic simulation*

Publishing history

Submitted: 6 July 2022
Accepted: 16 December 2022
Published: 04 January 2023

Cite as

Aittoniemi, E., Itkonen, T., Innamaa, S. (2023). Travel time, delay and CO_2 impacts of SAE L3 driving automation of passenger cars on the European motorway network. European Journal of Transport and Infrastructure Research, 23(1), 1-29.

[1] A: P.O. Box 1000, FI-02044 VTT, Finland E: elina.aittoniemi@vtt.fi
[2] A: P.O. Box 1000, FI-02044 VTT, Finland E: teemu.itkonen@vtt.fi
[3] A: P.O. Box 1000, FI-02044 VTT, Finland E: satu.innamaa@vtt.fi

1. Introduction

1.1 Background

Making sustainable and evidence-based policy decisions on new technologies requires comprehensive understanding of the potential impacts these technologies can have on a sufficient temporal and spatial scale. One such technology is automated driving, which has been highlighted as one of the potential solutions on the way to a sustainable, safe, equitable and carbon-neutral transport future (European Commission 2019, CCAM 2022, ERTRAC 2022). While vehicles equipped with automated driving systems (SAE level 3 (L3) and higher), hereafter referred to as AVs, are being tested on real roads around the world, they are not yet widely used by ordinary drivers in their daily lives. Measurements with a few vehicles in traffic do not translate to traffic-flow-level impacts at higher AV penetration rates. Therefore, impacts on traffic efficiency and emissions have generally been estimated with traffic simulations, using a variety of driver models both for AVs and for manual, human-driven vehicles (MVs) in different specific road environments and traffic conditions (Aittoniemi 2022).

In the current literature, the simplest road networks in simulations are theoretical single-lane motorways with on-ramps (Vanderwerf et al. 2002) or without them (Ntousakis et al. 2015). Other studies use generic motorway stretches a few kilometres in length with several lanes per direction, on-and off-ramps, and one or two fixed traffic volumes (Calvert et al. 2017). Some studies apply simulations on a specific motorway stretch of a few kilometres and use traffic volumes from real traffic counts, usually at peak hours (Stogios et al. 2019, Tomás et al. 2020). A few (Mattas et al. 2018, Bandeira et al. 2021, Rezaei and Caulfield 2021) have simulated more extensive real roads or small networks with traffic volumes from real traffic counts for a specific time, usually at peak hours.

An overview of literature in Table 1 shows that the most common indicators of interest in current studies addressing the efficiency and CO_2 impacts of driving automation have been throughput and capacity. A few studies have investigated impacts on CO_2 emissions. Due to the small number of studies on higher automation, the review also includes some results for lower-level automation. No clear distinction is usually made in simulation studies between the capabilities of vehicles equipped with driver assistance systems such as adaptive cruise control (ACC) and vehicles with higher level driving automation in terms of longitudinal driving, and restrictions of the operational design domain (ODD) or driver takeovers are typically excluded. Therefore, the type of automation addressed by the studies is described in terms of longitudinal and lateral vehicle motion control. Simulations have used traffic volumes that matched the estimated road capacity or peak hour traffic volumes. The desired time gaps that AVs aimed to keep to the vehicle in front varied from very short (0.45 s) to long (2.1 s). Most studies assumed uniform desired time gaps for AVs, while one study (Calvert et al. 2017) used distributions ranging from 0.3 s to 1.9 s (mean: 1.1 s) and 1.1 s to 1.9 s (mean: 1.5 s). In the literature, results on throughput and capacity varied from a 40% decrease to a 31% increase in throughput or capacity with a 100% AV penetration rate among passenger cars. With a 20–25% AV penetration rate, capacity or throughput varied from a 17% decrease to a 7% increase. CO_2 emissions varied from a 2% decrease to an 11% increase at a 100% AV penetration rate and a 2% decrease to no change at 20–25% AV penetration rates.

These studies can give some indication of the potential of automated driving in specific conditions, but do not allow conclusions to be drawn on impacts beyond these conditions, e.g., on a regional level over a longer period, for two main reasons. First, the frequency and duration of the simulated conditions on the real network are not considered. Second, impacts in other conditions commonly encountered on the roads, where the magnitude and direction of effects may differ, are excluded. Most available studies on the traffic flow efficiency impacts of automated driving have considered high traffic volumes only, often showing benefits for traffic flow. When only specific conditions are considered where impacts may be large, heightened expectations of the potential of AVs may arise, but the conditions considered do not represent the whole range of traffic conditions with different impacts. Consequently, information on the effects in limited situations is insufficient to serve as a basis for policy decisions. A comprehensive approach is needed to be able to assess impacts in conditions typically encountered in the real world.

Table 1. Overview of simulation studies addressing efficiency and CO_2 impacts of driving automation at AV penetration rates of 20–25 % and 100%.

Reference	Network	HDVs	Ramps	Traffic volume	Type of driving auto-mation	Indicator	AV desired time gap	Results with AV PR 20-25%	Results with AV PR 100%
Vander-werf et al. 2002	Generic, single lane	No	Yes	At capacity	Longi-tudinal	Capacity	1.0 s	+4%	+30%
							2.0 s	0%	-22%
Ntousakis et al. 2015	Generic, single lane	No	No	At capacity	Longi-tudinal	Capacity	1.0 s	+4%	+11%
							2.0 s	-17%	-40%
Calvert et al. 2017	Generic, three lanes	6%	Yes	At capacity (6270 veh/h)	Longi-tudinal and lateral (lane changes)	Through-put	1.1 s (mean)	0%	+7%
							1.5 s (mean)	-6%	-14%
Stogios et al. 2019	Motor-way in Toronto, several lanes	No	Yes	Peak hour	Longi-tudinal and lateral (lane changes)	Through-put	0.5 s	–	+26%
							2.1 s	–	-39%
Rezaei and Caulfield 2021	Motorway in Ireland, 4 lanes	No	Yes	Peak hour	Longi-tudinal and lateral (lane changes)	Through-put	0.45 s	7%	22%
							0.9 s	5%	16%
Mattas et al. 2018	Antwerp ring road, variable no. of lanes	(No)[4]	Yes	80% of peak hour	Longi-tudinal and lateral (lane changes)	CO_2	1.6 s	No change	-2%
				100% of peak hour					+6%
				120% of peak hour					+11%
Tomás et al. 2020	Motor-way in Portugal, 3-4 lanes	4% (HDV) 4% (buses)	Yes	Peak hour	Longi-tudinal and lateral (lane changes)	CO_2	0.5 s	-2%	–
Bandeira et al. 2021	Motor-way in Portugal, 2 lanes	No	Yes	Peak hour (21–43% of capacity)	Longi-tudinal and lateral (lane changes)	CO_2	0.5 s	Negli-gible	Negli-gible
Calvert et al. 2017	Generic, three lanes	6%	Yes	At capacity (6270 veh/h)	Longi-tudinal and lateral (lane changes)	Travel time	1.1 s (mean)	+3%	-26%
							1.5 s (mean)	+11%	-2%

*Note that Calvert et al. (2017) used time gap distributions of between 0.3 s and 1.9 s (mean: 1.1 s) and 1.1 s and 1.9 s (mean: 1.5 s).

[4] The article is ambiguous on whether HDVs were included in the simulations and emissions calculations.

The present study extends the current state of the art by taking a comprehensive perspective on the potential impacts of conditionally automated passenger cars on the entire European motorway network over a period of one year, taking into consideration the ODD of the AVs. Only the impacts caused by changed driving behaviour due to AVs are considered, assuming no changes in other influencing factors such as travel demand, vehicle fleet or accident-induced congestion. The prevalence of different conditions on the network relating to motorway type, speed limit and traffic volume are determined, effect sizes resulting from the presence of AVs in these conditions are estimated, and scaled-up estimates of potential changes in travel times, delay and CO_2 emissions on the European motorway network are provided for different AV penetration rates. The results can help in assessing whether automated driving can contribute to the EU's sustainability goals and improve traffic efficiency on motorways.

The study was part of the L3Pilot project, co-funded by the European Horizon 2020 programme (L3Pilot 2021). Within the project, extensive field tests in several European countries were performed with vehicles equipped with different automated driving functions (ADFs). As only single prototype vehicles were used on a given road at a time, impacts on traffic flow efficiency and the environment were studied with traffic microsimulation, set up in cooperation with vehicle manufacturers.

1.2 *Objectives*

The present study aimed to investigate comprehensively the potential impacts of vehicles equipped with an SAE Level 3 ADF on traffic flow efficiency and CO_2 emissions of European motorways over a period of one year. The impacts were isolated to cover solely those arising from changes in driving behaviour, while assuming no impact of automation on other potentially affected mechanisms such as travel demand, vehicle fleet or accident-induced congestion. Specifically, these three research questions were addressed:

1. How would *travel times* on the European motorway network change with different penetration rates of vehicles equipped with an L3 motorway ADF?
2. How would *delays* on the European motorway network change with different penetration rates of vehicles equipped with an L3 motorway ADF?
3. How would *CO_2 emissions* on the European motorway network change with different penetration rates of vehicles equipped with an L3 motorway ADF?

The indicators of interest were travel time, delay, and CO_2 emissions. Travel time was defined as the time it took vehicles to travel from start to end of the simulated network. Delay per vehicle was set as the difference in the free-flow travel time, which was defined either by the travel time at the desired speed or by the travel time at the given speed limit, whichever value was larger. A negative delay was disregarded so as not to reward illegal actions (such as time saved by speeding) as a benefit (Carsten and Tate 2005). CO_2 emissions concerned tailpipe emissions.

Temporally, impacts were assessed for each hour over one generic year (12-month-period), to be able to account for variations in traffic volumes with time of day, week and year. The spatial scope of the assessment was the motorway network of 30 European countries, referred to in the following as EU27+3, including the 27 EU member states as of 2020 as well as Norway, Switzerland, and the United Kingdom. As the objective was to determine the impacts of automation, no other changes to the traffic system were considered in addition to AVs.

2. Methodology

2.1 General approach

A snapshot approach was applied in the L3Pilot socioeconomic impact assessment to avoid uncertain predictions of the future and allow for determining the unique effects of driving automation. In the snapshot approach, impacts were assessed assuming that a certain proportion (penetration rate) of the present passenger car fleet in Europe would be equipped with a motorway ADF but otherwise traffic would remain as it is today. This approach allowed to assess solely the impacts arising from changes in driving behaviour due to automation, excluding other related impacts such as changes in amount of travel or vehicle powertrain and mass. We assumed that the ADF worked as intended and was used whenever the conditions fulfilled the requirements of the ODD.

The applied methodology for assessing potential impacts of motorway AVs on traffic flow efficiency and CO_2 emissions on a European level involved two main parts: 1) Estimation of the effect size as percentual changes of emissions with traffic microsimulation in representative conditions and 2) Scaling up these effects to the entire European motorway network. For both parts, it was necessary first to determine the frequency (in terms of length or vehicle kilometres travelled, VKT) of different motorway conditions regarding number of lanes, speed limits and traffic volumes in the EU27+3 countries. Thus, the distribution of traffic volumes was determined over time and space in different conditions. This information was used in the first step to set up simulation environments that are representative of the European network, and in the second step to scale up the determined effects in specific scenarios according to the prevalence of these scenarios on the network.

The European motorway network comprises roughly 80 000 km (European Commission 2021a; Figure 1) and has speed limits ranging mainly from 80 km/h to 140 km/h, as well as unrestricted sections in Germany. On a regional level, motorways vary in terms of e.g., number of lanes and speed limits. Further, traffic volumes on a network are known to vary greatly over time – both short-term, such as over each hour of a day, and long-term, such as over each month of a year (Transportation Research Board 2016). As AVs were expected to have different effects in different conditions, effect sizes were determined separately for different traffic scenarios, which describe the motorways in terms of number of lanes, speed limit and presence or absence of ramps as well as traffic volume in five categories. These traffic scenarios were designed to represent European motorways as closely as possible, based on OpenStreetMap data analysis and collection of traffic volumes from national authorities and contact points. In addition, historical weather data were used to determine whether the conditions for ADF use were met. Effect sizes in the different traffic scenarios were determined by microscopic traffic simulations.

Figure 1. Motorway network of EU27, Norway, Switzerland and the United Kingdom. Source: OpenStreetMap.

In practice, effect estimates for each indicator per traffic scenario were calculated per VKT, so that the effects from simulations could be matched to estimates of VKT driven on the European motorway network in the different traffic scenarios. This step was needed as no data was available on total delays, travel times or emissions of all vehicles on the European motorway network. Dividing the indicator sum for each vehicle type in a simulation by the total VKT driven by that vehicle type in the simulation resulted in the average value for each indicator per VKT. Scaled-up impacts were calculated for the traffic as a whole, consisting of automated and manually driven passenger cars and manually driven heavy-duty vehicles (HDVs). To be able to distinguish the impacts arising from the changed vehicle motion control and longer desired time gaps from other possible AV impacts, the VKT driven in different traffic scenarios was assumed to remain constant with the introduction of AVs.

2.2 *Effect estimation*

The effects of driving automation on traffic flow efficiency in different traffic scenarios were studied with microscopic traffic simulations using PTV Vissim (Version 2020). Four AV penetration rates of 5%, 10%, 30% and 100% were considered, in addition to a baseline without automation. Vehicle trajectories resulting from the simulations were further used to calculate changes in CO_2 emissions with the EnViVer tool (Eijk et al. 2014).

The field tests in L3Pilot were conducted with AVs still in prototype phase. As prototypes do not fit the assumption of a large-scale use of the technology, impact assessment was based on foreseen future technology, i.e., a "mature" ADF. This was defined together with car manufacturers as an ADF that is mature for usage by ordinary drivers on motorways (Bjorvatn et al. 2021). The definition included the driving behaviour of ADF-equipped AVs in terms of relevant model parameters such as desired time gap and the requirements for their ODD. The ODD requirements were set so that the ADF could operate in good weather conditions or in light or normal rain, and where lane markings were needed but could have small gaps. The motorway ADF was assumed to be activated once the vehicle had merged onto the main motorway from the ramp, and it could be used until merging onto the off-ramp.

As the study aimed to assess the effects in scenarios that were representative of the overall European motorway network, all combinations of European motorways regarding number of lanes and speed limits and each representing at least 1% of the total motorway network length on OpenStreetMap were simulated. This produced 13 different combinations of two- and three-lane motorways with speed limits ranging from 80 km/h to 140 km/h or unrestricted: two-lane motorways with all eight speed limit conditions and three-lane motorways with speed limits of 100, 110, 120 and 130 km/h and unrestricted. Vehicles on motorways with a 140 km/h speed limit and on unrestricted-speed motorways used the same desired speed distributions (Geistefeldt et al. 2017). Speed limits given in miles per hour were converted to kilometres per hour (km/h) and rounded to the nearest 10. The motorway types selected for simulation represent together approximately 85% of the motorway network length in the EU27+3 according to OpenStreetMap. To study the effects on motorways with and without ramps, each of these 13 combinations was applied to a motorway section without ramps and a motorway section with an on- and off-ramp. The length of the simulated motorway sections was 4.8 km and the ramps were situated midway. In the map data, a section was considered a ramp section if the nearest on- or off-ramp was closer than 2 km in either direction (based on OpenStreetMap). The share of sections with ramps on the EU27+3 motorway network was found to be on average 75% of the network length.

To account for potentially different effects in different traffic conditions, five traffic volume classes ranging from free-flow conditions to volumes near capacity were used: 500, 1000, 1500, 2000 and 2500 vehicles per hour per lane. In the simulations of ramp sections, the traffic volume to and from ramps was set to 10% of the main flow. In addition to passenger cars, HDVs were included in the simulations as they have a strong influence on traffic flow properties due to their large mass

(Moridpour et al. 2015) and different target speed on high-speed-limit roads. Simulated HDVs were not automated.

Studying empirical traffic data from seven countries showed that the HDV share in traffic is dependent on the traffic volume. Therefore, a fixed share of HDVs was associated with each traffic volume class, as shown in Table 2. Each combination of speed limit, number of lanes, presence of ramps, AV penetration rate and input traffic volume was repeated in 20 simulation runs of 30 minutes each (excluding a warm-up period of 5 min). In total, 13 000 simulations were carried out, comprising 149 million VKT. The results of different scenarios were combined by weighting with their prevalence in terms of VKT.

Table 2. Traffic volume classes and HDV share in traffic simulations

Nr of lanes per direction	**Two lanes**					**Three lanes**				
Volume class	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Average input traffic flow (veh/h)	1000	2000	3000	4000	5000	1500	3000	4500	6000	7500
HDV share	11.8%	9.4 %	8.2%	7.5%	6.6%	10.3%	8.2%	7.2%	6.6%	5.9%

Based on discussion with car manufacturers it was assumed that AVs aimed to keep a constant speed, and their desired speed in the simulations was set equal to the speed limit whenever it was 130 km/h or below, and to 130 km/h with higher allowed speeds. MVs followed the default desired speed distributions of Vissim. On average, MVs aimed to drive slightly above the speed limit at all speed limits except 130 km/h, where their average speed was below the limit, but there was substantial variation in the desired speeds of the MVs. For HDVs, an average desired speed of 86 km/h was applied at speed limits above 80 km/h. This value was defined as an average of the different legally allowed speeds across Europe (varying between 70 and 110 km/h; European Commission 2021b) weighted with the motorway length per country. The recommendations by Geistefeldt et al. (2017) for heavy vehicle desired speed distributions at speed limits of 80 and 90 km/h were used to define the desired speed distribution for HDVs.

Vissim has been recently upgraded to better allow for simulating AVs (Olstam et al. 2020), which are expected to exhibit less stochasticity in driving behaviour than human drivers. The main differences in the driving behaviour of AVs and MVs in the traffic simulations, in addition to less stochasticity for AVs, were the parameter CC1 (headway time), which was 1.05 s for MVs. For AVs it was set to 1.6 s, a time gap considered realistic by car manufacturers in L3Pilot. In addition, cooperative lane changes were enabled for MVs but not for AVs. The parameters used in the Wiedemann99 model are shown in Table 3.

Table 3. Wiedemann99 parameters used for manually driven cars (MVs), automated cars (AVs) and heavy-duty vehicles (HDVs).

	MVs	**AVs**	**HDVs**
Longitudinal parameters			
CC0: Standstill Distance (m)	1.50	2.00[5]	1.50
CC1: Time Gap (s)	1.05[7]	1.60[5]	1.05[7]
CC2: Following Variation (m)	4.00	0.00[6]	4.00
CC3: Threshold for Entering Follow. (s)	-8.00	-8.00	-8.00
CC4: Negative Following Threshold (m/s)	-0.30[7]	-0.10[6]	-0.30[7]

[5] Decision made within L3Pilot project together with OEMs

CC5: Positive Following Threshold (m/s)	0.35	0.10[6]	0.35
CC6: Speed Dependency of Oscillation (10^{-4} rad/s)	11.44	0.00[6]	11.44
CC7: Oscillation Acceleration (m/s^2)	0.25	0.10[6]	0.25
CC8: Standstill Acceleration (m/s^2)	3.50	3.50	2.50[7]
CC9: Acceleration at 80 km/h (m/s^2)	1.50	1.50	1.00[7]
Lateral parameters			
Accepted deceleration (m/s^2) own/trailing vehicle	-1.0/-0.75	-1.0/-1.0[6]	-1.0/-0.75
-1 m/s^2 per distance	200	100[6]	200
Cooperative lane change	on	off[5,6]	off[7]
Advanced merging	on	off[5,6]	off[7]
General setting			
Use implicit stochastics	on	off[6]	on

CO_2 emissions were calculated with EnViVer (Eijk et al. 2014), a microscopic emissions calculation tool based on the Versit+ emissions model (Smit et al. 2007), for all vehicle trajectories from the Vissim simulations. Due to the selected snapshot approach, driving automation was applied to a share of the current passenger car fleet. For this step, data on the European vehicle fleet in terms of average dimensions, age, and fuel type of passenger cars and HDVs was collected from different sources (see Table 4).

Table 4. Average vehicle characteristics of the European fleet.

	Manual and automated passenger cars	Heavy-duty vehicles
Vehicle age		
Average age (years)[8]	10.8	12.4
Share of age under 1 year[8]	5.3%	5.4%
Average exit age (years)[9]	19	19
Vehicle fuel type shares[8,10]		
Petrol	54.1%	1.7%
Diesel	41.9%	97.8%
LPG (Liquefied petroleum gas)	2.9%	0.5%
CNG (Compressed natural gas)	0.5%	–

The objective of the scaling up process was to produce an estimate of the potential changes to travel time, delay, and CO_2 emissions on the whole European motorway network when traffic flow contains a certain penetration rate of AVs, accounting also for the ODD of the ADF. The lack of data on the baseline situation, i.e., on the average travel times, delays and CO_2 emissions on the European motorway network in total as well as separately for each vehicle type and combination

6 Sukennik and Kautzsch (2018), using normal driving logic
7 Geistefeldt et al. (2017)
8 ACEA (2019)
9 Data found for three countries: Finland (21 years in 2019; Information Centre of Road Transport (2022)), Germany (18 years; Autoflotte (2014)) and the Netherlands (19 years; EnViVer). Average of 19 years assumed for EU27+3. Same value assumed for HDVs due to lack of data.
10 EAFO (2021)

of speed limit and traffic volume, posed a challenge to begin with. Therefore, scaling up was based on estimates of absolute effects, defined per VKT from traffic simulations, instead of using effects estimates as percentage change. The effect estimates were combined with total VKT estimates in corresponding traffic scenarios in conditions fulfilling the requirements set by ODD of the ADF (Innamaa et al., under review). Traffic volume was estimated for each hour of the year for each road section using all the hourly traffic volume data available from the countries.

Regarding the ODD of the ADF, the quality of motorway infrastructure was assumed to be of sufficient quality for automated driving on all motorways in the EU27+3. Thus, the only condition where ADFs could not be used was related to adverse weather conditions, and historical weather data on a European level was needed to determine whether or not the ODD requirements of the ADF were met at a given time and location. The VKT accumulated in conditions not fulfilling the the ODD requirements of the ADF were disregarded when determining the changes in indicator values. Next, a spatial reference unit was needed for assigning different motorway types and traffic volumes to different regions in Europe so that the differences in weather conditions and traffic volumes between different regions could be accounted for. For this purpose, the NUTS3 classification (Eurostat 2021), which divides Europe into roughly 1500 regions with populations ranging from 150 000 to 800 000, was selected. This approach allowed assigning different traffic volume classes to motorways located in different parts of Europe and its countries taking into account the local distribution of traffic and weather conditions and the overall motorway VKT of the country. The VKT in each of the NUTS3 regions was separated into VKT inside the ODD (with ADFs in use by passenger cars according to the penetration rate) and outside the ODD (with all vehicles manually driven). The threshold for heavy rain, out of the ODD of the AVs, was set to 7.5 mm/h. Snowfall above 1.0 mm/h was assumed out of the ODD. The European Centre for Medium-Range Weather Forecasts through the Copernicus Programme (Muñoz Sabater 2019) provided weather data for Europe on an hourly basis.

The temporal base unit for scaling up was set to one hour. Thus, matching the hour of traffic measurements acquired from the national authorities with the corresponding weather condition at that hour from the weather data (one reference point for each NUTS3 region) produced an overview of the weather conditions and traffic volumes for each hour of one year in each NUTS3 region for all motorway types in the region. Where hourly traffic volume data was not available, it was estimated based on European average traffic variation factors. The year of reference for traffic was 2019. Traffic volumes were collected by contacting the national contact points of each country. Five countries (Cyprus, Estonia, Latvia, Luxemburg and Malta) were excluded from analysis due to the small or non-existent motorway networks. Of the remaining 25 countries, data was obtained from 17 countries. Finally, the VKT estimates obtained with the formula traffic volume * road length were scaled to fit the total annual motorway VKT per country, as no VKT data was available on NUTS3 level. The country totals were obtained from the ecoDriver project (Jonkers et al. 2016). The simulated traffic volume classes were assumed to represent real traffic volumes as shown in Table 5.

Table 5. Traffic volume classes used in simulations and matched real-world traffic counts.

Traffic volume class	Traffic volume in simulation (veh/h/lane)	Associated traffic count data (veh/h/lane)
1	500	up to 750
2	1000	751-1250
3	1500	1251-1750
4	2000	1751-2250
5	2500	more than 2250

Scaled up indicator values were obtained by multiplying the indicator value per VKT for each penetration rate, estimated based on traffic simulations, with the estimated VKT in each traffic scenario in each NUTS3 region. These numbers were then summed up to a EU27+3-wide total. The overall result is the difference between the baseline condition and the appropriate penetration rate condition, as shown by the following equation (Innamaa et al., under review):

$$Impact_R = \sum_{ts} \left(\left(x_{ts,TR} - x_{ts,BL} \right) \cdot VKT_{ts,R} \right) \quad (1)$$

where

- $x_{ts,TR}$: Indicator under investigation, e.g., CO_2 emissions or delay, per VKT in traffic scenario ts in the treatment condition
- $x_{ts,BL}$: Indicator under investigation, e.g., CO_2 emissions or delay, per VKT in traffic scenario ts in the baseline condition
- $VKT_{ts,R}$: VKT in traffic scenario ts in region or other scope of interest R (baseline)
- The scope of interest R can be a specific speed limit or traffic volume class, in addition to a region.

To assess the variability of the results, a bootstrapping procedure was applied (Efron and Tibshirani 1986): Before calculation of the impact, each set of 20 simulation runs with identical conditions was randomly resampled with-replacement. This procedure was repeated a hundred times, yielding a hundred subtly different indicator values, which were then used to estimate a mean and a 95% confidence interval.

The process for determining potential impacts on the European motorway network is summarised in Figure 2.

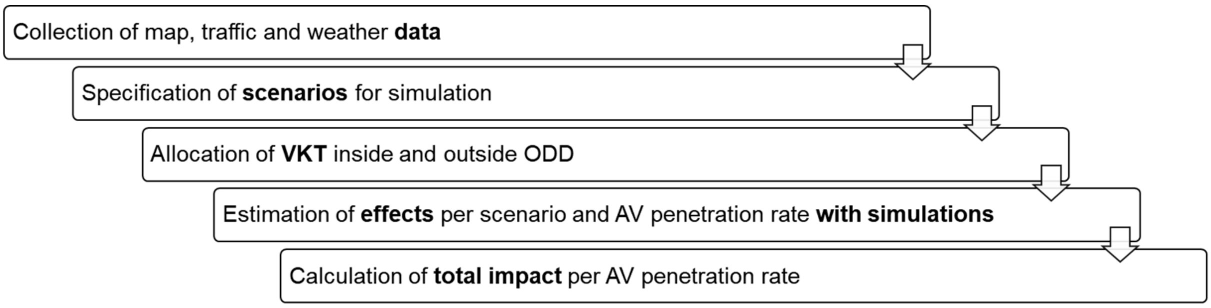

Figure 2. Determining the impacts of motorway ADF at European level. (VKT: vehicle kilometres travelled, ODD: operational design domain, AV: vehicles equipped with an automated driving function).

3. Results

3.1 Distribution of vehicle kilometres travelled on the European motorway network

The current distribution of VKT on the European motorway network in different traffic conditions and speed limits on an hourly basis was determined so that the effects from different simulations could be matched to the real network when forming the results at European level. Results of the analysis of traffic volume data from European motorways show that most VKT accumulates on roads with high speed limits and in low traffic volumes. Regarding speed limits, the highest share (30.3%) of VKT is driven on motorways with a speed limit of 130 km/h (Table 6). Motorways with a speed limit of 120 km/h account for 18.8% of VKT and unrestricted-speed motorways for 16.3%. Regarding traffic volumes, most (85.9%) VKT are driven in the lowest two traffic volume classes of up to 1250 vehicles per hour per lane, with the share of the lowest traffic volume (up to 750 veh/h/lane) being 58.9% and the second lowest (751–1250 veh/h/lane) 27.0%. The total number of resulting combinations of speed limit and traffic volume class was 39 (as no data was allocated to traffic volume class 5 at speed limit 140 km/h).

Table 6. Distribution of VKT in EU27+3 per speed limit and traffic volume class. Volume class 1: up to 750 veh/h/lane; 2: 751–1250 veh/h/lane; 3: 1251–1750 veh/h/lane; 4: 1751–2250 veh/h/lane; 5: over 2250 veh/h/lane.

Speed limit [km/h]		**80**	**90**	**100**	**110**	**120**	**130**	**140**	**None**	**Total**
Share of VKT	Total	3.0%	3.1%	12.2%	15.0%	18.8%	30.3%	1.3%	16.3%	
Share of VKT per speed limit and traffic volume class 1 to 5	1	56.5%	45.7%	44.4%	47.0%	69.2%	65.4%	77.4%	58.5%	58.9%
	2	34.6%	27.8%	33.7%	26.9%	23.9%	21.1%	22.3%	35.5%	27.0%
	3	6.8%	14.2%	13.9%	18.2%	3.1%	5.0%	0.3%	4.9%	8.0%
	4	1.6%	6.4%	5.1%	5.9%	0.4%	2.8%	0.01%	0.8%	2.8%
	5	0.6%	5.9%	2.9%	2.1%	3.4%	5.7%	-	0.3%	3.3%

The ten most common speed limit and traffic volume combinations, covering 79.6% of the annual VKT on the European motorway network, are shown in Table 7. Almost one fifth (19.3%) of all VKT on the European motorway network is driven at a speed limit of 130 km/h at traffic volumes of up to 750 veh/h/lane. Most of the other combinations account for a small share of the total VKT.

Table 7. The ten most common speed limit and traffic volume combinations on EU27+3 motorways (representing 79.6% of VKT). Volume class 1: up to 750 veh/h/lane; 2: 751–1250 veh/h/lane.

	Speed limit (km/h)	**Traffic volume class**	**Share of total VKT on EU27+3 motorways**
1	130	1	19.8%
2	120	1	13.0%
3	none	1	9.5%
4	110	1	7.1%
5	130	2	6.4%
6	none	2	5.8%
7	100	1	5.4%
8	120	2	4.5%
9	100	2	4.1%
10	110	2	4.0%

3.2 Impacts per speed limit and traffic volume class

To determine the overall impact of L3 automation of passenger cars on traffic efficiency and CO_2 emissions on the European motorway network, results from traffic simulations in representative scenarios were combined with estimates on the frequency, both spatial and temporal, of these scenarios on European motorways. In this section, as well as in section 3.3, the results are reported for specific speed limit and traffic volume conditions from traffic simulations. These results relate to effects on motorways in these conditions only, without accounting for the prevalence of the conditions on the whole network.

Simulation results for the five traffic volume classes, four AV penetration rates among passenger cars, and the baseline without AVs are shown in this section for speed limits of 90, 110 and 130 km/h. Each bar in Figure 3–Figure 5 shows the average indicator value per VKT for a specific speed limit, traffic volume and AV penetration rate. The results for all other speed limits, as well as the effect sizes, are provided in the Appendix A.

In the lowest four traffic volume classes with high AV penetration rates, travel times per VKT are slightly above the baseline for all three speed limits shown (Figure 3). An exception is the 130 km/h speed limit in the lowest two traffic volume classes, where average travel times at high AV penetration rates are shorter than at baseline due to the desired speed of AVs being higher than that of the average MV. In the highest traffic volume class, average travel times per VKT are on average 28.1%, 9.4% and 5.8% shorter than at baseline at a 30% AV penetration rate and speed limits of 90, 110 and 130 km/h, respectively, and 34.8%, 19.3% and 17.5 % shorter at a 100% AV penetration rate and the same speed limits, respectively.

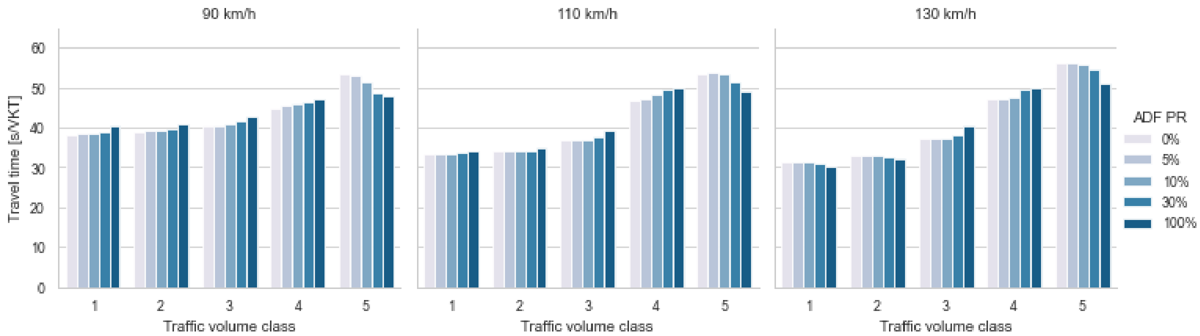

Figure 3. Average travel time in seconds per VKT for speed limits of 90, 110 and 130 km/h per traffic volume class and AV penetration rate among passenger cars on EU27+3 motorways. Volume class 1: up to 750 veh/h/lane; 2: 751–1250 veh/h/lane; 3: 1251–1750 veh/h/lane; 4: 1751–2250 veh/h/lane; 5: over 2250 veh/h/lane.

Figure 4 shows the average delay for the three speed limits. At a 100% AV penetration rate, delay is slightly greater with AVs than at baseline in the four lowest traffic volume classes. An exception is, again, the 130 km/h speed limit, where the delay is smaller at high AV penetration rates than at baseline in the two lowest traffic volume classes. In the highest traffic volume class, compared to the baseline, the average delay per VKT at a 30% AV penetration rate is 8.4%, 3.9% and 3.0% smaller at speed limits of 90, 110 and 130 km/h, respectively, and at a 100% AV penetration rate 10.4%, 8.1% and 9.2% smaller at the same speed limits, respectively.

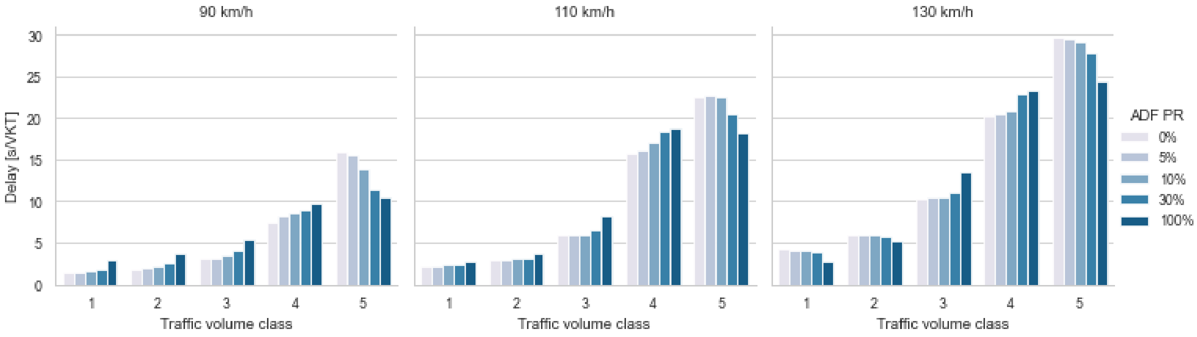

Figure 4. Average delay in seconds per VKT for speed limits of 90, 110 and 130 km/h per traffic volume class and AV penetration rate among passenger cars on EU27+3 motorways. Volume class 1: up to 750 veh/h/lane; 2: 751–1250 veh/h/lane; 3: 1251–1750 veh/h/lane; 4: 1751–2250 veh/h/lane; 5: over 2250 veh/h/lane.

Figure 5 shows the average CO_2 emissions per traffic volume class. CO_2 emissions per VKT on motorways are lower at a 100% AV penetration rate than at baseline, especially in the high traffic volume classes (by 14.7%, 14.1% and 14.9% at speed limits of 90, 110 and 130 km/h, respectively). With a 30% AV penetration rate, average emissions are lower by 8.5%, 5.4% and 4.7%, respectively. At lower traffic volumes, the effects are mixed and small.

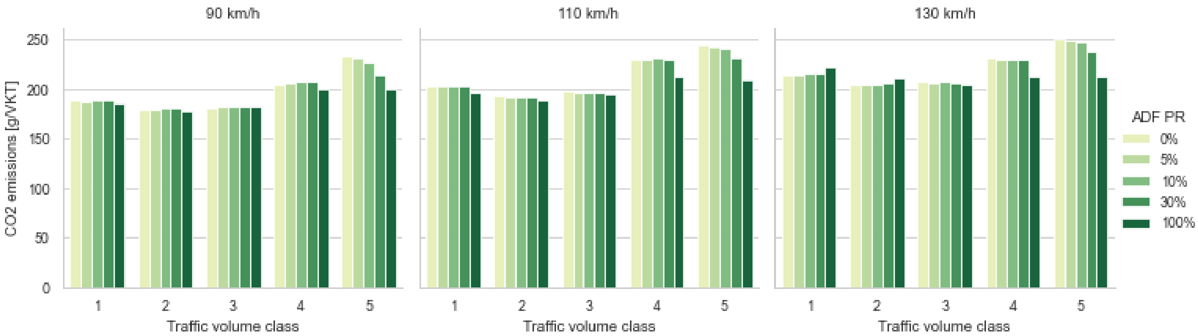

Figure 5. Average CO_2 emissions in grammes per VKT for speed limits of 90, 110 and 130 km/h per traffic volume class and AV penetration rate among passenger cars on EU27+3 motorways. Volume class 1: up to 750 veh/h/lane; 2: 751–1250 veh/h/lane; 3: 1251–1750 veh/h/lane; 4: 1751–2250/ veh/h/lane; 5: over 2250 veh/h/lane.

3.3 Most common conditions

This section shows the results for the ten combinations of speed limit and traffic volume that were found to be the most common on the European motorway network, representing 79.6% of the total VKT (as shown in Table 7). The average travel time in seconds per VKT in these combinations at baseline and with the four AV penetration rates is shown in Figure 6. Travel times are slightly (4.3% and 2.5%) shorter than at baseline with a 100% AV penetration rate among passenger cars at a speed limit of 130 km/h and traffic volumes of up to 750 and 1250 veh/h/lane, respectively. At speed limits of 100 and 110 km/h the travel times are slightly (2.6–5.5%) longer at a 100% AV penetration rate than at baseline.

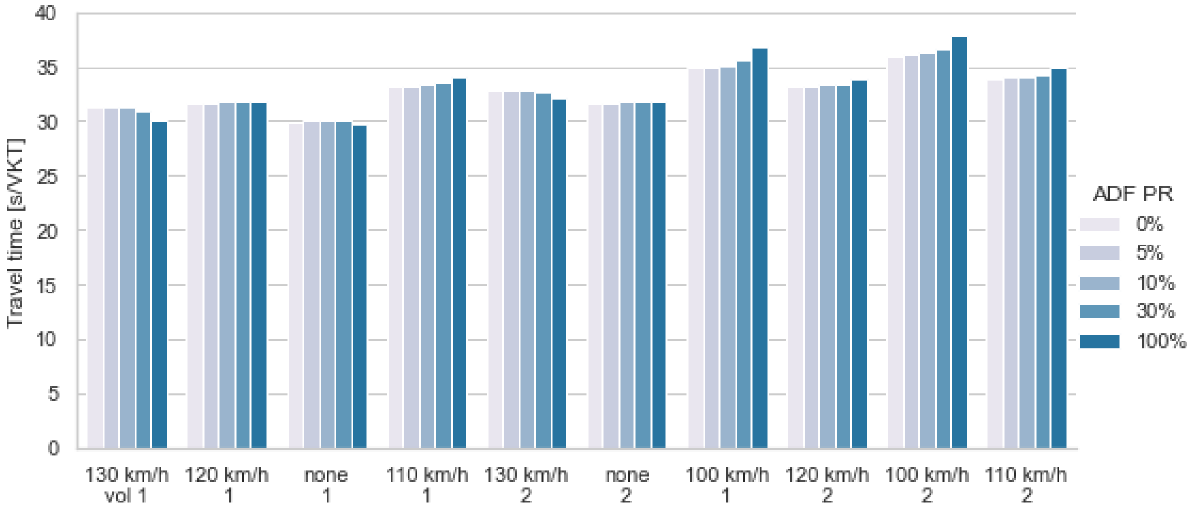

Figure 6. Average travel time in seconds per VKT for the most common combinations of speed limit and traffic volume class (indicated below bars) by penetration rate among passenger cars on EU27+3 motorways. Volume class 1: up to 750 veh/h/lane; 2: 751–1250 veh/h/lane.

Figure 7 shows the average delay in these most common speed limit and traffic volume combinations. At a speed limit of 130 km/h, the average delays are lower with AVs than at baseline (by 33.9% and 14.1% at traffic volumes of up to 750 and 1250 veh/h/lane, respectively) and higher than at baseline especially at speed limits of 100 to 110 km/h (by 21.5–85.6%). Here it should be noted that the absolute values of delay are small at low traffic volumes.

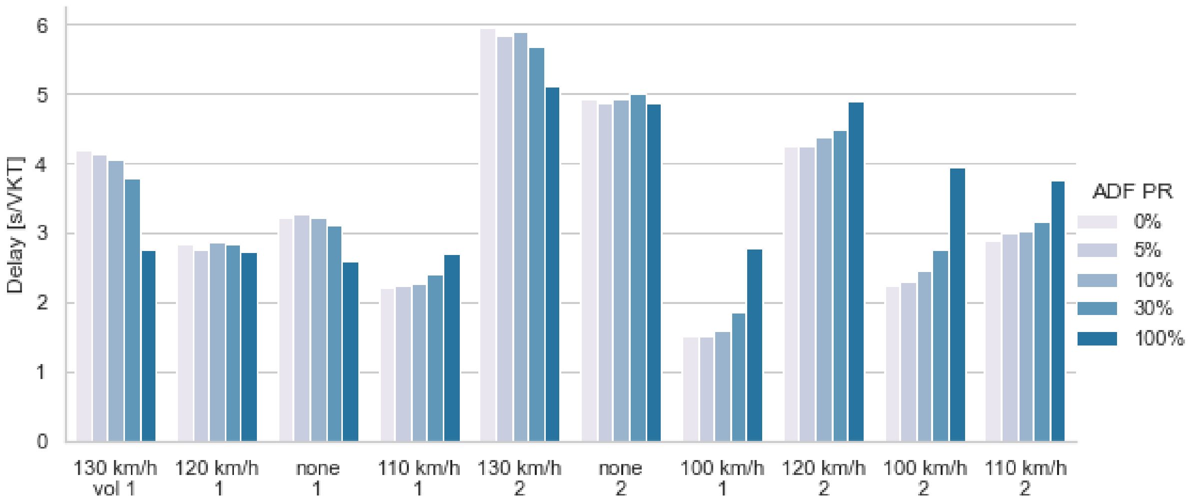

Figure 7. Average delay in seconds per VKT for the most common combinations of speed limit and traffic volume class (indicated below bars) by penetration rate among passenger cars on EU27+3 motorways. Volume class 1: up to 750 veh/h/lane; 2: 751–1250 veh/h/lane.

The average amount of CO_2 emitted per VKT in each of the ten most common speed limit and traffic volume combinations is shown in Figure 8. At a speed limit of 130 km/h, average CO_2 emissions per VKT are slightly higher (by 3.2% and 2.9% at traffic volumes of up to 750 and 1250 veh/h/lane, respectively) than at baseline at a 100% AV penetration rate among passenger cars. At speed limits of 100 and 110 km/h, average emissions are slightly lower (by 2.5–3.6%) at a 100% AV penetration rate. In other conditions, the effects are mixed and small.

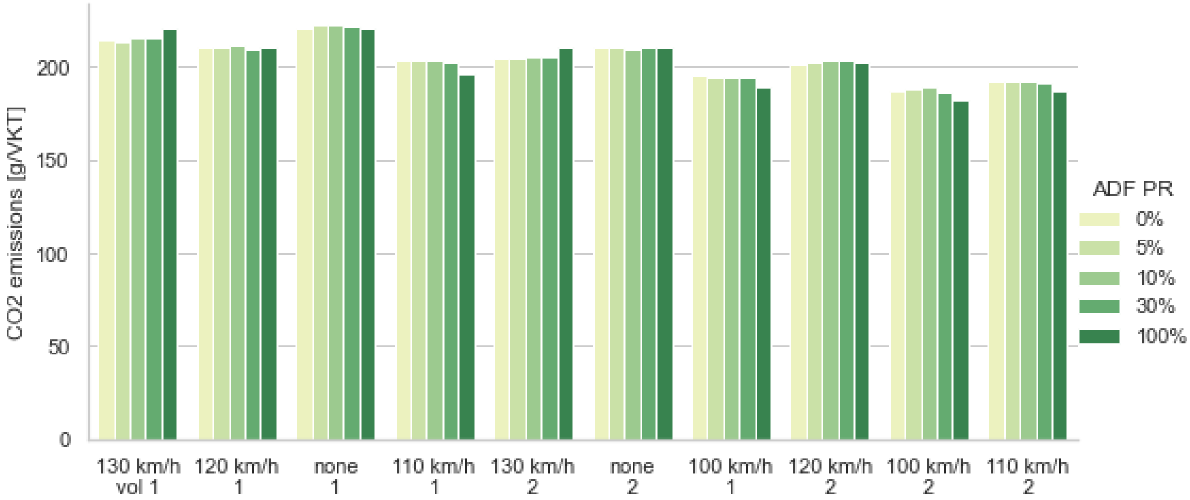

Figure 8. Average CO_2 emissions in grammes per VKT for the most common combinations of speed limit and traffic volume class (indicated below bars) by penetration rate among passenger cars on EU27+3 motorways. Volume class 1: up to 750 veh/h/lane; 2: 751–1250 veh/h/lane.

3.4 Overall impacts at EU27+3 level

Combining the results per indicator and VKT from the simulations and emissions calculations in different speed limit and traffic volume combinations (Section 3.2) with the spatial and temporal distribution of motorway VKT across Europe in these combinations (Section 3.1) provides an estimate of the overall impacts of AVs on the European motorway network for four AV penetration rates, compared to the baseline without AVs. Thus, the scaled-up results represent the impacts on the European motorway network as a whole, based on data over a time period of one year at one-hour intervals and aggregated over all NUTS3 regions.

The scaling up process produced estimates of the relative changes in travel time, delay and CO_2 emissions for AV penetration rates of 5%, 10%, 30% and 100% among passenger cars, compared to the baseline, on motorways of the EU27+3 countries (see Figure 9). Table 8 shows the magnitude of these effects. The reliability of the results was estimated with bootstrapping, which showed that the simulation results were rather consistent. Overall, with all passenger cars being automated, average travel times on motorways in Europe (EU27+3) would annually be 0.8% longer and delays 1.3% greater than currently. Average CO_2 emissions would, however, be 0.5% lower than today. The magnitude of impacts differs with AV penetration rates. The average delay is greatest at a 30% AV penetration rate. CO_2 emissions are highest at a 10% AV penetration rate, and smaller than at baseline at 30% and 100% AV penetration rates. The share of VKT driven within the ODD of the ADF was 94% of the total VKT driven on the European motorway network.

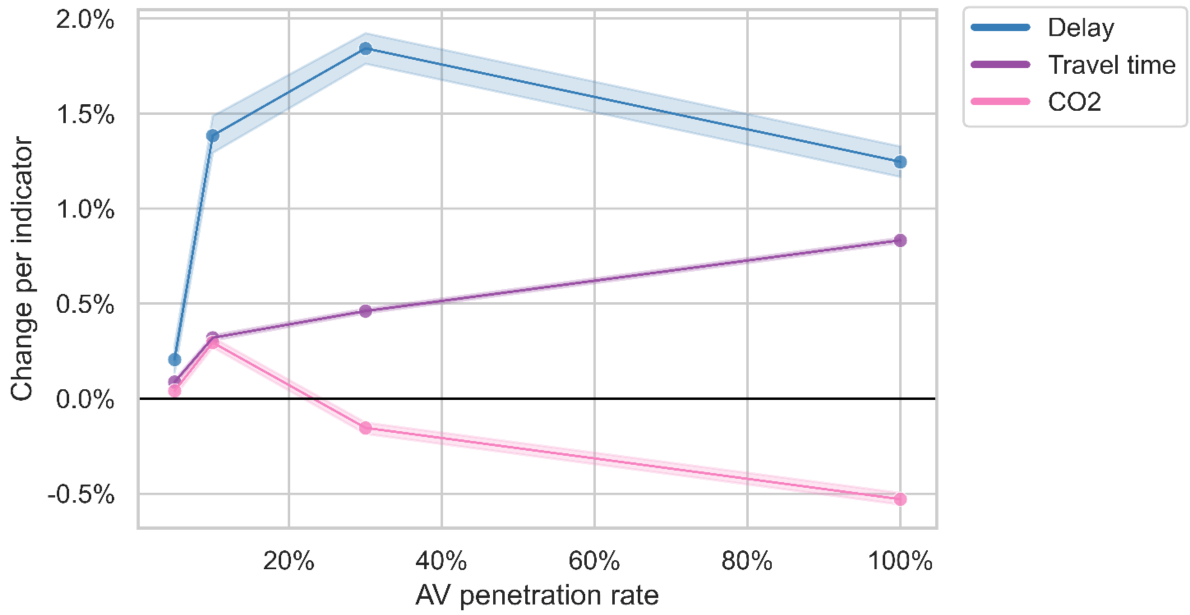

Figure 9. *Scaled-up results with relative changes in travel time, delay and CO_2 emissions at AV penetration rates of 5%, 10%, 30% and 100% among passenger cars compared to the baseline, with 95% confidence intervals based on the bootstrapping method.*

Table 8. Mean change in indicators (per VKT) for each AV penetration rate among passenger cars compared to the baseline with 95% confidence intervals based on the bootstrapping method.

	Travel time		Delay		CO_2	
AV PR	mean	95% CI	mean	95% CI	mean	95% CI
5%	0.09%	[0.07%,0.10%]	0.21%	[0.13%, 0.28%]	0.04%	[0.01%, 0.07%]
10%	0.32%	[0.30%, 0.33%]	1.38%	[1.29%, 1.48%]	0.29%	[0.27%, 0.32%]
30%	0.46%	[0.45%, 0.47%]	1.84%	[1.76%, 1.93%]	-0.15%	[-0.18%, -0.12%]
100%	0.83%	[0.82%, 0.85%]	1.25%	[1.16%, 1.33%]	-0.53%	[-0.56%, -0.50%]

4. Discussion

4.1 Main findings

This study extended the current state of the art by assessing comprehensively the potential impacts, induced solely by the changes in driving behaviour, of SAE L3 automated passenger cars on average travel times, delay, and CO_2 emissions on the European motorway network. This was achieved by 1) analysing the conditions (speed limit, presence or lack of ramps, number of lanes, traffic volume and precipitation) in which VKT accumulates on motorways, 2) conducting traffic simulations to determine changes in indicator values in different conditions with introduction of AVs at different penetration rates among passenger cars, and 3) combining the values per VKT with the estimated VKT driven, weighted by the spatial and temporal prevalence of the scenarios and accounting for the ODD of the ADF. All combinations of numbers of lanes and speed limits representing at least 1% of the total length of European motorways were included in the simulations. The total length of each of these motorway types, as well as the hourly traffic volumes and hourly weather conditions on them, were determined separately for each of the over 1500

NUTS3 regions over each hour of one year. Simulations were conducted for 13 different combinations of speed limit and traffic volume for four AV penetration rates (5%, 10%, 30%, 100% of passenger cars) and the baseline without AVs. Overall results were formed by summing the total indicator values at different AV penetration rates among passenger cars and comparing them to the baseline. The comprehensive approach distinguishes the study from current literature, where typically only a narrow set of conditions in terms of speed limit and traffic volume is included without consideration of the spatial and temporal prevalence of the conditions or potential impacts in other conditions.

The main finding of this study is that the overall impacts of the considered ADF across the entire European motorway network are rather small at all AV penetration rates. With all passenger cars automated, average travel times on motorways would be 0.8% longer and delays 1.3% higher than at present, while average CO_2 emissions would be 0.5% lower. Given that only 15% of the total VKT on European roads accumulates on motorways (data from Jonkers et al. 2016), the potential of an L3 motorway ADF to decrease road transport emissions seems negligible based on the assumptions of this study.

Other important outcomes of the study include the separate impact estimates provided for several speed limit and traffic volume combinations, the share of VKT driven within the ODD of the ADF (94%), and the finding that most (86%) of the motorway VKT in Europe are driven at low traffic volumes (up to 1250 veh/h/lane). The latter is the reason for the relatively small overall impacts, although larger benefits (up to a 13.5–15.0% drop in CO_2 emissions and 17.5–34.8% shorter delays) were found at high traffic volumes (over 2250 veh/h/lane) and a 100% AV penetration rate. Consequently, the impacts may be more substantial locally, for example on regularly congested urban motorways, where improvements would apply to a large number of travellers. Further, if traffic safety improves with introduction of AVs, less accident induced congestion will be experienced on busy roads. This would likely increase the total impact. Future work should examine the potential impacts on urban motorways in more detail.

The results show (Figure 9) that a large AV penetration rate is needed to achieve reductions in average CO_2 emissions. At low AV penetration rates (5% and 10%) among passenger cars the effects may even be undesired, because the total CO_2 emissions of motorway traffic in Europe increase slightly (by 0.3% at a 10% penetration rate). However, as high AV penetration rates on European motorways are unrealistic for years to come, awareness is needed of the potential deterioration of conditions in the near term. This finding is consistent with other studies also concluding that the effects might first be negative and that benefits to the traffic flow require large AV penetration rates (Calvert et al. 2017).

Also, average delays are higher at 10% and 30% AV penetration rates among passenger vehicles (1.4% and 1.8% above the baseline, respectively; Figure 9) than at 100% (1.3% higher than at baseline). The peak at an AV penetration rate of 30% is an interesting result derived from two findings: the effects of AVs on average delay vary at different speed limits, and the distribution of traffic (annual VKT) varies over those speed limits. While average delay compared to the baseline increases at lower speed limits (80–100 km/h), it decreases at higher speed limits (130 and 140 km/h and unlimited). With a 30% AV penetration rate, the increase in delay at lower speed limits dominates, leading to the peak in delay (Figure 9), while at a 100% AV penetration rate the decrease in delay at higher speed limits, together with the higher VKT driven at these higher limits, offset the increase. Part of the effect (increase in CO_2 at a low penetration rate) may also be explained by an increase in heterogeneity of traffic when only a few AVs are driving among human-driven vehicles. For interested readers, Table 10 and Figure 14 in the Appendix A illustrate the changes in delay at different speed limits and traffic volumes.

Differences between the results in specific conditions and those scaled-up to European level highlight the importance of a comprehensive approach, both spatially and temporally, when assessing the potential impacts of driving automation or other interventions that affect driving over longer periods. The consideration of eight different speed limits and five traffic volumes in the present study shows that impacts can differ substantially between different speed-limit motorways and at different traffic volumes. If the impacts are studied for specific conditions only and the prevalence of these conditions is not considered, as is the case in the current state of the art, estimates of overall impacts in a larger context cannot be made.

Substantial benefits for both efficiency and environmental indicators were seen with high AV penetration rates at high traffic volumes in this study as well as in some of the literature. However, it should be kept in mind that even large percentage decreases do not necessarily lead to low absolute values of delay and CO_2 emissions. Despite the decreases in travel times, delay and CO_2 being large with large traffic volumes, lowest values were seen at the lowest (efficiency) or low to moderate (emissions) traffic volumes (Figure 3–Figure 5).

To assess the effectiveness of automated driving as a measure to achieve better sustainability of transport, the results of the study were compared with a measure that would involve lowering the highest speed limits on European motorways using data derived in the scaling-up process. Average emissions per VKT at specific speed limits were multiplied with VKT in the speed limits to be lowered. Assuming that the VKT stayed the same, and that speed limits above 120, 110 or 100 km/h (including unrestricted speed limit) were capped at 120, 110 or 100 km/h respectively, overall CO_2 emissions on the European motorway network would drop by 1.4%, 3.7% and 6.5%, respectively. The reduction in CO_2 that could be achieved even with a moderate reduction in speed limits is thus notably larger than would be achieved with a 100% penetration rate of L3 automated vehicles among passenger cars. Note that these figures do not assume that MVs adhere to the speed limit; therefore, the reductions would be larger still if speed limits were strictly enforced. At the same capped speed limits, average travel times would increase by 0.8%, 3.2% and 7.0% respectively, and delays would decrease by 13.6%, 26.6% and 43.6%, respectively.

4.2 Methodological considerations

In the L3Pilot project, the AV behaviour for the simulations was set up together with ADF developers to reflect AVs mature for use by ordinary drivers on public roads. It should be noted that most findings from the literature are based on rather different, more theoretical assumptions of AV behaviour, most notably very short headways. These are, however, unlikely to be realised at least in the near term. Developers are not likely to implement shorter time gaps than needed by legal requirements or that human drivers use, unless significant advancements in connectivity, such as platooning, are achieved.

The presented results are subject to the assumptions made and the driving model used in the simulations. The capability of car-following models to capture differences between AVs and MVs has been questioned (Ciuffo et al. 2018). In this study, the main differences in driving behaviour of AVs compared to MVs were a larger desired time gap, more stable oscillation, and no variation in the desired speed. The desired speed of AVs is one of the main factors affecting the outcome of simulations. Without the possibility to validate the desired speed distribution with evidence of user preferences, it was assumed that AVs aim to drive at the speed limit when possible (or at most 130 km/h), in line with what is legal and technically possible. This assumption led to larger average speeds at a speed limit of 130 km/h than at the baseline. Existing simulation models are generally not well able to model lane change behaviour (Yu et al. 2021). The applied lane change behaviour of AVs and MVs was similar, the difference being that MVs took other vehicles better into account (cooperative lane change). If AVs turn out to be more cautious than MVs in lane changing, e.g., due to needing larger gaps, traffic flow may deteriorate especially in the vicinity of ramps.

The snapshot approach applied in the study has several benefits. It enables determining the isolated effects of adding driving automation to a certain share of passenger cars. In addition, the approach avoids the need to make predictions on parallel developments, such as the growth of electric vehicles in the fleet, or estimating when the different AV penetration rates will be realised in traffic. The main deficiency of the approach is that it is theoretical, as it is unrealistic to assume that the characteristics of the car fleet today would also be valid in the future. Rather, it will be new models in which ADFs are then installed.

The study assumed the same driving characteristics for AVs, MVs and HDVs across all European countries. In reality, driving styles in terms of speeds and acceleration are known to differ between different parts of Europe. Further, only one type of AV with homogeneous driving style was considered, although the driving parameters of AVs may differ among manufacturers and user preferences, and vehicles with different stages of driving automation will likely coexist on the roads.

The results are sensitive to assumptions made about desired speeds in different speed limit conditions. Due to a lack of detailed data, the default distributions of Vissim were used for manually driven passenger cars, and distributions by Geistefeldt et al. (2017) were used as a basis for the desired speed distributions of heavy vehicles. In general, Vissim is able to accurately reproduce the traffic characteristics of German motorways (Geistefeldt et al. 2017). While it is unknown how well these would apply to other parts of Europe, Germany's motorways represent a large share of the VKT driven on European motorways (22%; data from Jonkers et al. 2016).

This study focused on the direct impacts that can be expected on travel time, delay, and CO_2 on a European level due to different driving behaviour of AVs. Yet, it is expected that automation has other wide-reaching impacts as well, for example through changing personal mobility behaviour or reducing accidents (Innamaa et al. 2018), which would cause indirect impacts also on traffic efficiency and emissions. These potential changes unrelated to driving behaviour, such as an increase or decrease in VKT or a change in accident-induced congestion, were outside the scope of the study. Therefore, the results were scaled up using the VKT values determined for the baseline situation at each speed limit and traffic volume combination. However, it should be noted that in the simulations with AVs, fewer vehicles were able to traverse the network than at baseline, due to the higher time gaps kept by AVs. This translates to a decrease in motorway capacity. It is not clear what the effect of a lower network capacity would be. Drivers might be inclined to change their travel behaviour, e.g., change the timing of their trip or use other travel modes. Congestion would likely form on the motorways themselves (where drivers could switch on the ADF and use the increased driving time for other purposes) but also on the ramps and roads leading to the motorways and possibly on lower-level roads that drivers might divert to (in manual driving mode) if they are unable to enter the motorway. For the motorways themselves, the result would be that a larger share of VKT is driven at higher traffic volumes.

The methodology used in the study can be further refined by increasing the amount of empirical data on road infrastructure and traffic volumes, as well as by using more advanced driver models better able to capture differences between human drivers and automated vehicles in the simulations, when these models become available. Also, potential differences in local driving behaviour in different parts of Europe and in the characteristics of newer vehicles compared to the current average European fleet could be included. Better availability and harmonisation of traffic and infrastructure data on European roads would be highly beneficial. Baseline information on travel times, delays and CO_2 emissions on European motorways would enable direct calculation of impacts instead of the currently applied estimation using VKT.

4.3 Conclusion

The main objective of the study was to assess whether the changes in driving behaviour due to introduction of L3 automated passenger cars can contribute to sustainability goals and improve traffic efficiency on motorways. The results show that notable decreases in CO_2 emissions and benefits to traffic efficiency on a European level are unlikely with the AVs defined in this study. However, they are possible locally on roads with high traffic volumes and a high penetration rate of AVs. Other measures, such as lowering the speed limit, would likely be more efficient in achieving sustainability goals. When examining impacts of AVs for example as a basis for policymaking, it is important to not only review results applying in specific conditions but to consider the spatial and temporal prevalence of these conditions on the network.

Acknowledgement

The research leading to these results received funding from the European Commission Horizon 2020 program under the project L3Pilot, grant agreement number 723051. The information and views set out in this publication are the sole responsibility of the authors. The authors would like to thank Esko Lehtonen for his advice on bootstrapping, Henri Sintonen for analysis of OpenStreetMap data, Guilhermina Torrao for assisting with traffic data collection, and the ecoDriver project for providing estimates of VKT driven on European motorways.

References

ACEA (2019). Vehicles in use – Europe 2019. European Automobile Manufacturers Association, https://www.acea.auto/files/ACEA_Report_Vehicles_in_use-Europe_2019.pdf. European Automobile Manufacturers Association.

Aittoniemi, E. (2022): Evidence on impacts of automated vehicles on traffic flow efficiency and emissions: Systematic review. *IET Intelligent Transport Systems*, 16(10), 1306-1327. https://doi.org/10.1049/itr2.12219

Autoflotte (2014). Auf dem Schrottplatz: Nach 18 Jahren ist für Autos Schluss. https://www.autoflotte.de/nachrichten/artikel/auf-dem-schrottplatz-nach-18-jahren-ist-fuer-autos-schluss-1378445.html. Accessed February 15th, 2022.

Bandeira, J. M., Macedo, E., Fernandes, P., Rodrigues, M., Andrade, M., Coelho, M. C. (2021). Potential pollutant emission effects of connected and automated vehicles in a mixed traffic flow context for different road types. *IEEE Open Journal of Intelligent Transportation Systems*, 2, 364-383. https://doi.org/10.1109/OJITS.2021.3112904

Bjorvatn, A., Page, Y., Fahrenkrog, F., Weber, H., Aittoniemi, E., Heum, P., Lehtonen, E., Silla, A., Bärgman, J., Borrack, M., Innamaa, S., Itkonen, T., Malin, F., Pedersen, K., Schuldes, M., Sintonen, H., Streubel, T., Hagleitner, W., Hermitte, T., Hiller, J., Torrao, G. (2021). L3Pilot Deliverable D7.4: Impact evaluation results. Available at: https://l3pilot.eu/fileadmin/user_upload/Downloads/Deliverables/Update_14102021/L3Pilot-SP7-D7.4-Impact_Evaluation_Results-v1.0-for_website.pdf

Calvert, S., Schakel, W. J., Lint, J. W. C. Van. (2017). Will Automated Vehicles Negatively Impact Traffic Flow?, *Journal of advanced transportation*, 2017, 1–23. https://doi.org/10.1155/2017/3082781

Carsten, O. M., Tate, F. N. (2005). Intelligent speed adaptation: accident savings and cost–benefit analysis, *Accident Analysis & Prevention* 37(3), 407–416. https://doi.org/10.1016/j.aap.2004.02.007

CCAM (2022). CCAM Strategic research and innovation agenda 2021–2027. European leadership in safe and sustainable road transport through automation. Version 1.4, March 17th 2022. CCAM Partnership under the Horizon Europe Programme.

Ciuffo, B., Makridis, M., Toledo, T., Fontaras, G. (2018). Capability of current car-following models to reproduce vehicle free-flow acceleration dynamics. *IEEE Transactions on Intelligent Transportation Systems*, 19(11), 3594-3603. doi: 10.1109/TITS.2018.2866271

EAFO (2021). European Alternative Fuel Observatory. https://www.eafo.eu/. Accessed March 25th, 2021.

Efron, B., & Tibshirani, R. (1986). Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. *Statistical science*, 54-75. DOI: 10.1214/ss/1177013815

Eijk, A., Ligterink, N., Inanc, S. (2014). EnViVer 4.0 Pro and Enterprise Manual.

ERTRAC (2022). Connected, Cooperative and Automated Mobility Roadmap. ERTRAC Working Group "Connectivity and Automated Driving". European Road Transport Research Advisory Council.

European Commission (2019). CORDIS results pack on connected and automated driving. A thematic collection of innovative EU-funded research results. European Commission, March 2019. ISSN 2599-8293

European Commission (2021a). Statistical Pocketbook 2021. EU Transport in figures. Publications Office of the European Union, 2021. doi:10.2832/27610

European Commission (2021b). Going abroad, https://ec.europa.eu/transport/road_safety/going_abroad/index_en.htm (accessed June 2021).

Eurostat (2021). NUTS – Nomenclature of territorial units for statistics. https://ec.europa.eu/eurostat/web/nuts/background. Accessed March 25th, 2021.

Geistefeldt, J., Giuliani, S., Busch, F., Schendzielorz, T., Haug, A., Vortisch, P., Leyn, U., Trapp, R. (2017). HBS-konforme Simulation des Verkehrsablaufs auf Autobahnen [HBS-conform simulation of freeway traffic flow]. Berichte der Bundesanstalt für Straßenwesen, Heft V279.

Information Centre of Road Transport (2022). Average scrapping age of passenger cars. https://www.aut.fi/en/statistics/statistics_of_scrapped_vehicles/average_scrapping_age_of_passenger_cars. Accessed February 15th, 2022.

Innamaa S., Smith S., Barnard Y., Rainville L., Rakoff H., Horiguchi R., Gellerman H. (2018). Trilateral Impact Assessment Framework for Automation in Road Transportation. Version 2.0. Connected Automated Driving Europe. https://connectedautomateddriving.eu/wp-content/uploads/2018/03/

Trilateral_IA_Framework_April2018.pdf.

Innamaa, S., Aittoniemi, E., Itkonen, T., Sintonen, H., Torrao, G. (Under review). Method for scaling up traffic efficiency and environmental impacts from traffic simulations to European level.

Jonkers, E., Wilmink, I., Nellthorp, J., Gühnemann, A., Olsatm, J. (2016). Costs and benefits of green driving support systems. Deliverable D54.1 of the ecoDriver project.

L3Pilot (2021). Deliverable D1.7 Final project results. Available at https://l3pilot.eu/fileadmin/user_upload/Downloads/Deliverables/L3Pilot-SP1-D1.7-Final_project_results-v1.0_for_website.pdf.

Mattas, K., Makridis, M., Hallac, P., Raposo, M. A., Thiel, C., Toledo, T., Ciuffo, B. (2018). Simulating deployment of connectivity and automation on the Antwerp ring road. *IET Intelligent Transport Systems*, 12(9), 1036–1044. https://doi.org/10.1049/iet-its.2018.5287

Moridpour, S., Mazloumi, E., Mesbah, M. (2015). Impact of heavy vehicles on surrounding traffic characteristics. *Journal of advanced transportation*, 49(4), 535-552. doi: 10.1002/atr.1286.

Muñoz Sabater, J. (2019). ERA5-Land hourly data from 1981 to present, Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (accessed 24 March 2021), 10.24381/cds.e2161bac

Ntousakis, I. A., Nikolos, I. K., Papageorgiou, M. (2015). On Microscopic Modelling of Adaptive Cruise Control Systems. *Transportation Research Procedia*, 6(June 2014), 111–127. https://doi.org/10.1016/j.trpro.2015.03.010

Olstam, J., Johansson, F., Alessandrini, A., Sukennik, P., Lohmiller, J., & Friedrich, M. (2020). An approach for handling uncertainties related to behaviour and vehicle mixes in traffic simulation experiments with automated vehicles. *Journal of advanced transportation*. https://doi.org/10.1155/2020/8850591

Rezaei, A., Caulfield, B. (2021). Simulating a transition to autonomous mobility. Simulation *Modelling Practice and Theory*, 106, 102175. https://doi.org/10.1016/j.simpat.2020.102175

Smit, R., Smokers, R., & Rabé, E. (2007). A new modelling approach for road traffic emissions: VERSIT+. *Transportation Research Part D: Transport and Environment*, 12(6), 414-422. https://doi.org/10.1016/j.trd.2007.05.001

Stogios, C., Kasraian, D., Roorda, M. J., Hatzopoulou, M. (2019). Simulating impacts of automated driving behavior and traffic conditions on vehicle emissions. *Transportation Research Part D: Transport and Environment*, 76, 176-192. https://doi.org/10.1016/j.trd.2019.09.020

Sukennik, P., Kautzsch, L., 2018. Default behavioural parameter sets for Automated Vehicles (AVs). CoEXist deliverable D2.3.

Tomás, R. F., Fernandes, P., Macedo, E., Bandeira, J. M., Coelho, M. C. (2020). Assessing the emission impacts of autonomous vehicles on metropolitan freeways. *Transportation Research Procedia*, 47, 617-624. https://doi.org/10.1016/j.trpro.2020.03.139

Transportation Research Board (2016). Highway Capacity Manual 6th Edition: A Guide for Multimodal Mobility Analysis. Washington, DC: The National Academies Press. https://doi.org/10.17226/24798.

VanderWerf, J., Shladover, S. E., Miller, M. A., Kourjanskaia, N. (2002). Effects of adaptive cruise control systems on highway traffic flow capacity. *Transportation Research Record*, (1800), 78–84. https://doi.org/10.3141/1800-10

Yu, H., Jiang, R., He, Z., Zheng, Z., Li, L., Liu, R., Chen, X. (2021). Automated vehicle-involved traffic flow studies: A survey of assumptions, models, speculations, and perspectives. *Transportation Research Part C: Emerging Technologies*, 127, 103101. https://doi.org/10.1016/j.trc.2021.103101

Appendix A

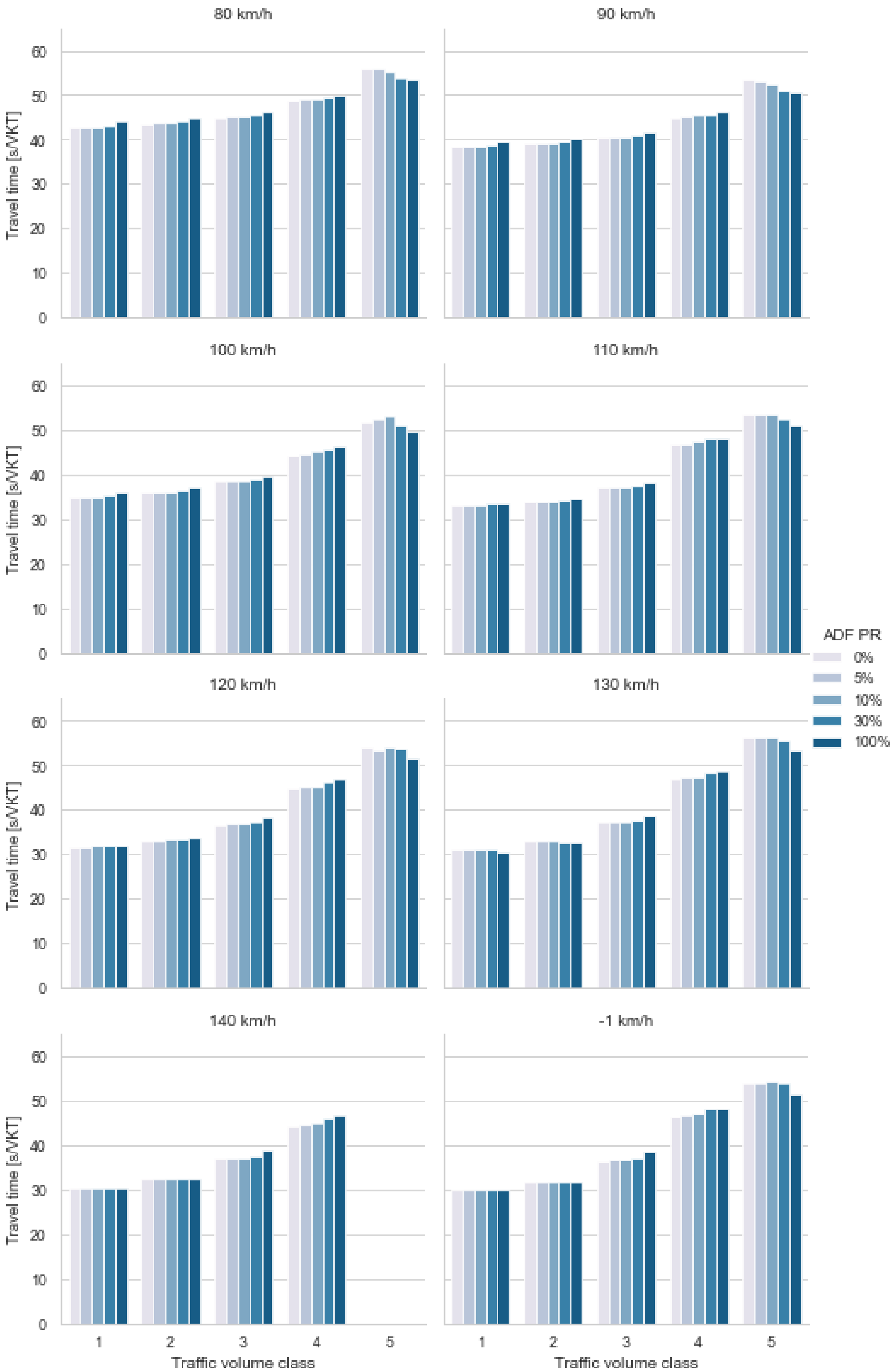

Figure 10. Average travel time in seconds per VKT for speed limits 80 to 140 km/h and unlimited (-1 km/h) per traffic volume class and AV penetration rate on EU27+3 motorways. Volume class 1: up to 750 veh/h/lane; 2: 751–1250 veh/h/lane; 3: 1251–1750 veh/h/lane; 4: 1751–2250 veh/h/lane; 5: over 2250 veh/h/lane.

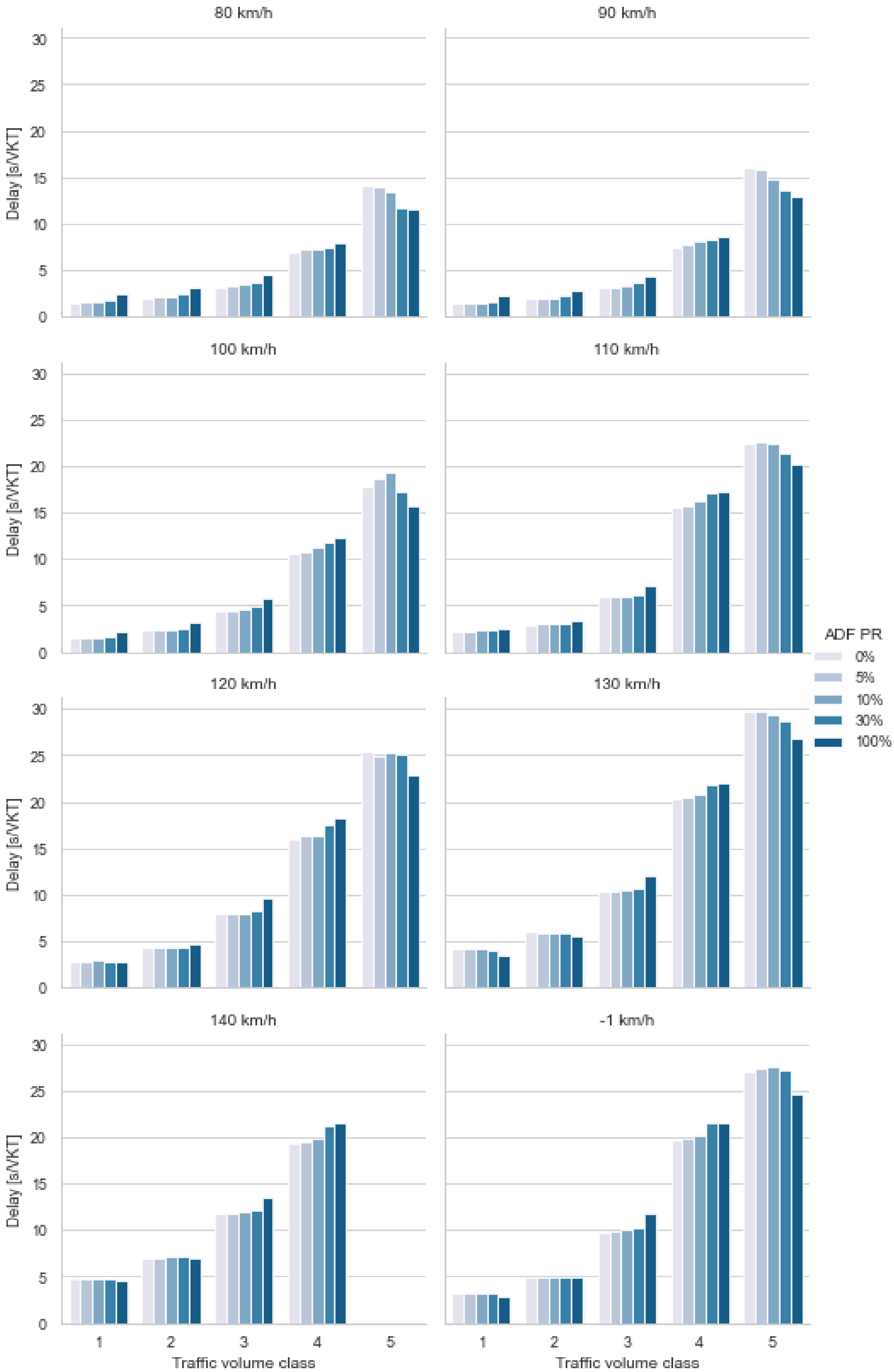

Figure 11. Average delay in seconds per VKT for speed limits 80 to 140 km/h and unlimited (-1 km/h) per traffic volume class and AV penetration rate on EU27+3 motorways. Volume class 1: up to 750 veh/h/lane; 2: 751–1250 veh/h/lane; 3: 1251–1750 veh/h/lane; 4: 1751–2250 veh/h/lane; 5: over 2250 veh/h/lane.

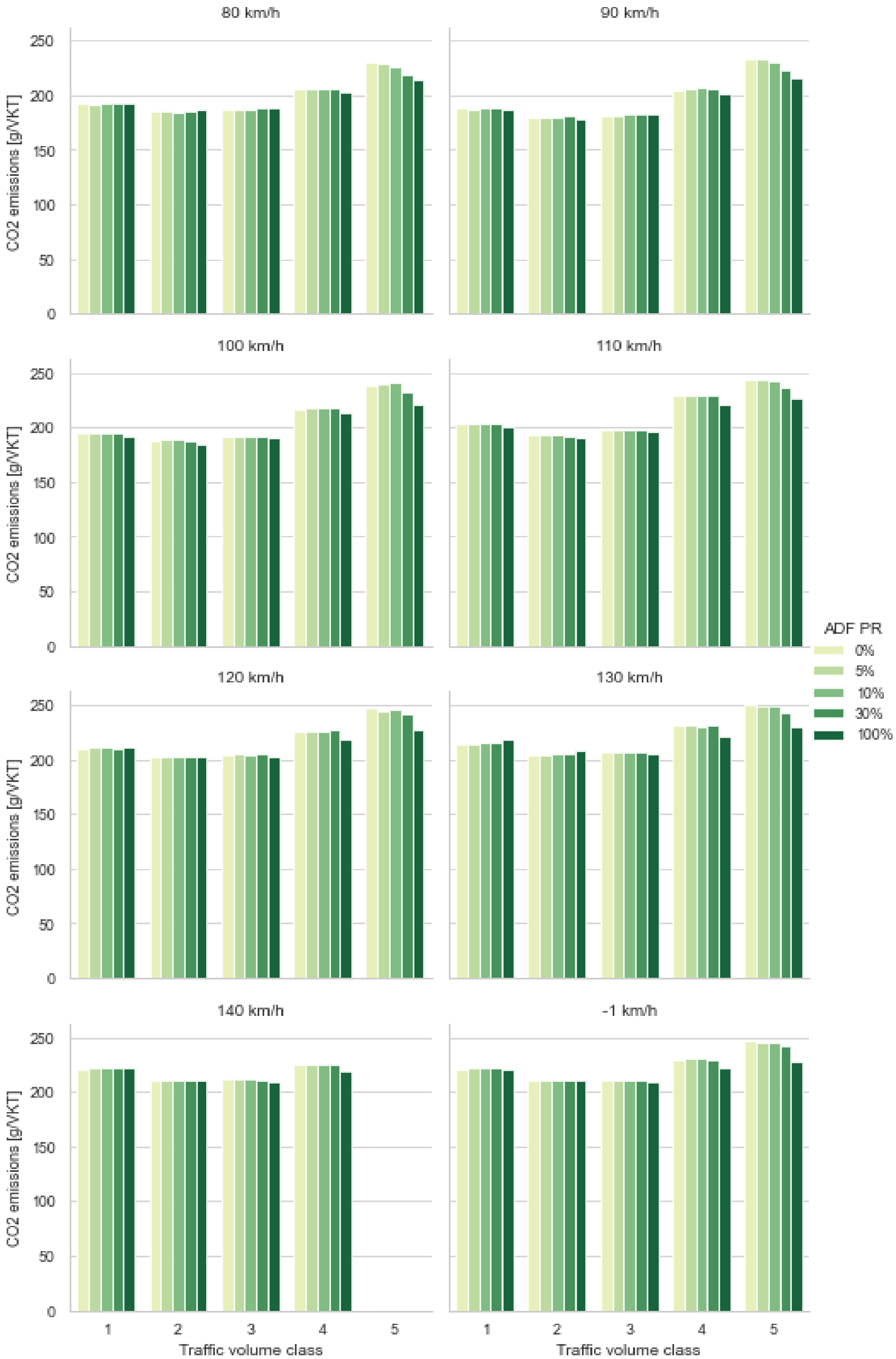

Figure 12. Average CO_2 emissions in grammes per VKT for speed limits 80 to 140 km/h and unlimited (-1 km/h) per traffic volume class and AV penetration rate on EU27+3 motorways. Volume class 1: up to 750 veh/h/lane; 2: 751–1250 veh/h/lane; 3: 1251–1750 veh/h/lane; 4: 1751–2250 veh/h/lane; 5: over 2250 veh/h/lane.

Table 9. Average travel time in seconds per VKT at baseline and changes with different AV penetration rates at different speed limits and traffic volumes

Volume class	AV %	Speed limit [km/h]							
		80	90	100	110	120	130	140	none
1 (up to 750 veh/h/lane)	0	*42.5*	*38.2*	*34.9*	*33.2*	*31.6*	*31.3*	*30.2*	30.0
	5	0.3%	0.2%	0.1%	0.2%	0.0%	-0.2%	0.7%	0.4%
	10	0.7%	0.6%	0.5%	0.4%	0.4%	-0.4%	0.5%	0.3%
	30	2.1%	1.9%	1.7%	0.9%	0.3%	-1.3%	0.1%	0.1%
	100	6.3%	5.7%	5.5%	2.6%	0.8%	-4.2%	-0.8%	-0.6%
2 (751–1250 veh/h/lane)	0	*43.5*	*38.9*	*36.0*	*33.9*	*33.1*	*32.9*	*32.2*	*31.7*
	5	0.7%	0.6%	0.3%	0.3%	0.1%	-0.4%	0.0%	-0.1%
	10	0.9%	0.9%	0.8%	0.5%	0.5%	-0.2%	0.4%	0.1%
	30	2.4%	2.1%	1.8%	1.0%	0.9%	-0.8%	0.3%	0.4%
	100	5.6%	5.2%	5.5%	3.0%	2.2%	-2.5%	-0.1%	0.3%
3 (1251–1750 veh/h/lane)	0	*44.9*	*40.4*	*38.3*	*37.0*	*36.6*	*37.1*	*36.9*	*36.5*
	5	0.4%	0.4%	0.1%	-0.1%	0.7%	0.3%	0.0%	0.8%
	10	1.2%	1.1%	0.6%	0.1%	0.5%	0.7%	0.8%	1.5%
	30	2.6%	2.6%	2.2%	1.4%	2.5%	2.2%	2.1%	3.1%
	100	5.8%	5.7%	6.4%	6.2%	8.9%	8.7%	9.1%	10.6%
4 (1751–2250 veh/h/lane)	0	*48.8*	*44.8*	*44.4*	*46.8*	*45.0*	*46.9*	*44.3*	*46.4*
	5	1.0%	1.6%	1.4%	0.8%	1.0%	0.7%	1.0%	1.0%
	10	0.9%	2.6%	3.3%	2.9%	1.4%	1.4%	2.2%	2.5%
	30	2.1%	3.5%	5.9%	5.9%	6.3%	5.7%	7.5%	7.6%
	100	3.8%	5.3%	8.1%	6.6%	8.8%	6.4%	9.4%	7.9%
5 (more than 2250 veh/h/lane)	0	*56.0*	*53.3*	*51.7*	*53.6*	*54.1*	*56.3*		*53.8*
	5	-0.7%	-0.6%	2.9%	0.3%	-2.0%	-0.1%		1.0%
	10	-2.6%	-3.7%	5.5%	0.0%	-0.3%	-0.8%		1.6%
	30	-8.0%	-8.4%	-2.0%	-3.9%	-1.3%	-3.0%		0.6%
	100	-8.7%	-10.4%	-8.0%	-8.1%	-9.1%	-9.2%		-8.9%

Table 10. Average delay in seconds per VKT at baseline and changes with different AV penetration rates at different speed limits and traffic volumes

Volume class	AV %	Speed limit [km/h]							
		80	**90**	**100**	**110**	**120**	**130**	**140**	**none**
1 (up to 750 veh/h/lane)	0	*1.5*	*1.4*	*1.5*	*2.2*	*2.8*	*4.2*	*4.7*	3.2
	5	5.3%	3.9%	-0.2%	0.9%	-2.0%	-1.3%	2.6%	1.6%
	10	13.4%	12.6%	6.2%	2.5%	1.4%	-2.9%	1.6%	0.0%
	30	40.3%	37.5%	24.7%	7.5%	0.3%	-9.5%	-0.8%	-3.4%
	100	127.5%	116.9%	85.6%	21.4%	-3.1%	-33.9%	-8.0%	-19.6%
2 (751–1250 veh/h/lane)	0	*2.0*	*1.8*	*2.2*	*2.9*	*4.2*	*6.0*	*7.0*	*4.9*
	5	13.2%	10.8%	2.1%	3.1%	0.5%	-1.7%	0.2%	-0.8%
	10	16.5%	15.3%	9.7%	4.1%	3.7%	-0.8%	1.8%	0.2%
	30	41.8%	36.5%	23.7%	9.3%	6.1%	-4.6%	1.2%	1.8%
	100	106.6%	96.5%	76.7%	29.6%	15.7%	-14.1%	-0.4%	-0.7%
3 (1251–1750 veh/h/lane)	0	*3.1*	*3.0*	*4.4*	*5.9*	*7.8*	*10.3*	*11.7*	*9.7*
	5	6.1%	5.0%	0.6%	-0.5%	3.2%	1.3%	0.6%	3.2%
	10	16.1%	13.7%	5.1%	0.6%	2.1%	2.5%	2.5%	5.6%
	30	35.9%	32.8%	18.2%	9.1%	11.8%	8.0%	7.2%	11.9%
	100	82.2%	74.7%	54.6%	39.1%	41.9%	31.3%	28.5%	39.5%
4 (1751–2250 veh/h/lane)	0	*6.9*	*7.4*	*10.5*	*15.7*	*16.3*	*20.2*	*19.3*	*19.7*
	5	6.9%	9.5%	5.7%	2.1%	3.0%	1.7%	2.1%	2.3%
	10	6.4%	15.9%	13.9%	8.5%	4.1%	3.3%	4.9%	5.7%
	30	14.7%	21.4%	25.0%	17.6%	17.4%	13.3%	17.2%	18.0%
	100	27.2%	32.0%	34.2%	19.5%	24.5%	14.9%	21.3%	18.3%
5 (more than 2250 veh/h/lane)	0	*14.1*	*15.9*	*17.8*	*22.5*	*25.4*	*29.6*		*27.1*
	5	-0.9%	-0.7%	1.0%	-0.4%	-1.8%	-0.6%		2.2%
	10	-3.3%	-2.8%	2.0%	-1.1%	-0.8%	-1.3%		3.3%
	30	-9.0%	-8.5%	-4.6%	-5.3%	-3.9%	-4.7%		1.2%
	100	-13.5%	-14.7%	-14.2%	-14.1%	-14.8%	-15.0%		-17.7%

Table 11. Average CO_2 emissions in grammes per VKT at baseline and changes with different AV penetration rates at different speed limits and traffic volumes

Volume class	AV %	Speed limit [km/h]							
		80	90	100	110	120	130	140	none
1 (up to 750 veh/h/lane)	0	*191.6*	*188.0*	*195.2*	*203.5*	*210.2*	*214.4*	*221.0*	221.0
	5	-0.1%	-0.9%	-0.2%	-0.1%	0.2%	-0.2%	1.2%	0.9%
	10	1.3%	-0.1%	-0.3%	-0.2%	0.6%	0.6%	1.1%	0.8%
	30	0.8%	0.0%	-0.4%	-0.7%	-0.1%	0.5%	0.5%	0.1%
	100	0.6%	-1.2%	-2.8%	-3.6%	0.4%	3.2%	0.6%	0.0%
2 (751–1250 veh/h/lane)	0	*184.7*	*179.6*	*187.6*	*192.5*	*201.9*	*204.6*	*210.8*	*210.1*
	5	-0.2%	0.0%	0.4%	-0.1%	0.4%	-0.3%	-0.2%	0.1%
	10	-0.4%	0.2%	0.9%	-0.2%	0.5%	0.2%	0.1%	-0.1%
	30	0.7%	0.5%	-0.9%	-0.7%	0.6%	0.3%	0.1%	0.0%
	100	1.9%	-1.2%	-2.8%	-2.5%	0.3%	2.9%	-0.3%	0.4%
3 (1251–1750 veh/h/lane)	0	*185.7*	*181.2*	*191.7*	*197.6*	*204.4*	*206.8*	*212.4*	*210.9*
	5	0.1%	0.1%	-0.3%	-0.7%	0.3%	-0.1%	-0.9%	-0.4%
	10	1.2%	0.7%	-0.2%	-0.6%	-0.1%	0.0%	-0.5%	-0.1%
	30	1.7%	0.7%	-0.7%	-0.7%	0.2%	-0.1%	-1.7%	-0.6%
	100	2.3%	0.5%	-2.2%	-1.4%	-1.5%	-1.6%	-2.9%	-2.2%
4 (1751–2250 veh/h/lane)	0	*204.5*	*204.6*	*216.0*	*229.2*	*227.0*	*230.8*	*224.2*	*229.9*
	5	0.9%	0.7%	0.9%	0.5%	-0.2%	-0.4%	0.9%	0.7%
	10	0.3%	1.6%	1.6%	0.9%	-0.8%	-0.5%	0.4%	0.5%
	30	0.2%	1.4%	1.8%	0.1%	0.3%	-0.4%	0.8%	0.1%
	100	-2.6%	-2.8%	-2.9%	-7.4%	-6.1%	-8.3%	-4.1%	-6.6%
5 (more than 2250 veh/h/lane)	0	*229.6*	*233.5*	*237.7*	*244.1*	*247.0*	*249.9*		*246.4*
	5	-0.9%	-0.7%	1.0%	-0.4%	-1.8%	-0.6%		-0.9%
	10	-3.3%	-2.8%	2.0%	-1.1%	-0.8%	-1.3%		-0.4%
	30	-9.0%	-8.5%	-4.6%	-5.3%	-3.9%	-4.7%		-3.3%
	100	-13.5%	-14.7%	-14.2%	-14.1%	-14.8%	-15.0%		-14.5%

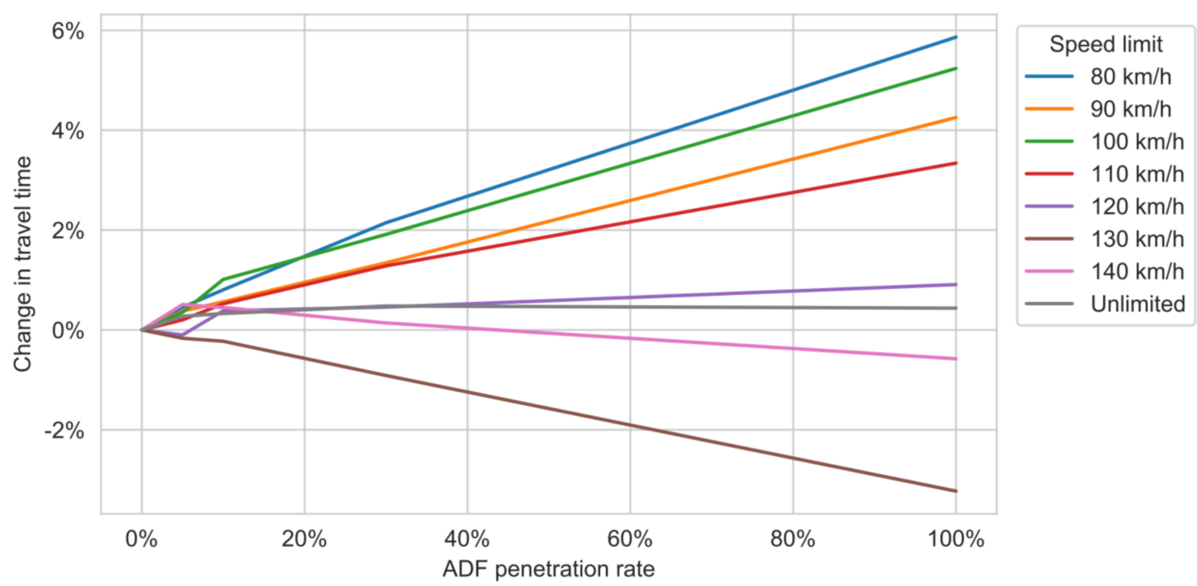

Figure 13. Scaled-up results with relative changes in travel time at AV penetration rates of 5%, 10%, 30% and 100% among passenger cars compared to the baseline at different speed limits

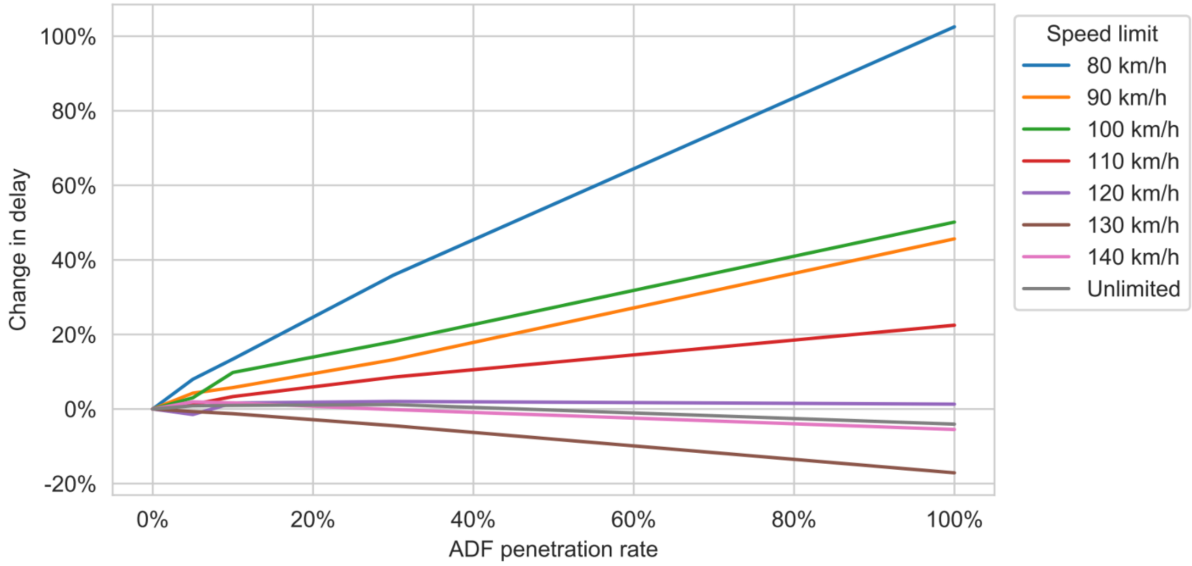

Figure 14. Scaled-up results with relative changes in delay at AV penetration rates of 5%, 10%, 30% and 100% among passenger cars compared to the baseline at different speed limits

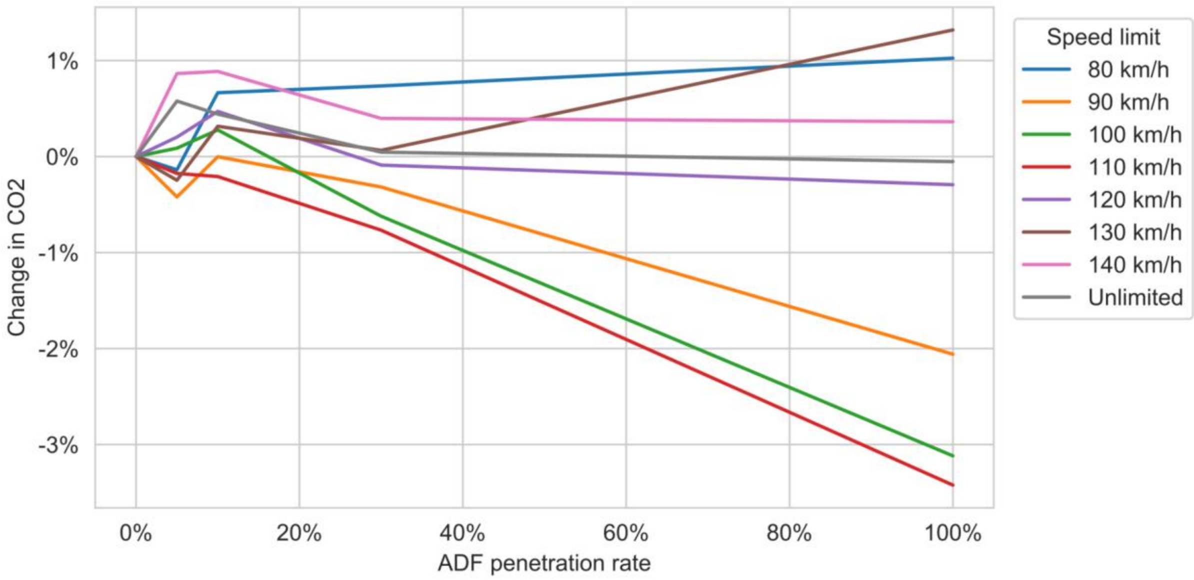

Figure 15. Scaled-up results with relative changes in CO_2 at AV penetration rates of 5%, 10%, 30% and 100% among passenger cars compared to the baseline at different speed limits