Accelerating Safe and Sustainable Transportation: Smart Cars Communicating with Smart Roads

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Executive Summary

With rising global temperatures and Greenhouse Gas (GHG) emissions, climate action is high on the priority list for many countries. The GHG emissions for EU27 countries have declined about 24.3% from 1990 to 2019, but the transportation sector has seen a rise of 13%. As of 2019, the transportation sector accounts for about 25% of the EU27 GHG emissions, of which the road transportation, i.e., personal mobility, trucks, taxis, buses, etc. account for 74%.

Road transportation has the highest potential to reduce emissions. However, the current internal combustion engine (ICE) technology will not achieve the EU's long term goal net zero emission goal by 2050. This indicates that newer technologies such as electrification of vehicles, vehicle automation, and operational and mobility efficiency measures – the focus of this study – need to be considered to realize the defined targets. Additionally, there is a need for tools to assess these technologies and make the best choice moving forward.

This study addresses this objective by providing a quantitative assessment of the connected mobility in a digital and sustainable society of the future. In this regard, the achievable gains by simulation of different European urban and highway scenarios based on urban scenarios in Germany, accounting for different penetration rates of connected vehicles during both peak and off-peak hours are presented in terms of reduced GHG emissions (CO_2), without compromising on the comfort and safety of the road users.

Quantitative Assessment of Connected Mobility applications in EU27 countries

EU27 is a political and economic union of diverse countries in Europe, including roughly 98,000 medium, and large cities and rural areas. By most definitions, Europe has no megacities; rather, there are multiple wider-city regions with populations over 10 million. This diversity results in different roadway traffic that needs to be captured and modelled at the city-level to quantitatively assess the effect of new technology mixes. The mobility model must capture the traffic patterns of different regions based on factors such as population demographics, motorization rate, location of residences and offices, availability of public transportation systems, in addition to driver behaviours, emission models.

To a large extent, these mobility trends track to similar city sizes in EU27. Hence, to reduce the simulation costs and time, an intelligent sampling approach is used to choose representative scenarios for EU27.

This study classifies the different city and rural regions of EU27 into three categories:

- **Tier 1 (Big City) with population greater than 500,000.**
- **Tier 2 (Small City) with population between 100,000 and 500,000.**
- **Tier 3 (Rural Area) with population lower than 100,000.**

The mobility trends in similar sized cities in EU27 is comparable during both peak and off-peak hours. For example, in rural areas and small towns, personal vehicles are predominantly used rather than public transportation. The usage is reversed in metropolitan cities where there is good connectivity and a high frequency of public transportation services. The peak and off-peak hours include different trips that people undertake daily.

Peak hours (e.g., 6-9 am) are characterized by person trips to either their work or school, whereas the off-peak hours (e.g., 12-3 pm) are characterized by trips for odd chores and shopping activities.

The goal (see Figure 1) is to model the selected representative city-based scenarios[1] for both peak and off-peak hours, introduce different connected mobility applications, and extrapolate the simulation results using a Machine Learning (ML) model across the EU27 countries.

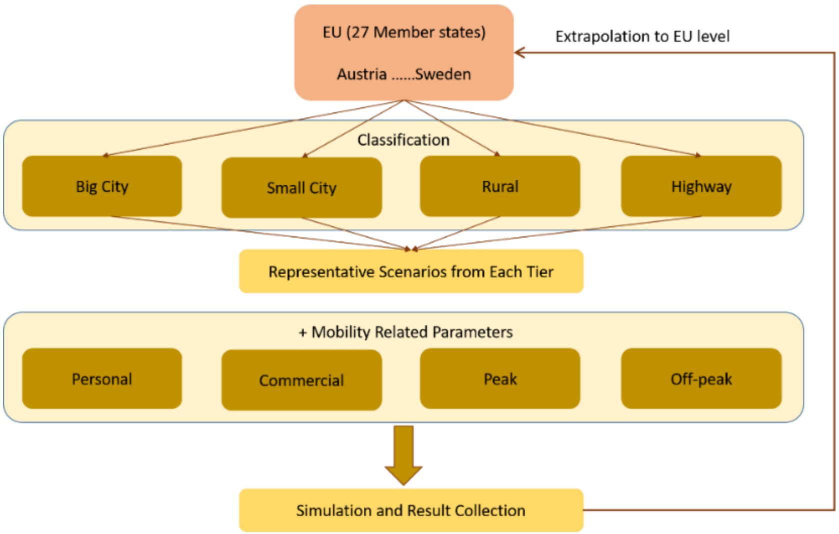

Figure 1: Methodology to quantitatively assess the effects of connected mobility applications in EU27

This study also classifies the different connected mobility applications (see Figure 2) as:

- Level 1: Applications that have reached technological and regulatory maturity and can be deployed and integrated with ease into the current traffic infrastructure.
- Level 2: Applications that need more technological and regulatory maturity, with improved vehicle automation.
- Level 3: Applications that provide a more futuristic outlook, i.e., the end goal of urban and highway traffic management.

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[1] Henceforth, "representative city-based scenarios" is simply referred to as "representative scenarios".

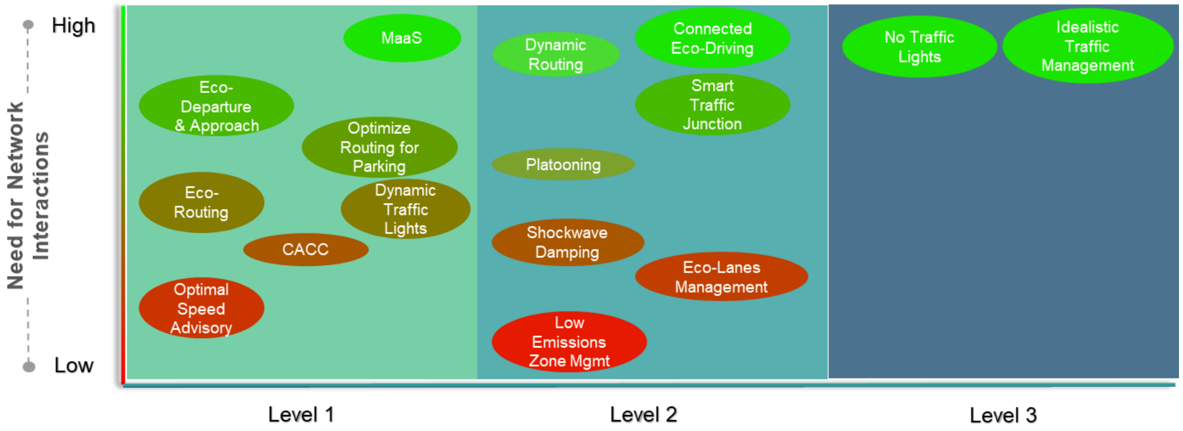


Figure 2: Classification of different connected mobility applications and their need for network interactions

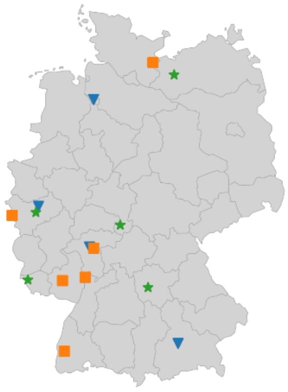
The market penetration of connected vehicles also plays a vital role. To optimize the traffic efficiency, more information must be readily available to the existing and future automated vehicles. The different connected mobility applications can pool the information provided by these connected vehicles, analyse it, and then optimize local and regional traffic, i.e., traffic at a microscopic and macroscopic level, to smooth the traffic flow in cities and on highways.

Simulation Overview

Germany is chosen to select the representative scenarios as it has a rich curated data of mobility statistics and trends. Table 1 shows the selected scenarios in each Tier and their locations in Germany.

Table 1: Representative scenarios and their locations in Germany

Tier	City	Symbol
1	Bremen, Cologne, Frankfurt am Main, Munich	▼
2	Aachen, Freiburg im Breisgau, Kaiserslautern, Lübeck, Mannheim, Offenbach am Main	■
3	Ansbach, Brühl, Fulda, Merzig, Schwerin	★



To replicate mobility in these cities, factors such as demographics, motorization rate, location of residential and commercial buildings are considered. These are the bases to define activities and trips during both the peak and the off-peak hours.

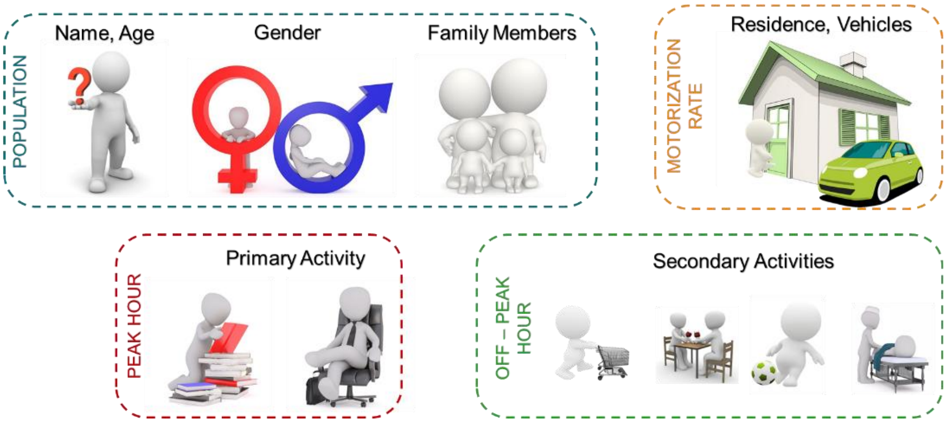


Figure 3: Factors considered for modelling the mobility in every representative scenario

A subset of connected mobility applications is chosen and developed with the aim of reducing GHG emissions by optimizing the traffic efficiency and travel times of the vehicles.

- **For urban scenarios, one Level 1 application – Dynamic Traffic Lights (DTL), and two Level 2 applications – Dynamic Routing (DR) and Smart Traffic Junction (STJ) have been selected.**
- **For the highway scenarios, a Level 1 application – Optimal speed advisory, and 1 Level 2 application – Platooning, is chosen.**

Furthermore, while direct C-V2X communication is needed for connected mobility and safety applications, mobile networks are sufficient to meet the sustainability services. The combination of the two modes allow for full coverage and no gaps, as C-V2X PC5 will work where there is no network coverage.

Additionally, penetration rates of 0, 20, 50, 80 and100%) of connected vehicles are considered for both peak and off-peak hours in every representative scenario.

Effect of Connected Mobility applications in Urban Scenarios

The average CO_2 emission savings in the representative scenarios of Germany can be seen in Table 2 for both peak and off-peak hours, when using DR[2]+JO[3].

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[2] DR = Dynamic Routing.

[3] JO = Junction Optimization. JO includes the use cases Dynamic Traffic Lights and Smart Traffic Junction.

Table 2: Emission Savings for Representative Scenarios in Germany

Tier	Penetration Rate (%)	CO_2 emissions savings (%)	
		Peak Hours	Off-peak Hours
1	20	21.88	23.54
	50	27.05	28.79
	80	26.68	31.39
	100	24.32	32.24
2	20	14.50	16.57
	50	21.58	23.93
	80	24.32	26.79
	100	24.91	29.12
3	20	12.89	16.54
	50	21.61	23.16
	80	25.58	26.07
	100	28.99	27.77

The results indicate that a combination of connected mobility applications have the potential to reduce emissions corresponding to the increase in the penetration of connected vehicles. It is noted that there is a dip in savings for peak hours in Tier 1 cities when increasing the penetration rate from 80% to 100%. This can be attributed to the stochastic traffic models that lack real-time information from the cities.

It is important to understand the scale and equivalency of emission savings (i.e., how does 1% emission savings in Tier 1 cities compares to other Tier cities) across different Tiers.

- **1% emission reduction during the peak hours in Cologne (Tier 1) is equivalent to 2.5% savings in Mannheim (Tier 2) and 11.62% savings in Schwerin (Tier 3).**
- **1% emission reduction during the off-peak hours in Cologne (Tier 1) is equivalent to 1.72% savings in Mannheim (Tier 2) and 7.08% savings in Schwerin (Tier 3).**

The emission equivalency is a comparator (across Tiers) reflecting the effectiveness of the same connected mobility applications in different Tiers. The effectiveness (of the applications) is controlled by the impact of the number of vehicles and the possible congestions, irrespective of the time of the day. However, emission equivalency has no bearing on the individual gains in a city. As indicated in Table 2 and Table 3, the emission savings within a city during the off-peak hours is, generally, higher, or like the peak hours. This can be attributed to, primarily, lower density of vehicles on the city roads, when compared to the peak hours. To simplify, the road capacity is almost never exceeded during off-peak hours, resulting in better local and global optimization by the concerned connected mobility application(s).

The immediate introduction of connected vehicles (at 20% penetration rate) also has significant effects on the travel times of the vehicles. It is estimated that the drivers can save annually 15 hours in Bremen, 5 hours in Cologne, 3 hours in Frankfurt, and 2 hours in Munich annually during the peak hours[4].

The extrapolation of the simulation results is achieved using a Random Forest Regressor (RFR). The emission savings for all tiered cities across EU27 can be seen in Table 3. A RFR is a supervised learning algorithm wherein an estimator is fit using different decision trees on various sub-samples of the dataset and uses averaging to improve prediction. It is predicted the emission savings by using a labelled dataset with different features (i.e., independent variables) such as motorization rate, population, penetration rate, etc., to predict the CO_2 emissions (i.e., the dependent variable).

Table 3: Emission savings for all cities in EU27

Tier	Penetration Rate (%)	CO_2 emissions savings (%)	
		Peak Hours	Off-peak Hours
1	20	12.75	17.56
	50	16.75	23.66
	80	20.18	27.09
	100	20.64	28.51
2	20	14.22	15.77
	50	22.38	22.99
	80	25.65	26.43
	100	27.97	28.34
3	20	10.00	15.59
	50	17.39	21.23
	80	20.62	22.70
	100	23.91	24.15

The immediate impact of the introduction of connected vehicles (at 20% penetration rate) in EU27 cities (approximately):

- **Tier 1: emissions can be reduced by 13% during peak hours and 18% during off-peak hours.**
- **Tier 2: emissions can be reduced by 14% during peak hours and 16% during off-peak hours.**
- **Tier 3: emissions can be reduced by 10% during peak hours and 16% during off-peak hours.**

In line with the simulation results, the usage of connected mobility applications reduce the emissions with increase in penetration rates. However, for certain Tier 1 cities, less performance improvement is observed due to higher number of vehicles and high complexity traffic patterns

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[4] Considering a drive time of 1 hour. The INRIX report [20], wherein the dataset offers relationship between delay (time spent at junctions, per vehicle per year) and the economic cost (per driver, per city). The estimated annual time savings are extracted by adapting the study's results to the baseline of the report.

(higher number of consecutive signalized intersections, bottleneck roads, saturated road capacity, etc.).

Conclusion and Recommendations

This study shows that already a limited number of connected mobility applications allow to significantly reduce GHG emissions and travel times. Furthermore, the applications not only focus on improving traffic efficiency, but also on driver comfort and safety. Thus, connected mobility based on connected and automated driving can contribute to achieve the proposed EU climate action goals [1] in the transportation and mobility sector. This transformation of the mobility landscape will enable societal and economic benefits.

The study highlights that across European cities of different populations (categorized into 3 Tiers in this study), introduction of connected mobility applications holds the potential to reduce emissions. At least 13% during peak hours and up to 18% during off-peak hours can be reduced by already introducing 20% connected vehicles in EU27 cities. Individual countries might show even better emission savings. For example, at least 13% during peak hours and up to 24% during off-peak hours can be reduced in German cities. Moreover, it can be estimated that at least 2 and up to 15 hours of travel time could be saved annually.

Based on this study, the following recommendations could be considered by EU countries:

- Implementing a sustainable connected and automated driving ecosystem considering its key potentials to reduce emissions and improve air quality, increase safety and decrease travel time.
- Encouraging a timely and EU-wide roll-out of 5G/Beyond 5G (B5G) infrastructure to advance and unlock new features of connected mobility applications to increase capacity for improved driving experience, increased comfort and new services.
- Supporting innovation-driven regulatory frameworks and accelerating decision-making process for the implementation and deployment of connected mobility and future technologies. The aim is to enable a fully connected mobility landscape in Germany and other European countries, realizing the contributions to the climate action goals. Such a landscape will provide an ideal platform to improve safety as well as boost productivity.
- Supporting public and private collaboration to foster digital platforms for future growth toward connected mobility.

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List of Acronyms

Abbreviation	Term
ACC	Adaptive Cruise Control
CACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Message
COA	City Optimization Applications
C-V2X	Cellular Vehicle to Everything
DR	Dynamic Routing
DT	Decision Tree
DTL	Dynamic Traffic Lights
E2E	End-to-End
EU	European Union
HOA	Highway Optimization Applications
ICE	Internal Combustion Engine
IVIM	Infrastructure to Vehicle Information Message
JO	Junction Optimization
LAU	Local Administrative Unit
LKW	Lastkraftwagen
ML	Machine Learning
NUTS	Nomenclature of Territorial Unit for Statistics
PKW	Personenkraftwagen
PLAT	Platooning
RFR	Random Forest Regressor
RSU	Road Side Unit
STJ	Smart Traffic Junction
SUMO	Simulation of Urban Mobility
SWD	Shockwave Damping
TJM	Traffic Junction Manager
TraCI	Traffic Control Interface
V2I	Vehicle to Infrastructure
V2P	Vehicle to Pedestrian
V2X	Vehicle to Everything
VSL	Variable Speed Limit

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1 Introduction

The objective of this study is to demonstrate the benefits of Connected Mobility applications, at the European level by means of simulation studies. In this regard, the project takes a multi-step approach of selecting representative scenarios, modelling realistic traffic based on user mobility, developing models for connected mobility applications, and finally curating the results in terms of reduced CO_2 emissions and travel time.

In the first step, as outlined in Figure 4, the overall European Union (EU) traffic has been classified into four different scenarios namely - “Large Urban”, “Small City”, “Rural area”, and “Highway”. These four scenarios capture the population and traffic demographics of any given European country. Each scenario is associated with peak and off-peak hour traffic, as well as personal and commercial mobility.

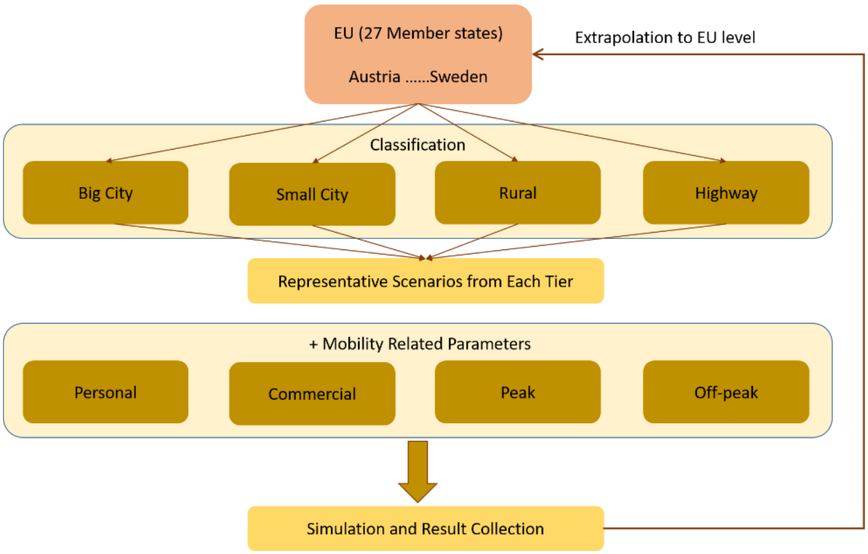

Figure 4: Overview of Representative Scenarios

The simulation methodology as outlined in Figure 5 includes three main steps – selection of representative scenarios, mobility modelling and modelling of connected mobility applications.

For the selection of representative scenarios, all German cities and towns are classified based on their population density into three tiers. A mobility model is generated for each scenario (Tier 1,2 or 3) that represents the different traffic patterns considering the cities’ population demographics, location of office/residential areas, age, gender, family members (i.e., household size), car ownership ratio and motorization rate. For the highway scenarios, the mobility model is defined based on the vehicle flow rates.

Connected mobility applications are modelled and analysed to understand their impact in terms of reduced CO_2 emissions, increased traffic throughput and decreased travel time. These uses cases are classified based on the technological & regulations maturity, need for network interactions and implementation friendliness. In addition, the modelling plan on implementation of selected use cases are described in detailed (city or highway scenarios, assumptions, and parameters) in deliverable D2.

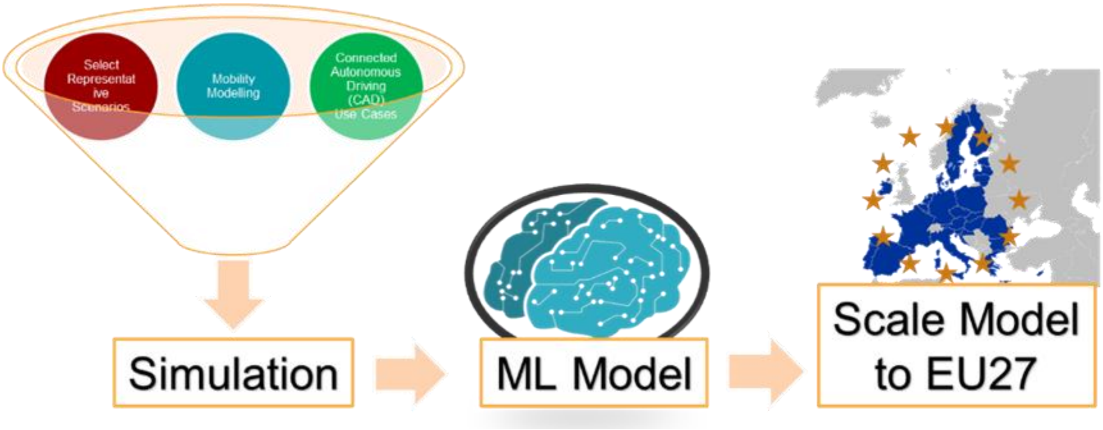

Figure 5: Overview of Simulation Methodology

Results are gathered and compared by simulating the scenarios with and without the connect vehicles and applications. Moreover, the combined effects of different connected mobility applications are also simulated and analysed.

Finally, the achieved benefits from the simulation methodology for the selected representative scenarios are extrapolated to European level by using Random Forest Regression (RFR), a Machine Learning (ML) estimator based on decision trees.

This deliverable is organized as follows. Chapter 2 explains the considered connected mobility applications in detail for both city and highway scenarios. Chapter 3 explains the selection of representative scenarios along with the traffic modelling. Chapter 4 presents the results of the simulation studies and Chapter 5 shows the results of EU level extrapolation.

2 Connected Mobility Applications

Different connected mobility applications are collected and are shown below:

- Level 1 – Applications that have reached technological and regulatory maturity and can be deployed/integrated with relative ease into the current traffic infrastructure.
- Level 2 – Needs some more maturity in terms of technology and regulation, with improvement in vehicle automation.
- Level 3 – Futuristic outlook i.e., driverless vehicles (unknown regulatory roadmap).

Figure 6: Connected Mobility applications categorized per Level

The need for network availability and interactions for the different connected mobility applications can be seen in Figure 7. The considered connected mobility applications can function with either CV2X (Cellular-Vehicle to Everything) or ITS-G5 that provide direct communication amongst vehicles (V2V) and between vehicles and infrastructure (V2I). C-V2X not only provides better range, capacity, and performance to help realize these connected mobility applications, but also easily adapts to the futuristic use cases involving V2P (Vehicle to Pedestrian) communications. These advantages of C-V2X over ITS-G5 help to collect/disseminate the information from/to different sources to provide both macro and micro traffic analysis and optimization in the city in real-time. Moreover, this decision is based on our extensive link and system level simulation campaigns [2] that show the performance superiority of C-V2X compared to Intelligent Transportation Services-G5 (ITS-G5).

Since implementation of all use cases is difficult under the scope of the project, a subset of these applications is selected for implementation. Additionally, the proposed applications are envisioned to be used both as a standalone case and in conjunction with one another. This provides us with an opportunity to analyse and understand the effects of connected mobility applications, both individually and as a group.

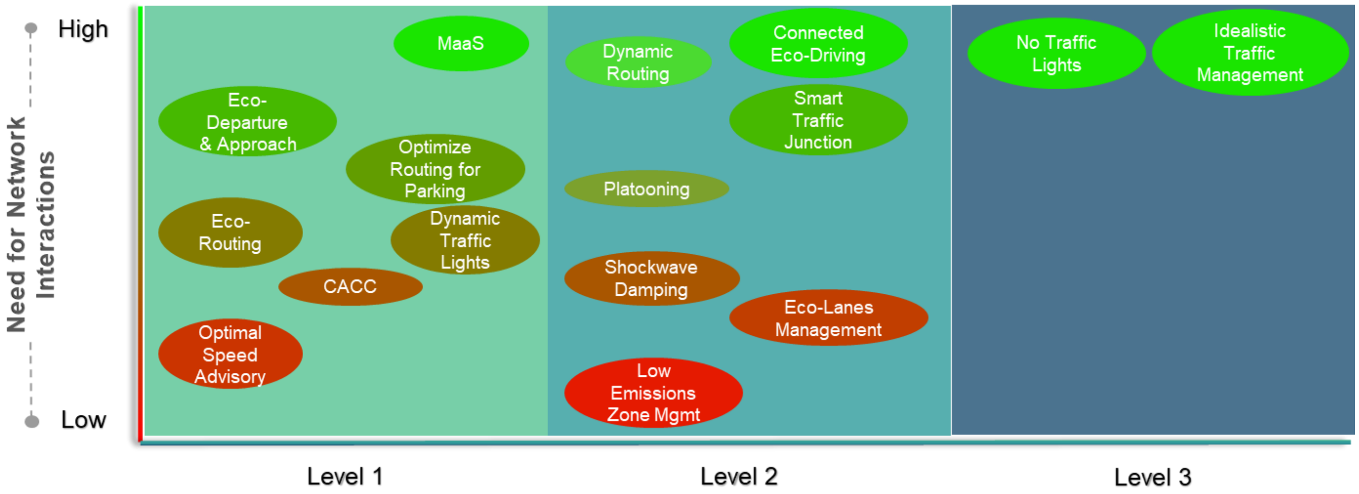

Figure 7: Need for network interactions for different Connected Mobility Use Cases

The implemented applications were divided into two categories – City Optimization Applications (COA) and Highway Optimization Applications (HOA).

2.1 City Optimization Applications (COA)

This category consists of traffic efficiency applications that are relevant for a city/urban/town scenario. A subset of applications is chosen from Figure 6, namely – Dynamic Traffic Lights (DTL), Smart Traffic Junction (STJ) and Dynamic Route Assignment (DR). DTL and STJ aim to optimize the traffic at signalized junctions, whereas DR aims to improve the vehicle's route within the city.

2.1.1 Dynamic Traffic Lights (DTL)

The aim of DTL is to improve the traffic congestion by reducing the waiting time of the vehicles at signalized intersections. Connected vehicles communicate with the system (e.g., a Road Side Unit (RSU) or Traffic Junction Manager (TJM)) to dynamically control the green phase timing of the signal. This minimizes the vehicle queue lengths and fuel consumption [3] [4] [5] at signalized intersections in the city.

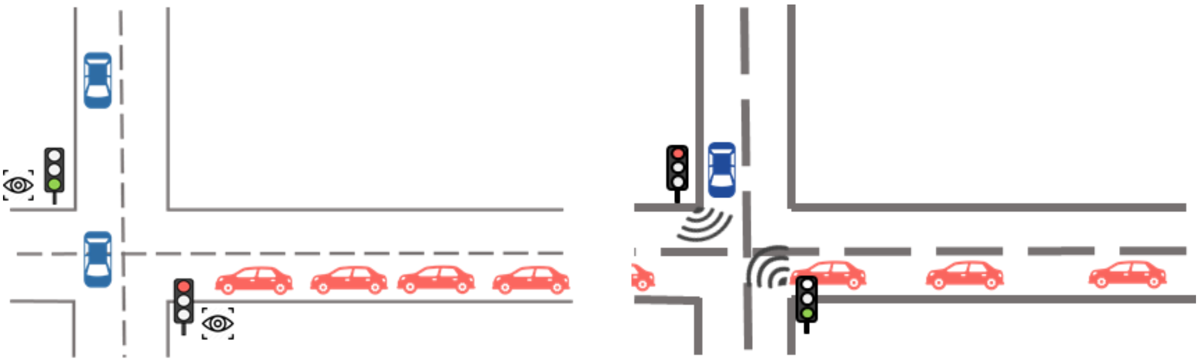

Figure 8: DTL at junctions with V2I

DTL enables V2I communication between vehicles and the TJM at the junction and helps in proactively switching between the signal phases based on the current state of the traffic at the junction. The TJM observes and records the traffic conditions, and then determines the red/yellow/green phase timing for each lane, and how long it will last. For example, as shown in Figure 8, the green phase is switched from the lane with no vehicles waiting at the junction, to a lane with multiple vehicles waiting. By doing so, the traffic flow is controlled, and the overall junction throughput is increased. The DTL algorithm takes the lane-specific CO_2 emission and lane-specific waiting time into account, and regulates them, so that an optimized and smoother traffic flow is achieved, where the CO_2 emission and waiting time are reduced.

2.1.2 Smart Traffic Junction (STJ)

Smart traffic junctions are mainly designed for metropolitan cities, where enormous number of vehicles travel daily [3] [6]. For this, C-V2X communication technology is used with the TJM [6]. The vehicles provide its optimal speed information to the TJM to reduce the waiting time at the intersection, that leads to reductions in the CO_2 emissions [3] [6].

Currently, vehicles create stop and go waves (refer Figure 9) at traffic junctions due to the reaction times inherent to each human driver i.e., when the signal turns green, the first driver takes x_1 seconds to react and accelerate. After x_1 seconds, the second driver takes $x_1 + n$ seconds to react and accelerate, and so on. This creates a “stop and go wave” that is increasingly propagated towards the end of the vehicle chain. This results in less traffic capacity (or higher waiting times) at signalized junctions.

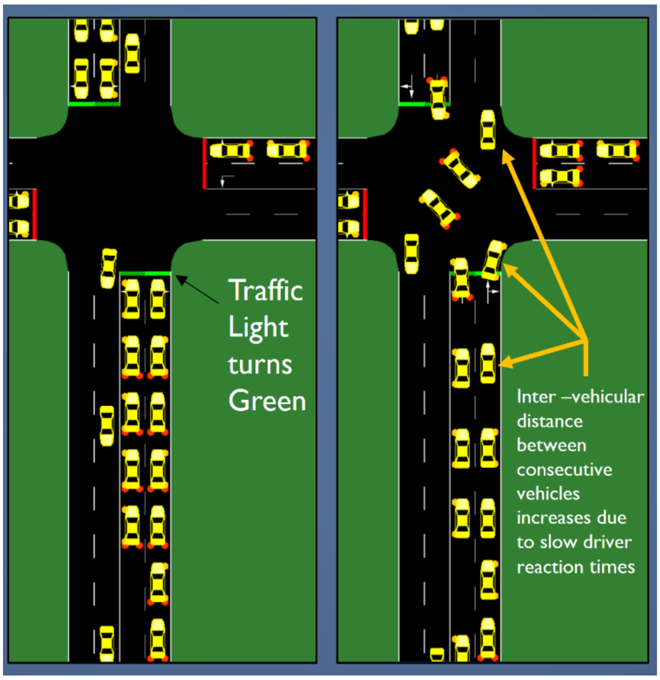

Figure 9: A stop and go wave at a signalized junction as viewed in SUMO

To mitigate this problem, we assume a TJM takes over the control of vehicles leaving the intersection. When the signal turns green, all the vehicles are instantaneously accelerated with no reaction lags. Once the vehicles leave the intersection the control is gracefully restored to the vehicles by the TJM.

As the STJ is a level 2 application, we also assume that the vehicles can be automated to a certain capacity.

2.1.3 Dynamic Route Assignment (DR)

Shortest Path Routing is the simplest and common routing approach, where every vehicle drives from the start point to the end point with the shortest distance, just like the drivers tend do in the real world. Time of travel is not considered when the routes are assigned. Therefore, the Shortest Path Routing is used to map the normal vehicle's driving strategy into the simulation as the baseline.

DR enables the simulation to change the vehicle's route automatically, according to the current traffic characteristics. DR works by giving some or all vehicles the capability to re-compute their route (at insertion) as per the current state of traffic on the city roads, and thus, adapts to traffic jams (in principle) and other changes. Thus, DR assigns routes to vehicles with the least time cost and avoiding the congested city roads.

2.2 Highway Optimization Applications (HOA)

HOA refers to applications that are relevant for highway scenarios. Here, we consider two use cases – Platooning (PLAT) and Shockwave Damping (SWD).

2.2.1 Shockwave Damping (SWD)

Shockwave or a phantom wave is a disruption in traffic flow caused by either high density of traffic (higher traffic flow than capacity) at bottlenecks, or due to human error (random lane changing, braking/slowing down in lane). A space-time diagram for a typical shockwave can be seen in Figure 10. The region is red represents the shockwave and its diminishing tail (with respect to time) shows that the shockwave is being dissipated.

Formation and propagation of shockwaves at bottlenecks has been researched quite extensively. However, the formation of shockwave on a stretch of road without bottlenecks was first recreated by a team of Japanese researchers [7] in 2008. The researchers were able to successfully demonstrate the formation of the shockwave and the dynamical phase transitions leading up to a traffic jam from a free flow state. One of the solutions to reduce the number of shockwaves is Adaptive Cruise Control (ACC). In mixed traffic flows with a penetration rate as low as 10% for ACC, a strong reduction in traffic congestion is noted in [8]. However, [8] [9] also note that an increase in the penetration rate of ACC has a negative influence on the system performance, as it can lead to congestion at bottlenecks due to the low adaptability of the technology to its preceding vehicles' change in speed. With improvements in wireless communications, Cooperative Adaptive Cruise Control (CACC) is also seen as a viable option to reduce shockwaves [10]. [11] notes that a relatively high percentage (50 and above) of CACC penetration is required to justify a significant increase in travel speeds and reduction in formation of shockwaves at bottlenecks. Another solution is variable speed limits (VSL) to reduce congestion at bottlenecks. [12] shows that the total travel time for vehicles at bottlenecks can be potentially reduced by 22%. [13] displays that using VSL can reduce the effective area of congestion, and in turn reduce the impact of shockwaves.

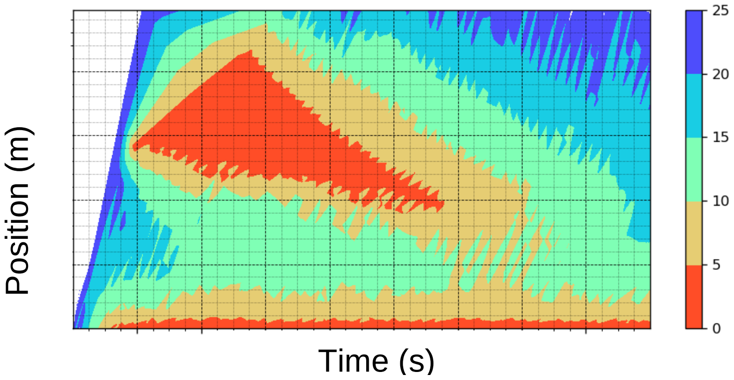

Figure 10: Space-time diagram for a typical shockwave in a highway. The colormap represents the vehicle speeds in m/s.

To dissipate shockwaves, we propose the vehicles be provided speed advisories via dissemination of IVIMs (Infrastructure to Vehicle Information Message) from RSUs or other connected vehicles. The RSU collects the information from all connected vehicles and correspondingly calculates a speed advisory to not be propagate the shockwave. The speeds are calculated based on the current state of the traffic, i.e., depending on the incoming and outgoing flow rates of different sections of the highway. In the downlink, the IVIMs can help the vehicles adapt their speeds in accordance with the upstream vehicles (that are currently part of a shockwave) and help damp the shockwave at a much faster rate.

2.2.2 Platooning (PLAT)

Platooning is the linking of two or more vehicles (trucks) in a convoy, using connectivity technology and automated driving support systems. These vehicles automatically maintain a set, close distance between each other when they are connected for certain parts of a journey, for instance on highways.

To highlights the benefits of Platooning, we use Simpla, a platoon plugin for SUMO (configured using TraCI Python). Simpla offered four operational modes to form the platoon [14]:

- Platoon leader mode
- Platoon follower mode
- Platoon catch-up mode
- Platoon catch-up follower mode

When the connected vehicles start being populated on the road (in the simulation) and platooning is activated, the first vehicle acts as a leader. Vehicle driving behind the platoon leader acts as a platoon follower, whilst maintaining its inter-vehicular distance. In the platoon catch-up mode, vehicle tries to join the platoon which within its range. In the platoon catch-up follower mode, the platoon leader itself comes in catch-up mode to join another platoon. Some parameters such as vehicle type mapping, platooning gap, catch-up distance, speed factors and vehicle selector are considered to configure Simpla files with SUMO [14].

A simplified use case with a single platoon is considered to analyse the effects of connected mobility on CO_2 emission and fuel consumption. A platoon is formed with vehicles at different intervehicle distance. The vehicles are assumed to have CACC function which maintains the constant inter vehicle gap that is maintain by Simpla controller [14].

Two lane highway scenario is defined with a dedicated lane for the platoon trucks. Two simulations are performed with the same number of vehicles, type of vehicle on the same highway stretch. Firstly, normal randomized traffic is simulated with trucks and passenger vehicles. Further, another simulation where connected truck platoons are defined with background passenger cars.

3 Selection of representative scenarios

In this section, the selection of representative scenarios for both COA and HOA are explained.

3.1 Representative scenarios for COA

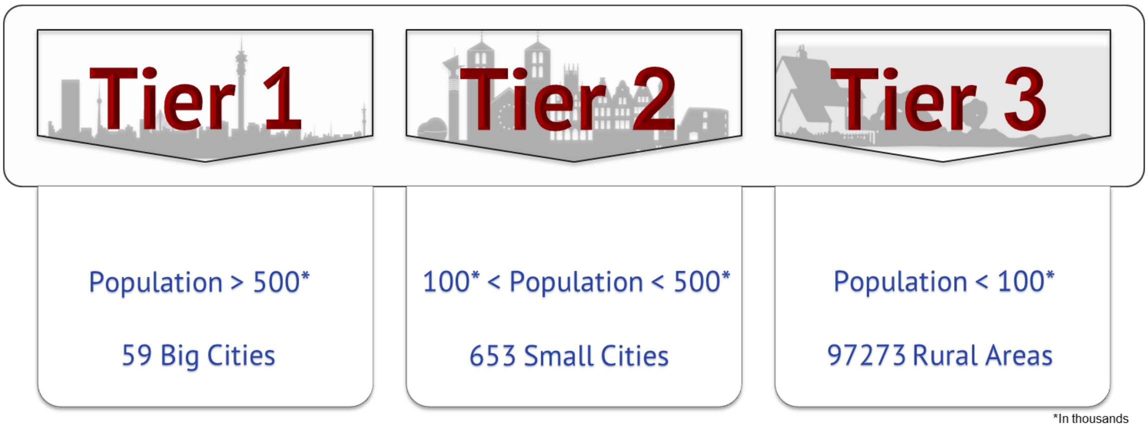

Figure 11: Tiers classification for all Urban regions in EU27

As shown in Figure 11, all urban regions in EU27 are classified into 3 tiers – Big Cities, Small Cities and Rural Areas, based on their population. The EU27 regions are classified based on their population figures, which is also specified in Figure 11.

To select the representative scenarios, we first classify the different cities from Germany into the 3 Tiers and extract additional information for each of these German cities such as population density, vehicle ownership ratio, commute time, population distribution (based on gender and age) and household statistics, etc.

The statistics for the country of Germany is as follows:

- Total area – 357,386 km^2
- Total population – 83,166,711
- Population density – 235.2 people per km^2
- Average motorization rate – 572 (per 1000 inhabitants)

The distribution of the population of Germany per region is as follows:

- Cities (Tier 1)– 29.6 %
- Towns and Suburbs (Tier 2) – 32.7 %
- Rural areas (Tier 3)– 37.7 %

The Nomenclature of Territorial Unit for Statistics (NUTS) subdivisions of Germany can be found in Table 4.

Table 4: NUTS statistical regions of Germany [15]

Regions	NUTS Level	Number
States	1	16
Districts	2	38
Counties	3	401
Municipalities	LAU (4/5)	11087

In the next step, the Municipalities are divided into three tiers – Tier 1, 2, and 3 respectively based on the population. The density for each of these tiers can be seen in the Figure 12.

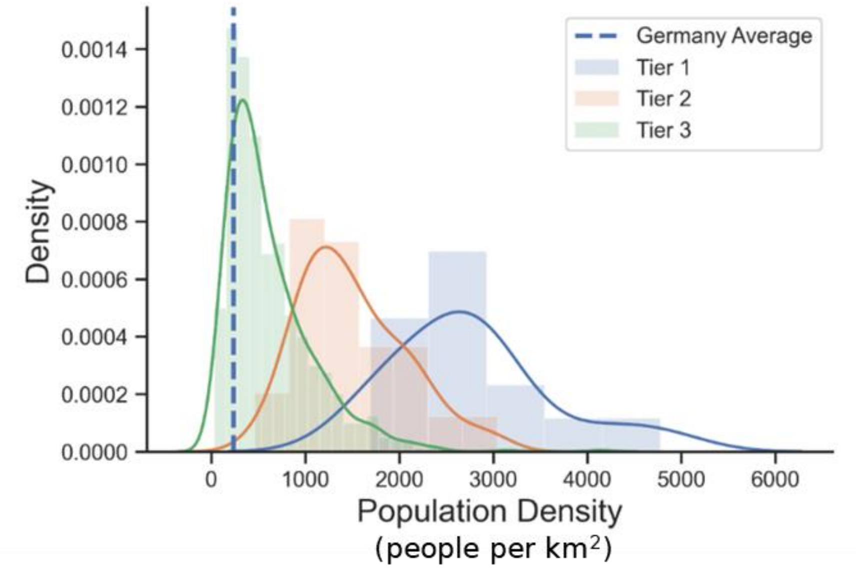

Figure 12: Population Density of German Cities (per tier)

Note: As the majority of Gemeinden in Germany belong to the Tier 3, the overall density for the Tier 3 region is quite high, thereby, making the other 2 Tiers virtually undetectable in the Figure 12. Hence, the figure includes Gemeinden that comprise 60% population of Germany to better demonstrate the Tier 1 and 2 Gemeinden.

Once the Tier classification is complete, we selected 5 (6 for Tier 2) candidate scenarios from each Tier in such a way that the population density is uniformly distributed between the minimum and maximum of each tier. This gives us a total of 16 representative scenarios. The selected scenarios can be found in the Table 5.

Table 5: Selected representative scenarios per tier

Sr. No.	Tier-1	Tier-2	Tier-3
1	Bremen	Aachen	Ansbach
2	Cologne	Freiburg im Breisgau	Brühl
3	Frankfurt am Main	Kaiserslautern	Fulda
4	Munich	Lübeck	Merzig
5	-	Mannheim	Schwerin
6	-	Offenbach am Main	-

The selection of representative scenarios was also done in such a way that it covers the different regions of Germany. This can be seen from the Figure 13, with the locations of the scenarios on the German map (divided at NUTS 2 level).

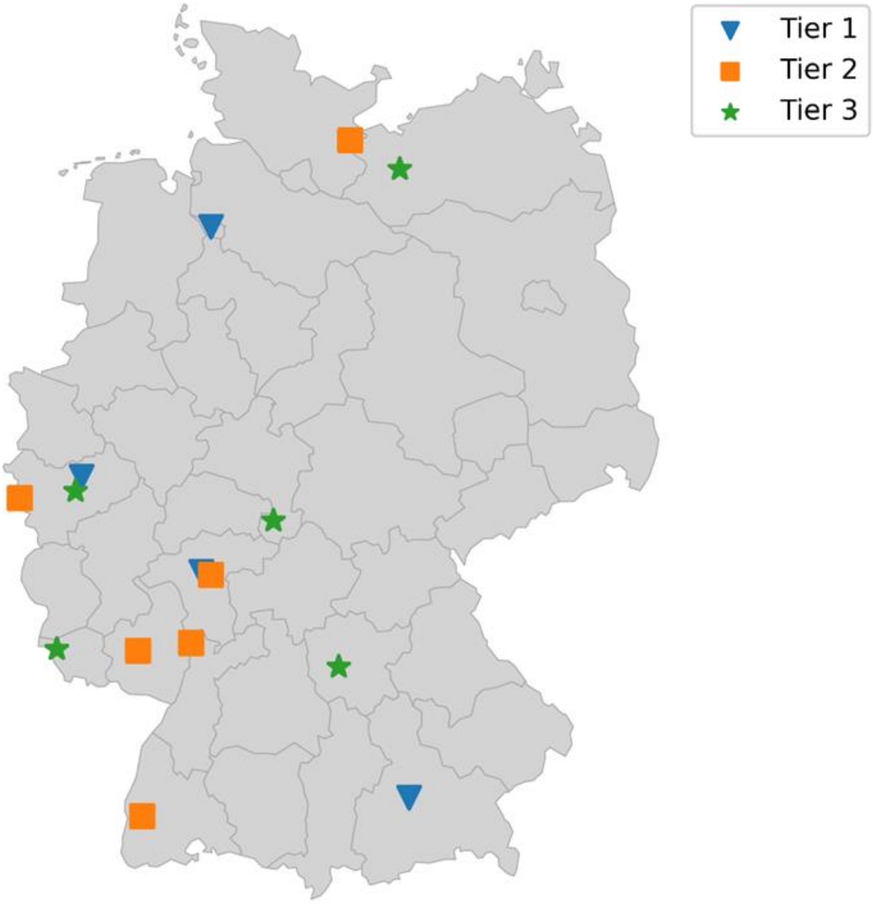

Figure 13: Representative Scenarios in Germany

3.2 Generation of vehicular traffic for COA

For the city scenario, vehicle trips are generated from the population demographics of the scenario to be simulated. Owing to the time budget of the project and the complexity of the simulations involved, an abstraction on the User-centric Mobility Model is made, i.e., only vehicles (no multi-modality) are generated with specific sources and destinations (city-specific), and for two periods of 3 hours. The first 3-hour period (between 6-9 am) defines the peak hour traffic and the second (between 12-15 pm) characterizes the off-peak hour traffic. By introducing a wide variety of vehicle parameters, we generate enough randomness to reflect realistic traffic models for the period simulated.

3.3 Selection of representative scenarios for HOA

To select the representative scenarios for HOA, different highway types are selected to accurately represent different highways in all countries in EU27. Considering the sizes of all highways in EU27 countries, i.e., the total road length, it is feasible to replicate a small subsection of different highway types in the simulation environment.

The highway types (refer Figure 14) considered are 3 lane highways, 2 lane highways, and highways with zipper merges, i.e., lanes converging into 1. Each of these types is shown in the Figure below. Additionally, the highways are subjected to different maximum road permissible speeds – 90, 130 and 200 kmph.

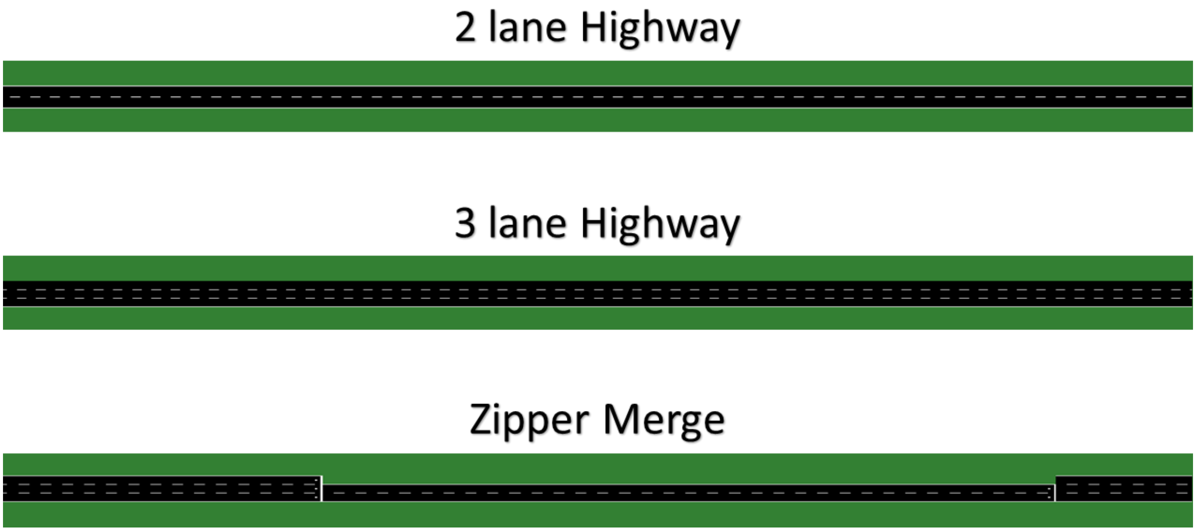

Figure 14: Types of highways as representative scenarios for HOA

3.4 Generation of vehicular traffic for HOA

The vehicular traffic for HOA is divided into 2 broad categories – passenger vehicles (PKW) and trucks/trailers/buses (LKW). Each of these categories can be further broken down into vehicles of different lengths and parameters such as maximum acceleration and deceleration, maximum vehicle speed, etc. Additionally, different driver profiles are also introduced by changing the reaction times, acceleration, and deceleration patterns, etc. in the simulation environment.

As the traffic state of any lane can be macroscopically defined by the vehicle flow rate (vehicles per hour), we introduce different flow rates – 2400, 1800, 1440, 1200, 900, 720, 600 and 360. Each of these flow rates can be used to reflect a different part of the day and also different parts of the highway. For example, during peak hours, a highway section leading into any Big City should experience a high vehicle flow rate, which can be closely represented by the flow rate of 2000 – 2400 vehicles per hour per lane.

4 Simulation & Results

In this section, the results of the simulation campaigns conducted on the selected representative scenarios are presented.

4.1 Simulation setup

The simulation interval is defined for peak and off-peak hours. In this case, the peak hours are defined between 06:00 and 09:00 in the morning, and the off-peak hours are defined between 12:00 and 15:00 in the afternoon. The simulation step is set to one second in SUMO, which means the vehicle positions and speeds are updated every second.

Furthermore, while direct C-V2X communication is needed for connected mobility and safety applications, mobile networks are sufficient to meet the sustainability services. The combination of the two modes allows for full coverage and no gaps, as C-V2X PC5 will work where there is no network coverage.

The number of vehicles for each tier cities depends on the city demographics, i.e., the total population, population density, total area, motorization rate, etc. In Table 6, an example of parameters for each Tier is listed. To generate vehicle trips, parameters such as the total number of vehicles (or the motorization rate) and the multi-modal transportation rate for work trips and for free time trips are selected. This indicates the number of vehicles that will be introduced in the simulation for each simulation time interval in both the peak and the off-peak hours.

Also, the effect of the connectivity is evaluated by introducing different number of connected vehicles, i.e., *penetration rate*, in each tier city, for both peak and off-peak hours. The goal is to see how the percentage of connected vehicles in a certain region affects the performance of the optimization applications, and which penetration rate is optimum for the emission and traffic throughput.

KPIs are defined for evaluating the simulation results, i.e., the average CO_2 emission in g/km (see), the average speed in km/h, which reflect the emission and the traffic flow.

For the case of City Optimization Applications (COA) when comparing 0% penetration rate to 100% penetration rate of connected vehicles, a total of 6 simulation instances (3 for peak hours and 3 for off-peak hours) are simulated for every representative scenario:

1. Benchmark - Using shortest path routing and no Junction Optimization[5] (JO) applications enabled.
2. Single application - Using dynamic routing and no JO applications enabled.
3. Group applications - Using dynamic routing and JO applications enabled.

To evaluate the effects of different penetration rates of connected vehicles, 2 simulation instances (1 for peak hour and 1 for off-peak hour) are simulated for every representative

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[5] DTL and STJ are categorized together as JO applications.

scenario – with group connected mobility applications enabled, i.e., using DR and JO applications. The applications are active and exchange information only with the connected vehicles available in each simulation.

For the case of HOA, for every selected road network type, 2 simulations instances were run – one without the HOA applications enabled and another with the HOA applications enabled.

Table 6: An example of parameters used for generation of city traffic per Tier

		Ansbach	**Kaiserslautern**	**Cologne**
Population		41,798	100,030	1,087,863
Total Area in km^2		99.91	139.7	405.01
Tier		3	2	1
Population Density in person/km^2		418.36	716.03	2686.02
Total passenger vehicles		21435	55,660	391,030
Motorization Rate (per 1000 inhabitants)		512	557	355
Vehicle distribution in households in %	No autos	27	29	41
	1 auto	56	53	47
	2 or more	17	18	11
Multi-modal transportation for work trips in %	Walk	15	14	11
	Bicycle	18	15	24
	Shared Cars	6	4	3
	Single Person Car	56	50	33
	Train	6	17	29
Multi-modal transportation for shopping trips in %	Walk	28	38	45
	Bicycle	12	10	15
	Shared Cars	13	12	8
	Single Person Car	44	33	23
	Train	3	7	8
Multi-modal transportation for free time activity in %	Walk	34	36	34
	Bicycle	9	10	17
	Shared Cars	23	22	16
	Single Person Car	30	24	14
	Train	4	8	19

4.2 Results

In this sub-section, the specific simulation results for the representative scenarios are included.

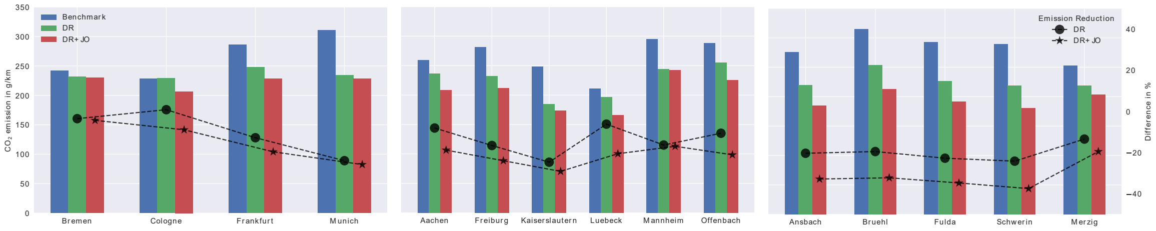
4.2.1 Results – COA

The average CO_2 emissions per vehicle for all Tiers in Germany are shown in Figure 15 and in Figure 16. The figures also show the effect of emission reduction by introduction of both DR and DR+JO scenarios. Detailed simulation result for each scenario can be found in Appendix A.

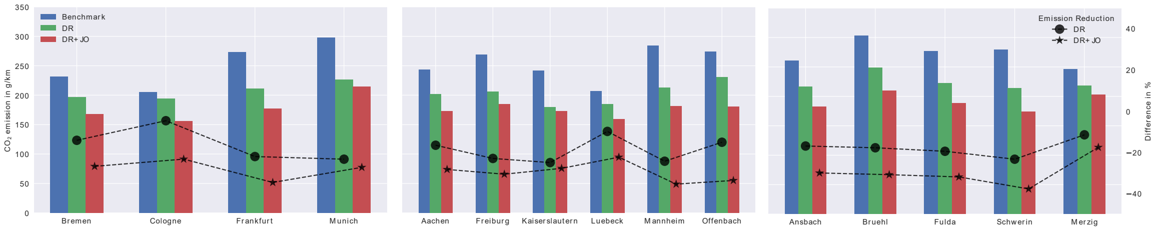
For peak hour traffic in Tier 1 cities, a reduction of CO_2 emissions up to 27% can be achieved. For example, the lowest reduction effect can be seen in Cologne when only DR is implemented. This is because there is a high influx of vehicles in Cologne during the peak hours from the nearby municipalities. However, for the same traffic model, with the introduction of JO applications with DR, emission reductions up to 9% can be seen in Cologne. This indicates that the junctions are over-congested and connectivity at signalized intersections can help reduce the overall emissions across the city.

Also, vehicle speed is greatly increased in all Tier 1 cities by applying DR, and thus, the flow of traffic within the cities is smoother.

The emission savings are even higher for the off-peak hour traffic, sometimes as high as 35% This can be attributed to lower density of vehicles on the city roads. (Note: this lower density is relative to the peak hours in the city. Tier 1 cities generally, have a high number of vehicles at given time of the day.)

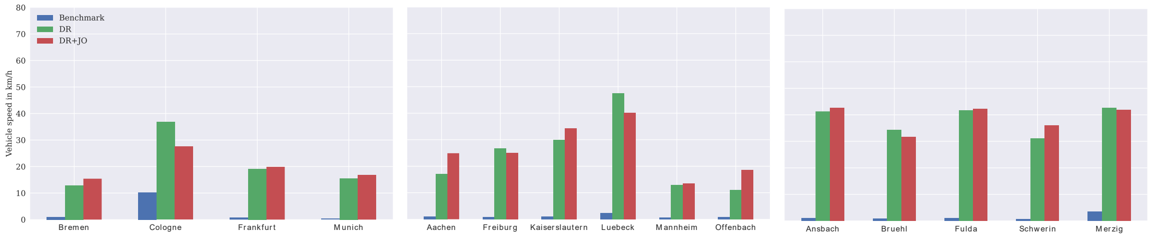


(a) Tier 1 cities in peak hours (b) Tier 2 cities in peak hours (c) Tier 3 cities in peak hours



(d) Tier 1 cities in Off-peak hours (e) Tier 2 cities in Off-peak hours (f) Tier 3 cities in Off-peak hours

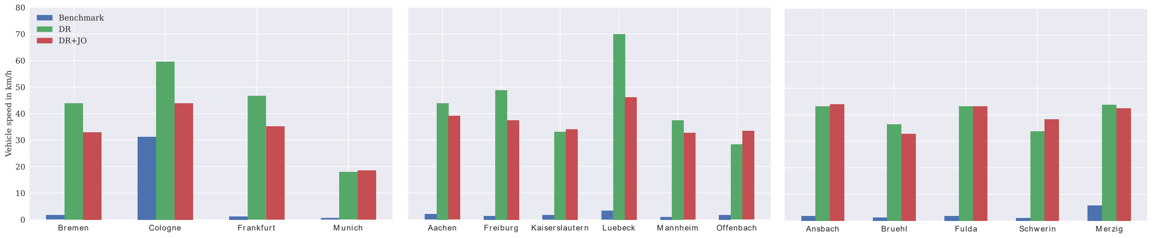
Figure 15: Average CO_2 emission for all tier cities in Germany



(a) Tier 1 cities in peak hours

(b) Tier 2 cities in peak hours

(c) Tier 3 cities in peak hours



(d) Tier 1 cities in Off-peak hours

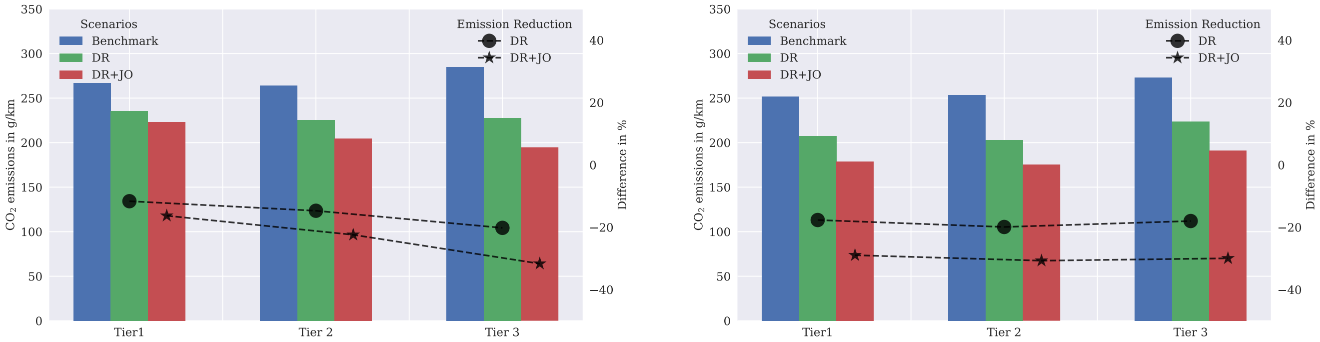
(e) Tier 2 cities in Off-peak hours

(f) Tier 3 cities in Off-peak hours

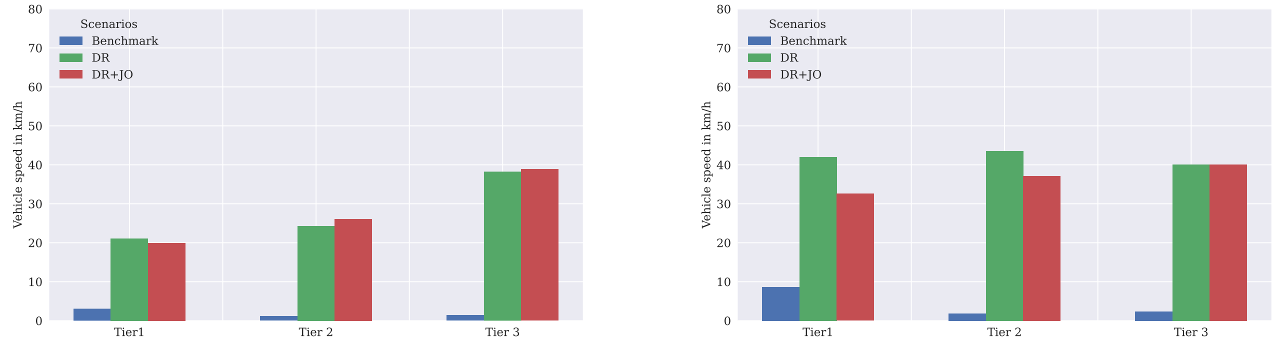
Figure 16: Average vehicle speed for all tier cities in Germany

For Tier 2 Cities the results are shown in Figure 15(b) and (e), and Figure 16(b) and (e). These cities also follow a similar trend as the Tier 1 cities, i.e., with introduction and addition of connected mobility applications, we see reductions in CO_2 emissions. The Tier 2 cities are generally characterized by lower traffic density and lower number of vehicles coming into the city during the peak hours (when compared to the Tier 1 cities). This results in emission savings in the range of 19 – 30% during the peak hours and 17 – 36% during the off-peak hours. Tier 3 Cities are characterized by low traffic densities, lesser availability of public transportation (when compared to Tier 1 and 2 cities), lesser number of signalized intersections and higher usage of personal vehicles. The results are shown in Figure 15(c) and (f), and Figure 16(c) and (f), that show that the CO_2 reduction is more or less consistent for all of the considered scenarios up to 38%, irrespective of the time of the day.

Figure 17 shows the overall averaged results of CO_2 emissions and vehicle speeds for all the Tiers during peak and off-peak hours. As the results show, for all Tier cities, an average reduction in CO_2 emission is achieved from 10-30%, where the Tier 1 cities have less reduction compared to Tier 3 cites.



(a) Averaged CO$_2$ emission for all tier cities in peak hours (b) Averaged CO$_2$ emission for all tier cities in off-peak hours



(c) Averaged vehicle speed for all tier cities in peak hours (d) Averaged vehicle speed for all tier cities in off-peak hours

Figure 17: Average CO$_2$ emissions and speed using Dynamic Routing in Peak Hours for all Tier cities

4.2.2 Results – Penetration Rate

In this section, the effect of the penetration rate of connected vehicles is studied. Different penetration rates of connected vehicles – 0%, 20%, 50%, 80% and 100% for Tier 1, 2 and 3 cities are simulated. Here, all connected vehicles use the DR with JO applications. The results for simulation time of 1 hour for both peak and off-peak hours are presented below.

The 1-hour results are collected due to the complexities involved in simulating the representative Tier 1 cities, for both peak and off-peak hours. To maintain homogeneity, similar 1 hour window results are also obtained for the Tier 2 and 3 cities.

In Figure 18, CO$_2$ emissions for all Tier cities in Germany with different penetration rates are shown. Generally, with increasing penetration rate, reduction in CO$_2$ can be achieved. For Tier 3 cities, the CO$_2$ emission is reduced thanks to the lower number of vehicles and less signalized junction in the Tier 3 cities. Also, the improvement is increased at a higher penetration rate and achieve its maximum at 100%. As for some special cases with a very small population and motorization rate, the connected mobility applications can already gain its optimized performance at lower penetration rate, such as the city of Merzig, the performance of connected mobility is already optimized at 20%.

However, in several Tier 1 and Tier 2 cities during the peak hours, the CO$_2$ emission is not further reduced at higher penetration rate, and instead shows a marginal increase, for example, Tier 1 cities of Frankfurt and Munich, Tier 2 city of Aachen. Analysis of this problem and a potential solution is proposed in Section 4.2.2.2 Results – Automatic Rerouting).

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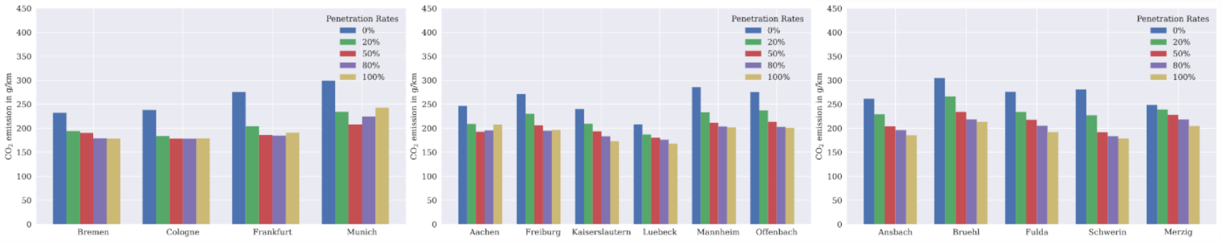
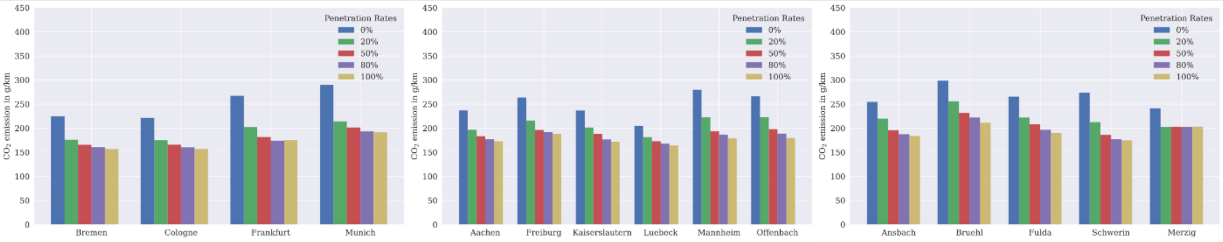


(a) Tier 1 cities at peak hours (b) Tier 2 cities in peak hours (c) Tier 3 cities in peak hours

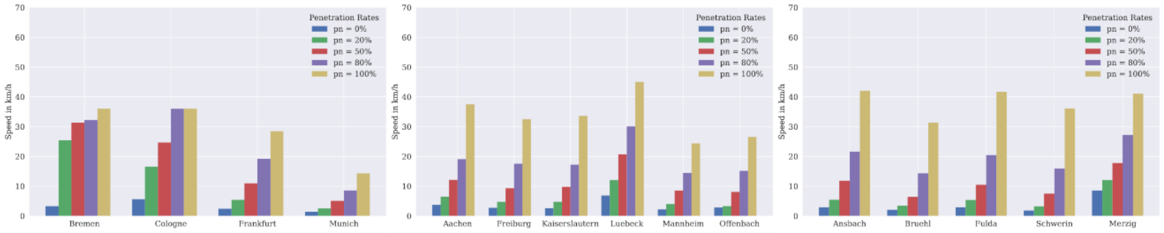


(d) Tier 1 cities in off-peak hours (e) Tier 2 cities in off-peak hours (f) Tier 3 cities in off-peak hours

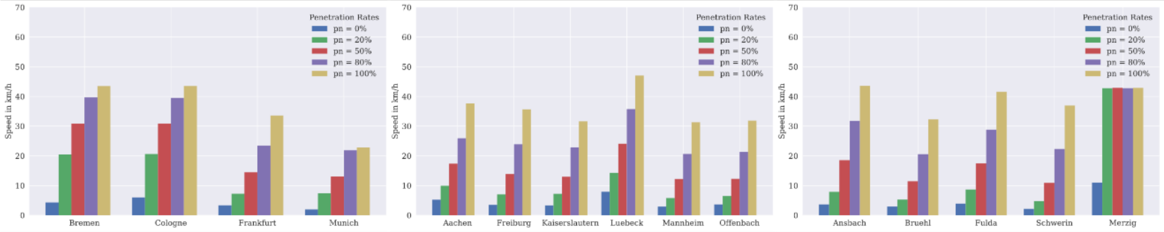
Figure 18: CO₂ emissions for different penetration rates of connected vehicles in Tier 1, 2 and 3 cities

Also, the average vehicle speed for different penetrations is shown in Figure 19**.** The average vehicle speed increases greatly with the increasing penetration rate. In other words, the more connected vehicle involved in the traffic network, the higher the traffic throughput.

In Figure 20, averaged CO_2 emissions and vehicle speeds for all representative Tier 1, 2 and 3 cities can be seen. From the results a general trend in the CO_2 emissions can be seen – CO_2 emissions are reduced with the increase in penetration rate, i.e., the higher the number of connected vehicles on the city roads, the lower the CO_2 emissions.

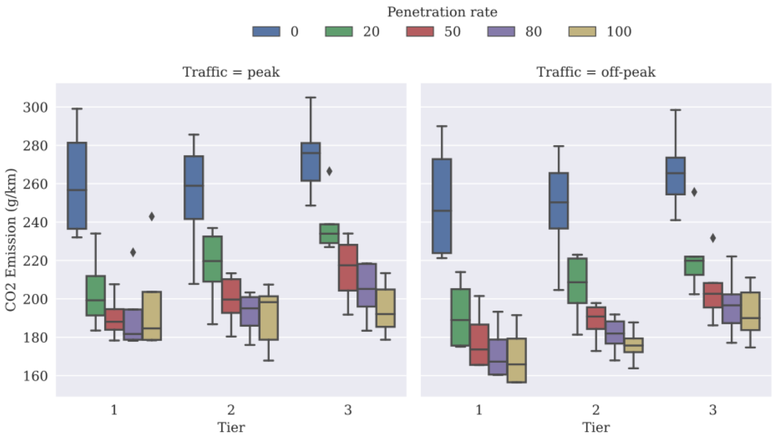


(a) Tier 1 cities at peak hours (b) Tier 2 cities in peak hours (c) Tier 3 cities in peak hours

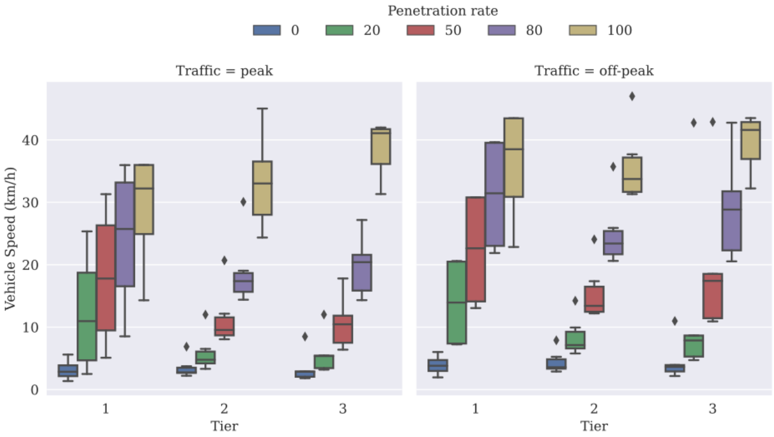


(d) Tier 1 cities in off-peak hours (e) Tier 2 cities in off-peak hours (e) Tier 3 cities in off-peak hours

Figure 19: Average vehicle speed for different penetration rates of connected vehicles in Tier 2 and 3 cities



(a) Average CO_2 emissions

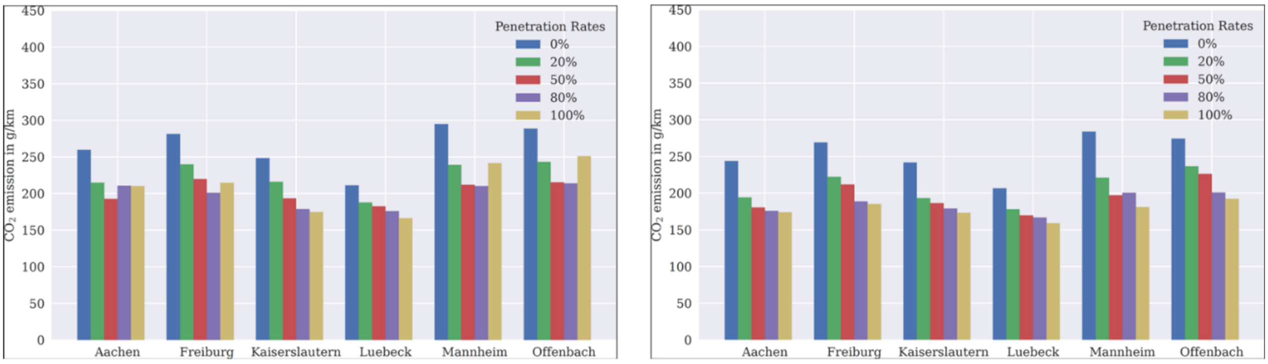


(b) Average vehicle speed

Figure 20: Categorical plot of average CO_2 emissions for different penetration rates of connected vehicles in Tier 1, 2 and 3 cities

4.2.2.1 3-hour simulations

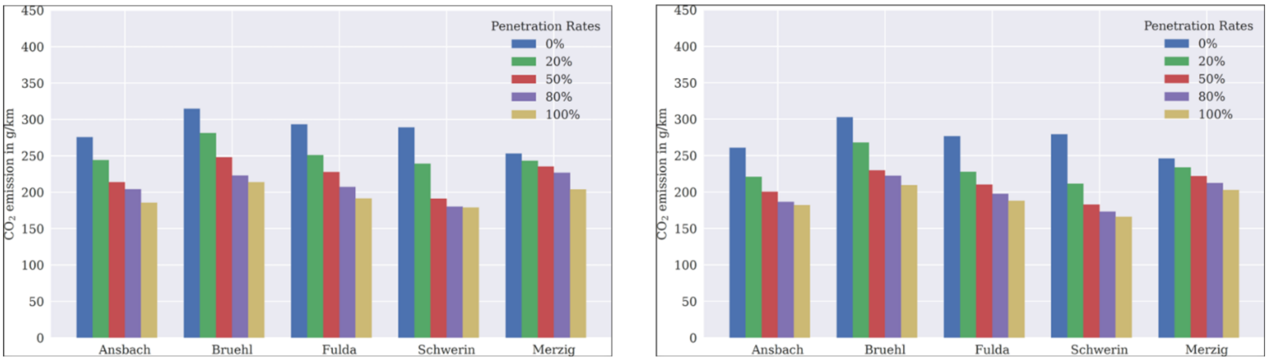
In this subsection, results for different penetration rates of connected vehicles in Tier 2 and Tier 3 cities are presented. This subsection also shows that the reduced simulation time does not have a huge bearing on the results.



(a) Tier 2 cities in peak hours

(b) Tier 2 cities in off-peak hours

Figure 21: CO_2 emissions for different penetration rates of connected vehicles in Tier 2 cities



(a) Tier 3 cities in peak hours (b) Tier 3 cities in off-peak hours

Figure 22: CO₂ emissions for different penetration rates of connected vehicles in Tier 3 cities

Figure 21 and Figure 22 show the CO2 emissions for different penetration rates of connected vehicles in Tier 2 and Tier 3 cities, respectively. Here too, we see that in some Tier 2 cities like Freiburg, Mannheim and Offenbach, the 100% penetration rate results in higher emissions than its 80% counterpart. Analysis and a potential solution of this is also provided in Section 4.2.2.2 Results – Automatic Rerouting).

To understand the effect of reducing the simulation time from 3-hour to 1-hour, we see how closely the recorded results for CO2 emissions are correlated. For Tier 2 cities, the correlation between the 3-hour and 1-hour results is 0.9857 for the peak hours and 0.9738 for the off-peak hours. This shows a strong correlation for both peak and off-peak hours, and proves that the simulation time has little to no impact on the emission savings.

Similarly for Tier 3 cities, the correlation between the 3-hour and 1-hour results is 0.9917 for the peak hours and 0.9626 for the off-peak hours. A strong correlation, here too, proves that the simulation time has little to no impact on the emission savings.

4.2.2.2 Results – Automatic Rerouting

In Tier 1 and 2 cities during peak hours, emissions were higher with 100% penetration rate than with 80% penetration rate of connected vehicles. The increase in emissions is because of the consistent traffic congestion caused by high vehicle densities at the signalized junctions during the peak hours, which lowers the performance of connected mobility applications and causes more stop-and-go behavior when managing the traffic. This is primarily due the route assignment from the DR algorithm. The assignment accounts for shorter travel times and does not predict the future congestion spaces. This results in similar road sections and signalized junctions being assigned.

To eliminate the bad performance of the applied use cases due to high congestions and over-usage of the same junctions (see Figure 18(a)), we implement the rerouting of vehicles when signalized junctions (on their route) are congested. The TJM broadcasts the current congestion state to the oncoming vehicles and allow them to reroute themselves. The routing approach works by re-computing their route periodically, where it considers the current and recent state of traffic in the network and thus, a new route is assigned to the connected vehicles. The results of the automatic rerouting are presented in the Figure 23, wherein simulations for city of

Mannheim and Offenbach am Main are conducted, to eliminate the ‘Google effect’ of the DR algorithm in Tier 1 and Tier 2 cities during the peak hours, for example the city of Frankfurt am Main and Aachen are selected.

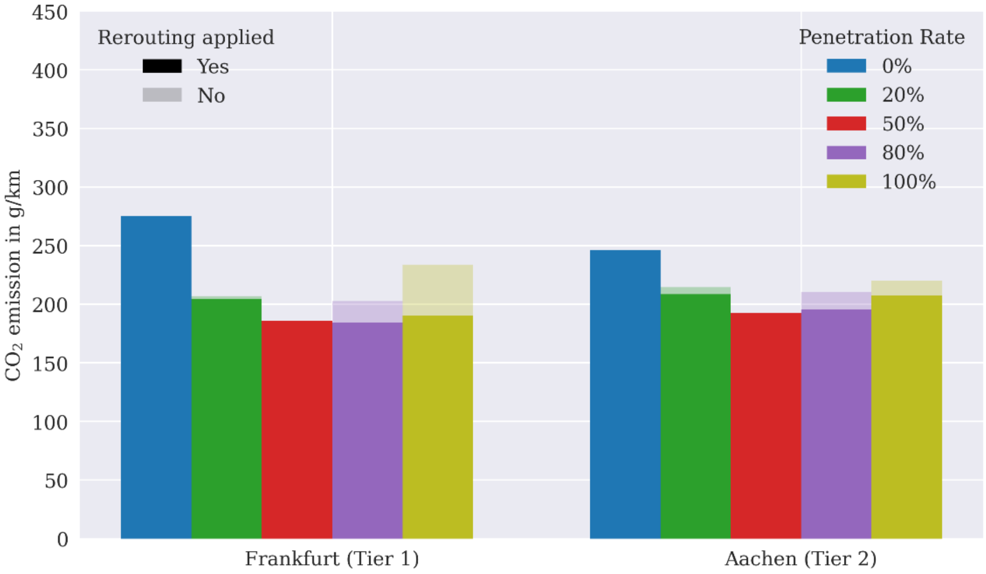


Figure 23: CO₂ emissions for Frankfurt and Aachen with and without rerouting

As shown in the results, by deploying the AR, the CO2 emissions can be further reduced at higher penetration rates (the solid bars) like 80% and 100%, which helps to smooth the “Google effect” from the DR algorithm. However, the AR cannot fully solve the problem caused by the algorithm itself during the peak hours with high traffic congestion at the junctions, since the CO2 emissions at 80/100% are slightly higher than that at 20% penetration rate.

Thus, there is not only a need to add more microscopic data to further optimize the traffic flow, but also add connected mobility applications that further optimize the traffic conditions in the city.

4.2.3 Results – HOA

For the HOA, the connected mobility applications were simulated individually.

4.2.3.1 Shockwave Damping (SWD)

A typical shockwave is characterized by decrease in speed and consequently an increase in emissions and fuel consumption, due to the constant acceleration and deceleration by multiple vehicles. This can also be evidently seen in the Figure 24. The red lines (dashed, dotted and solid) represent the vehicles with no connectivity. And thus, higher emissions and lower speeds can be found irrespective of the type of highway. Introducing connected vehicles with a 100% penetration rate (blue line in Figure 24), there is a reduction in CO_2 emissions and an increase in average vehicle speeds. This indicates that the downstream vehicles adapt their speeds w.r.t. the shockwave upstream, and hence, the shockwave is 'damped' and dissipated faster.

But introducing connected vehicles does not imply that the emissions will be reduce when a shockwave is damped at a faster rate. This case can be seen in Figure 24 c). At higher vehicle flow rates (>2300 vehicles per hour), even though the shockwave is damped (can be seen by the overall increase in speeds), the average emission per vehicle has increased. On the other end of the spectrum, at lower vehicle flow rates (<600 vehicles per hour), the emissions can sometimes increase with 100% connected vehicles and depends on the type of vehicles on the road at that given time. This is to say that if there are more trucks than passenger vehicles, the overall speeds would reduce and hence, lower emissions than the scenario with higher passenger vehicles than trucks.

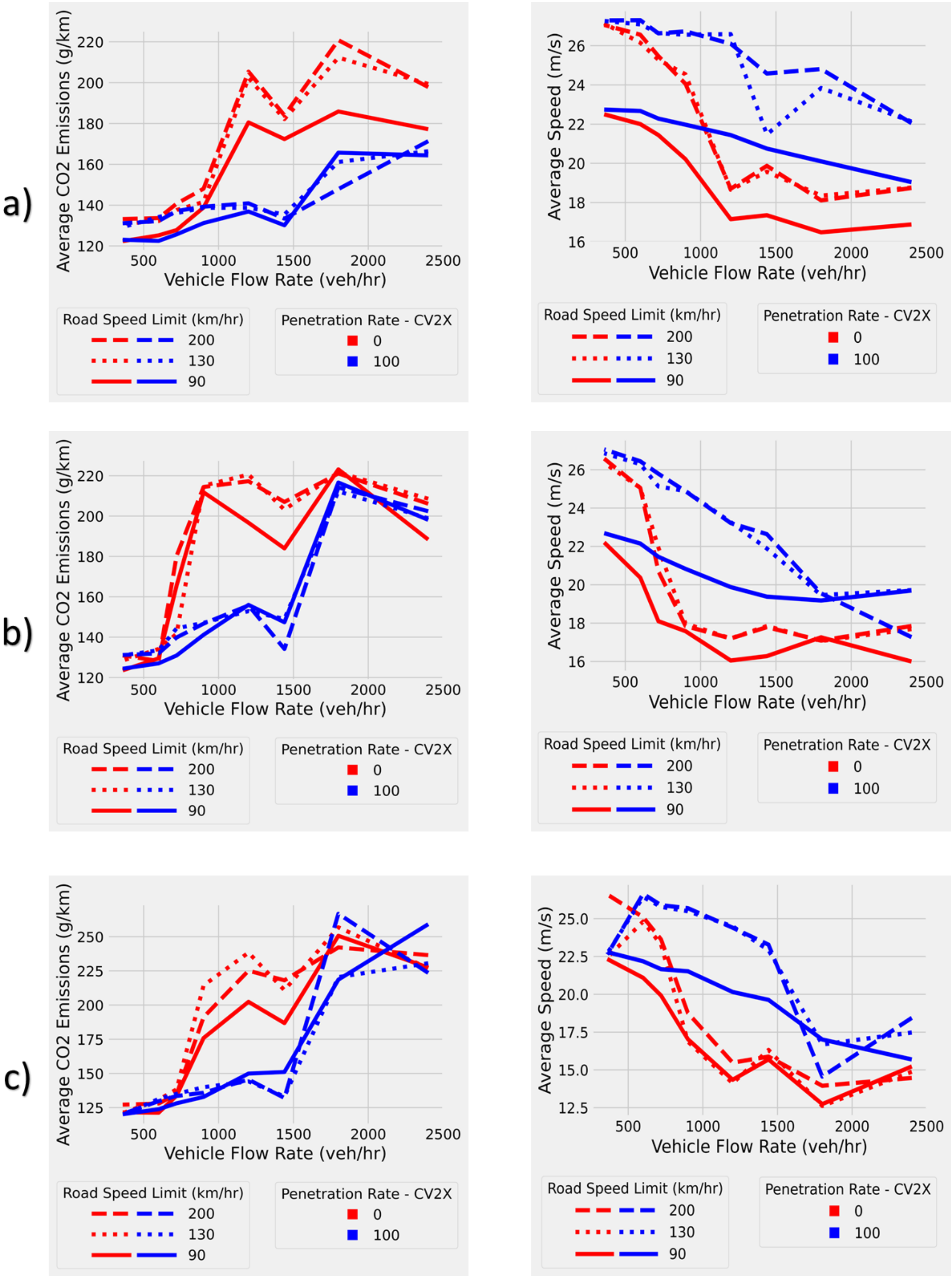


Figure 24: Average CO_2 emissions and speed of each vehicle in different highway types – a) 3 Lane; b) 2 Lane; c) Zipper merge

4.2.3.2 Platooning (PLAT)

In this use case, a 7km long 2-lane highway with no off-/on-ramps is defined using SUMO. For the realistic approach, different platoons are formed with dynamic background traffic. The analysis considers peak hours and off-peak hours traffic for the vehicle flow rates (veh/hr) of 1550 and 420. The simulation is performed twice for each traffic scenario – once without and once with platooning enabled.

For both the traffic scenarios, 75% trucks and 25% passenger vehicles are generated. Based on the distance between the vehicle, platoons between the trucks are formed as they enter the highway. The right most lane is designated to be the lane which supports platooning i.e., vehicles that wish to form a platoon must strictly adhere to this lane. This is an implementation keeping in mind the safety of other vehicles and avoid disruptions in the platoon. i.e., other vehicles breaking up the platoon. However, other vehicles may also drive in this lane i.e., some of the background vehicles (passenger vehicles) can enter the right most lane along with the platoon trucks without interrupting the platoons.

Table 7: Results with total vehicular flowrate of 1550 veh/hr

Run	Conditions	Average CO_2 (g/km)	Average fuel consumption for the total simulation per vehicle (mL)	Average Speed (ms^{-1})
1	Normal	158.55	1.65	24.21
2	With Platooning (Platoon Trucks– 1162 Passenger Vehicles– 388)	155.86 (1.69%)	1.60 (3.03%)	23.74 (1.94%)

As shown in Table 7 and Table 8, for the flow rate of 1550 veh/hr, average CO_2 is reduced by 1.69%, fuel consumption reduction by 3.03% and mean speed of the vehicle is decreased by 1.94% when evaluated with platoons use case.

As compared to the peak hour's simulation, off peak hours traffic with a flow rate of 420 veh/hr shows less benefits in terms of CO_2 reduction and can in fact consume more fuel. In this case, CO_2 is reduced by 0.22% and average speed by 0.7%. Due to the sparse traffic, vehicles accelerate/decelerate more often to join the platoon, and this has a negative effect in the form of increased fuel consumption.

Table 8: Results with total vehicular flowrate of 420 veh/hr

Run	Conditions	Average CO_2 (g/km)	Average fuel consumption for the total simulation per vehicle (mL)	Average Speed (ms^{-1})
1	Normal	157.54	1.64	24.23
2	With Platooning (Platoon Trucks – 315 Passenger Vehicles – 105)	157.19 (0.22%)	1.65 (-0.61%)	24.06 (0.70%)

5 Extrapolation to European level

5.1 EU27 – Overview

For statistical purposes, the EU has developed a geocode standard for referencing the subdivisions of its member countries, i.e., NUTS. Each member country is divided into 3 levels as shown in the Table 9 below. Each member country has a specific name for each NUTS level.

Table 9: Number of regions per NUTS level - EU27 [16]

NUTS Level	Number of Regions – EU27
1	92
2	242
3	1166

For the extrapolation of the data to the EU Level, we would consider the NUTS 2 Level (refer Figure 25) as a reference (before BREXIT). A ML model is developed per Tier from the simulation data collected for the 15 representative scenarios. Different features such as population density, motorization rate, etc. is used to fit this ML model. Then, by extracting the number of different cities (per tier) in each NUTS 2 region, the ML model is used to extrapolate the results to each and every city in the NUTS 2 region, Finally, the results are averaged for the NUTS 2 region as a whole.

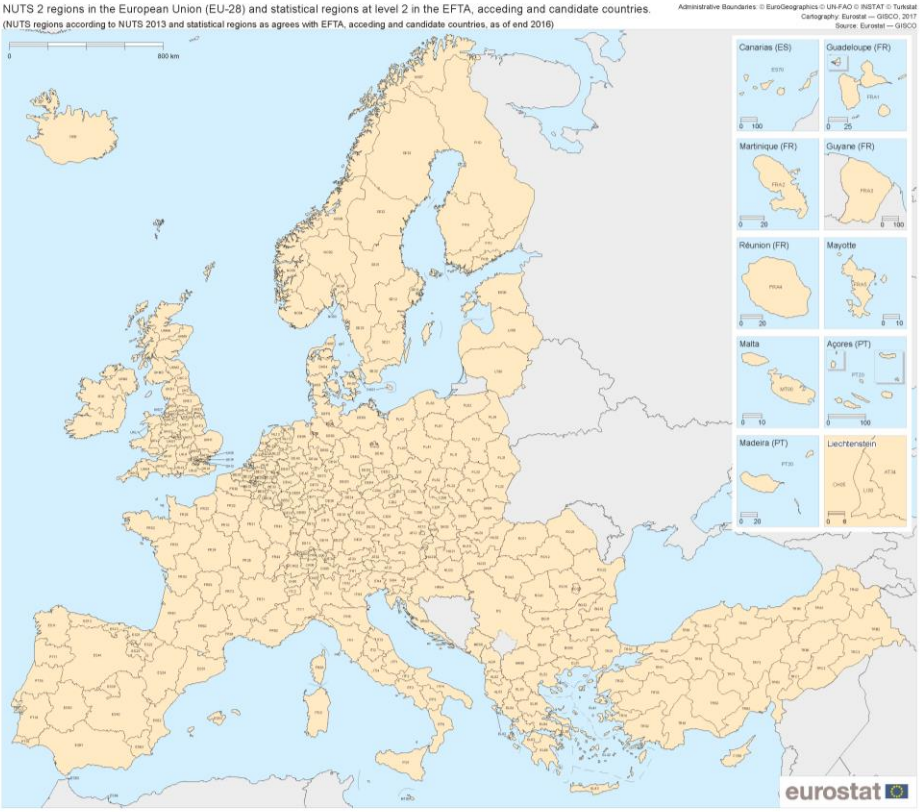


Figure 25: NUTS 2 regions in EU27 [17]

5.2 Prediction model

To understand the benefits of connected mobility at the European level, we use ML models that are fitted on the simulated scenarios. For this purpose, we use RFR model, that is well suited for learning both linear and non-linear trends in the data.

RFR belongs to the family of Ensemble learning where the predictions from multiple ML algorithms are combined to make more accurate predictions. The core of the RFR is a Decision Tree (DT) that splits into sub-nodes based on if-else conditions. A Random Forest (refer Figure 26) is an ensemble of decision trees that are constructed randomly such that

1. Each tree is created from a different sample of rows and at each node, a different sample of features is selected for splitting
2. Each of the trees makes its own individual prediction
3. These predictions are then averaged to produce a single result.

Due to averaging, RFR produces a better prediction than using DTs.

The objective of using RFR is to predict the CO_2 emissions using benchmark (shortest routing) and then the emissions when using COA. The difference between both these predictions would give the gain when using connected mobility.

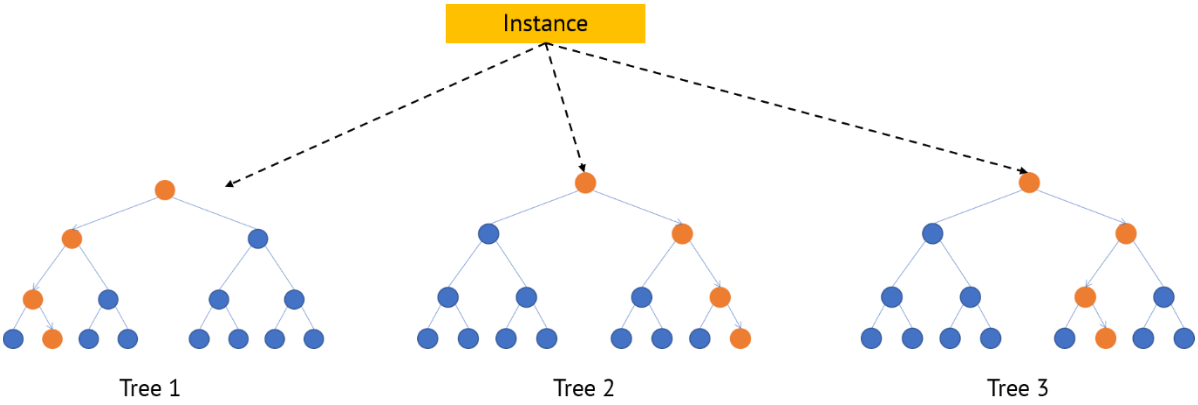


Figure 26: Random Forest Estimator Illustration

5.2.1 Data preparation & Training

The input data (X_train) comes in the form of the table as shown in Table 10. The output variable (y_train) is the CO_2 emissions.

The test data (X_test) set comes in the form of the EU27 NUTS 3 level with different cities in different EU countries. The data of each city (population, Motorization rate etc.) were collected and augmented so as to get it in the same format as X_train. Varying penetration rates of connected vehicles are also considered for each city. To fill the missing data (motorization rate), we used the average from the NUTS 2 level.

Table 10: Input features to RFR

Feature	Description
Population	Population of the selected city (int)
Motorization rate	Vehicles / 1000 people (float)
Time of day	Peak / Off-peak (Binary)
Routing type	Shortest / Dynamic (Binary)
Penetration Rate of Connected Vehicles	0, 20, 50, 80, 100 (int)
Tier	1, 2 or 3 (int)
Use Case	True / False (Boolean)

Finally, the model is trained on X_train and is used for predicting the CO_2 emissions on the X_test.

5.2.2 Model Prediction

The results of the model prediction are summarized here.

5.2.2.1 Prediction with different combinations of COA

These prediction results are aimed to reflect the influence of the COA for different city tiers, with 100% penetration rate of connected vehicles. Figure 27 shows the box plot showing all the predicted emissions (g/km) for all the different tiers, whereas Figure 28 shows the mean predicted emissions for different combinations of COA for every Tier.

With 100% penetration rate it is evident that there can be significant emission reductions irrespective of the city tier. In line with the simulation results, the use of DR reduces the emissions considerable for Tier 2 and Tier 3, and the addition of JO only shows a slight improvement. This is due lesser number of signalized intersections generally found in Tier 2 and Tier 3 cities. However, for Tier 1, the addition of JO shows significant performance gain compared to using only DR. The gain is more pronounced for off-peak scenarios since the vehicle density does not reach the critical point where the road's capacity is saturated.

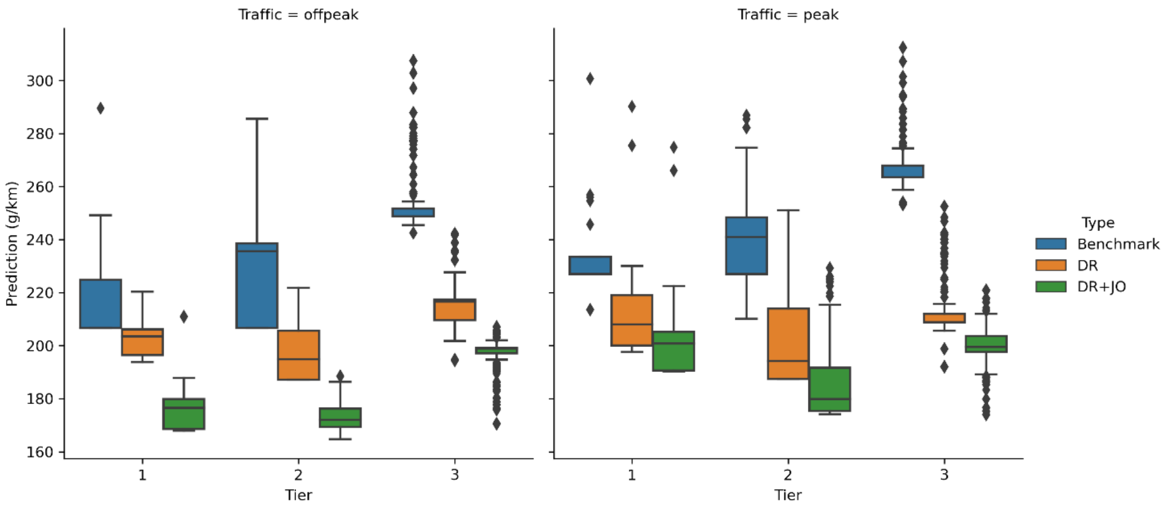


Figure 27: Predictions of RFR for different combinations of COA and traffic hours

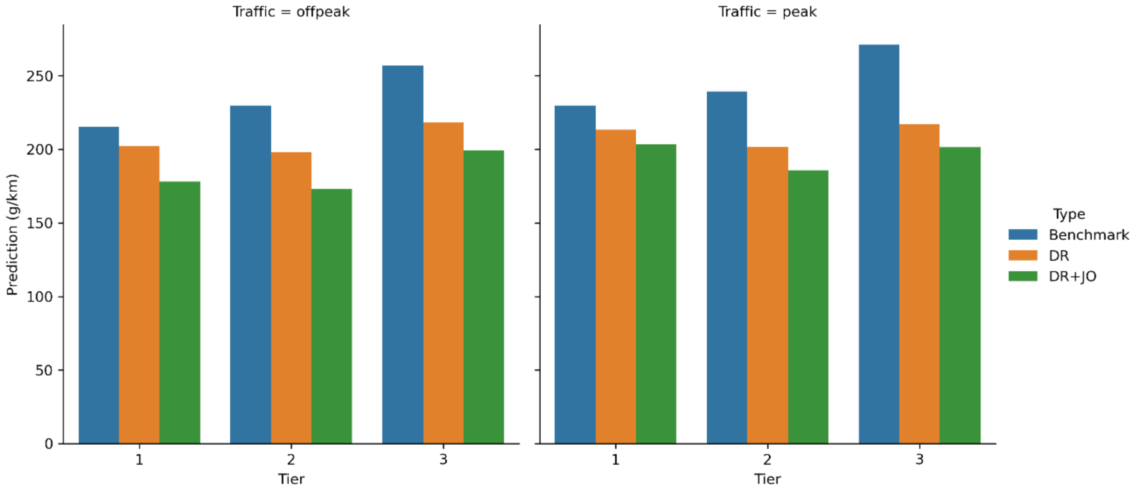


Figure 28: Mean predicted emissions for different schemes and traffic hours

5.2.2.2 Prediction with different Penetration Rates of Connected Vehicles

The effect of emission reduction at the EU27 level by varying the penetration rates of connected vehicles is also predicted by employing a RFR model. The results of the predicted CO_2 emissions for all European cities for the simulation time of 1-hour are presented in Figure 29. The result shows a general trend in CO_2 emission reductions for all tier cities – higher the penetration rate (connectivity), more emission reductions can be achieved, with introduction and addition of connected mobility applications. Moreover, mean predicted emissions are shown in Figure 32.

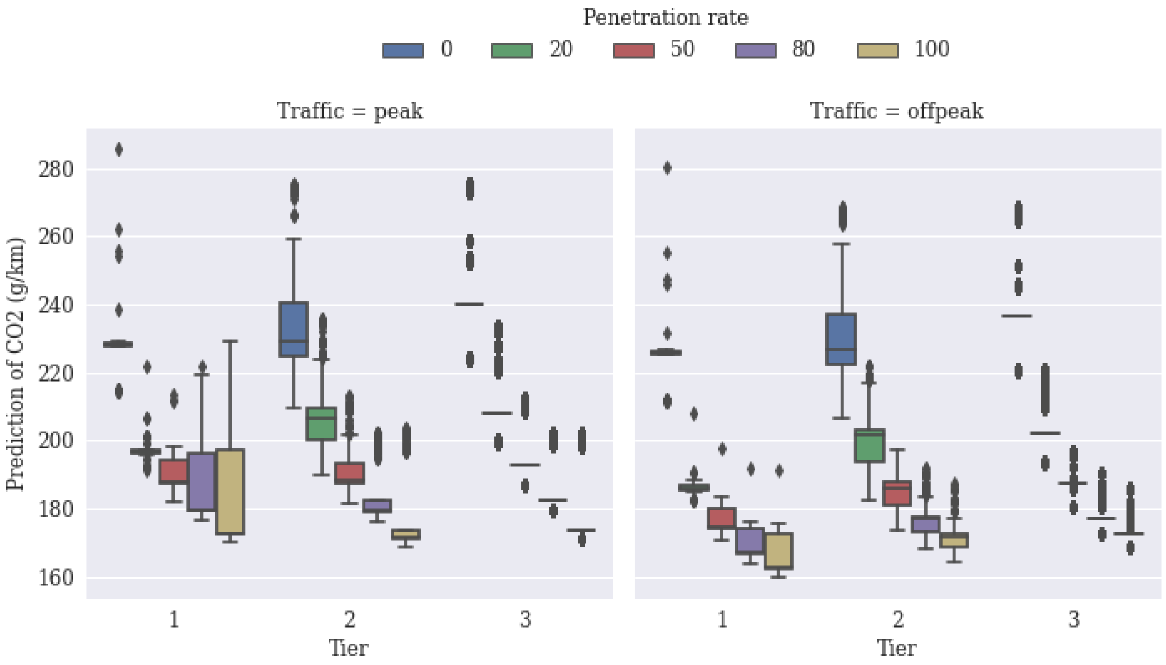


Figure 29: Predictions of RFR for different penetration rates of connected vehicles and traffic hours

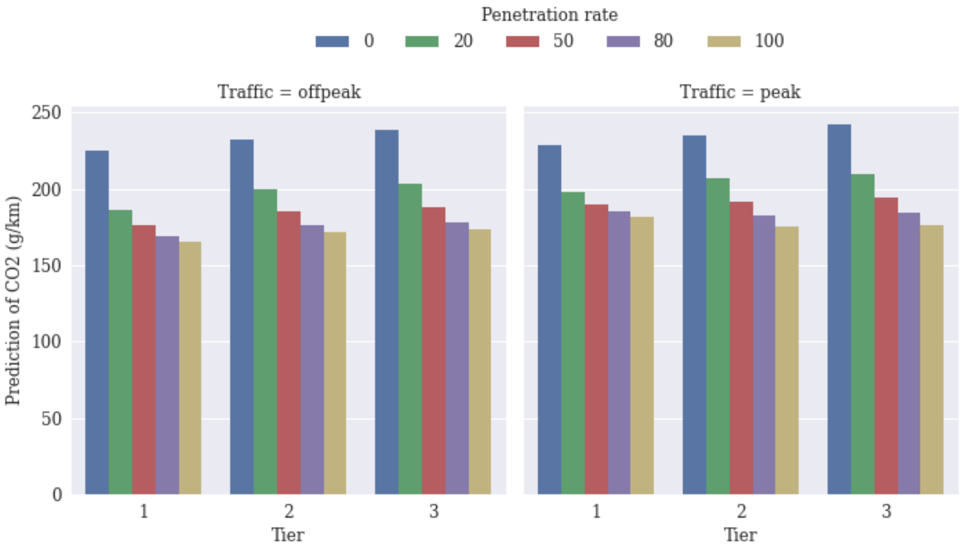


Figure 30: Mean predicted emissions for different penetration rates of connected vehicles in city tiers

5.2.3 Model Feature Importance

A useful characteristic of RFR is its ability to assign feature importance. This can be seen from Figure 31, that shows the importance of each feature on the overall performance. The population and the choice of routing (dynamic / shortest) are the two most important features, followed by Motorization rate and the usage of the connected mobility applications itself. The scenario (off-peak / peak) and the city tier has little effect in the prediction performance.

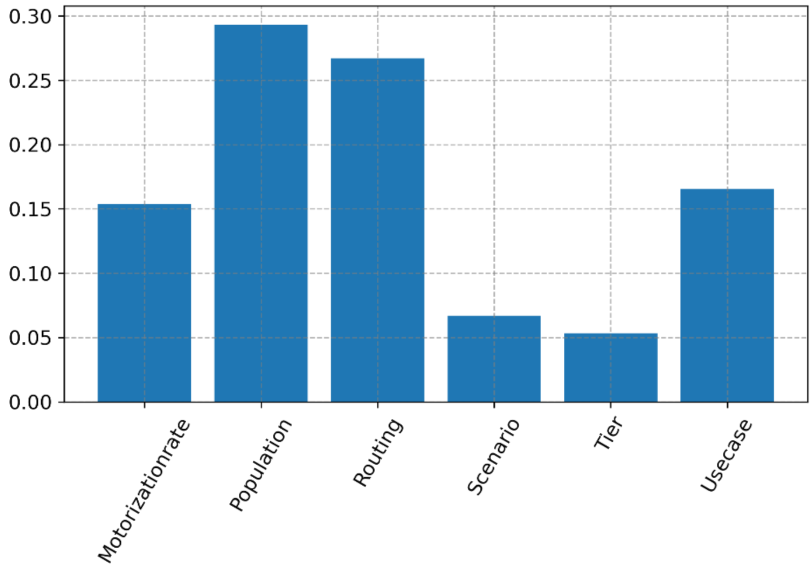


Figure 31: Feature Importance for RFR for different combinations of COA

Routing was used as a feature in the 0 vs 100% case as we had 3 simulation scenarios:

- Shortest routing (0%)
- DR (100% penetration rate)
- DR with JO (100% penetration rate)

Here, we study the effect of both routing and JO applications.

However, in the simulations for penetration rates, all penetration rates are simulated with DR+JO applications. So, this makes the feature 'Routing' redundant, and is now replaced with 'Penetration rate' (refer Figure 32). The prediction performance is heavily reliant on the penetration rate of the connected vehicles, followed by motorization rate and population.

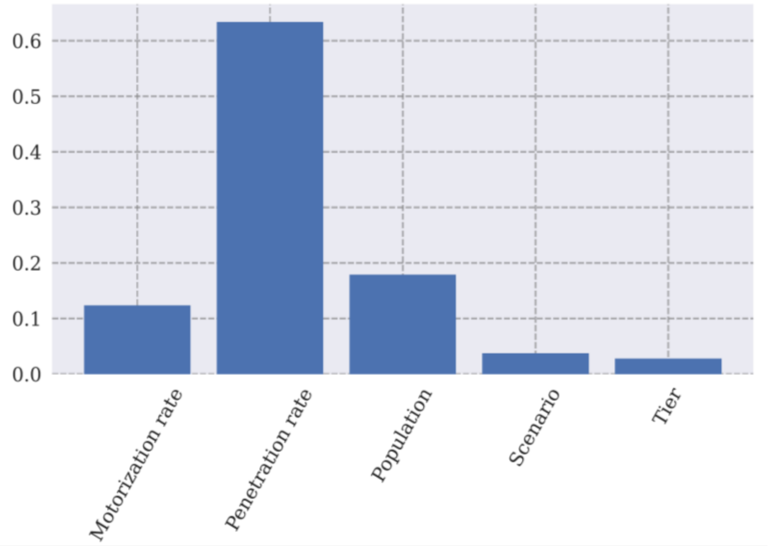


Figure 32: Feature Importance for RFR for different penetration rate of connected vehicles

6 Summary

In this study a simulation-based approach is adopted to demonstrate the potential of connected mobility applications in primarily decreasing the emissions, whilst increasing the overall traffic efficiency. Our novel simulation strategy includes selection of representative scenarios to represent any rural area and any city (medium-/large-sized) in Europe. Realistic vehicular traffic based on user mobility behaviour is generated for the representative scenarios based on information such as motorization rate, population demographics, etc.

This simulation-approach provides us with a unique opportunity to plug-in any connected mobility application and understand the benefits provided by it on an individual basis. Moreover, since the connected mobility applications of the future are envisioned to work in tandem with each other, we developed a hybrid framework where multiple connected mobility applications (DR + JO) are combined as one larger application and therefore demonstrate cumulative benefits. Furthermore, different penetration rates of connected vehicles are introduced into the city network with DR+JO applications enabled. These scenarios of different penetration rates (0%, 20%, 50%, 80% and 100%) allow us to reflect reality at different stages in the future. For the highway, connected mobility applications such as Platooning and SWD are demonstrated individually.

The immediate impact of the introduction of (as low as) 20% connected vehicles in German cities (approximately):

- Tier 1: emissions can be reduced by 22% during peak hours and 24% during off-peak hours.
- Tier 2: emissions can be reduced by 15% during peak hours and 17% during off-peak hours.
- Tier 3: emissions can be reduced by 13% during peak hours and 17% during off-peak hours.

Finally, the results obtained are used to fit an ML model whose objective is to predict the CO_2 emission reductions for any given city in EU27 for both different combinations of COA and penetration rates.

The immediate impact of the introduction of (as low as) 20% connected vehicles in EU27 cities (approximately):

- Tier 1: emissions can be reduced by 13% during peak hours and 18% during off-peak hours.
- Tier 2: emissions can be reduced by 14% during peak hours and 16% during off-peak hours.
- Tier 3: emissions can be reduced by 10% during peak hours and 16% during off-peak hours.

The immediate introduction (at 20% penetration rate) also has significant effects on the travel times of the vehicles. It is estimated that the drivers can save annually 15 hours in Bremen, 5 hours in Cologne, 3 hours in Frankfurt, and 2 hours in Munich annually during the peak hours[6] (approximately).

It is important to understand the scale and equivalency of emission savings (i.e., emission savings in Tier 1 cities compared to other Tier cities) across different Tiers.

- 1% emission reduction during the peak hours in Cologne (Tier 1) is equivalent to 2.5% savings in Mannheim (Tier 2) and 11.62% savings in Schwerin (Tier 3).
- 1% emission reduction during the off-peak hours in Cologne (Tier 1) is equivalent to 1.72% savings in Mannheim (Tier 2) and 7.08% savings in Schwerin (Tier 3).

Connected Mobility applications have great potential to reduce emissions in EU27 countries. However, Tier 1 cities need a variety of city specific connected mobility applications, especially during the peak hours, to microscopically optimize the in the traffic flow in the city, i.e., taking the city layout and local regulations into consideration. Similar considerations must be given for all densely packed cities with high volume of traffic on the city roads.

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[6] Considering a drive time of 1 hour during the peak hours.

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Appendix A – Simulation Results

This section contains the simulation results for all representative scenarios, including the emission reductions and speed gains for each of the scenarios. The following legends/abbreviations are used for all the graphs below:

- Benchmark – Shortest routing
- DR – Dynamic Routing
- JO – Junction Optimization
  - JO includes DTL and STJ

A.1 Tier 1 – Big Cities

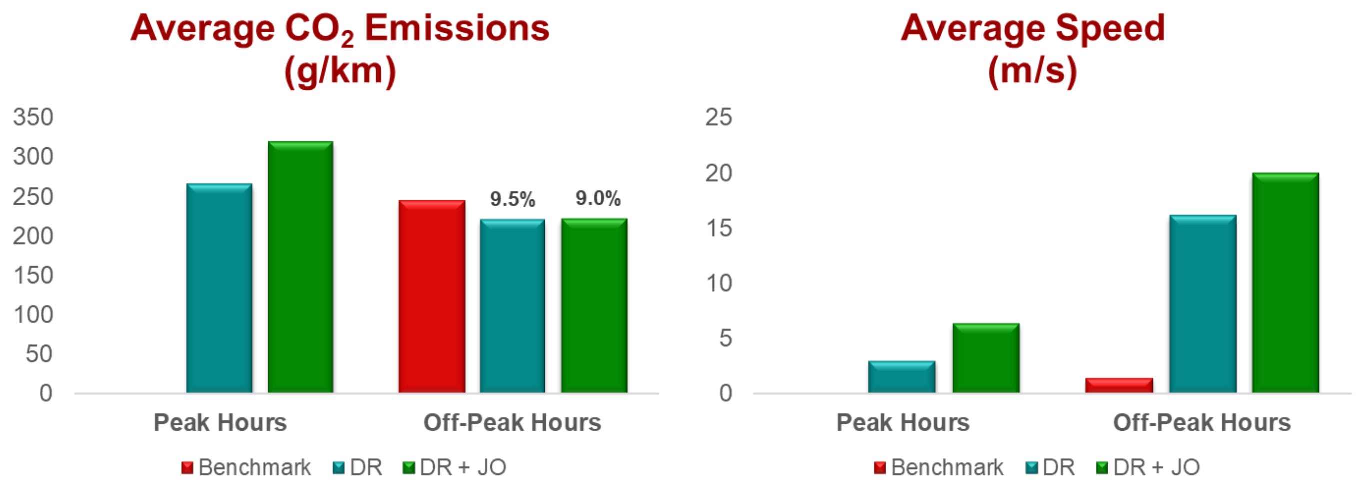

Figure 33: Berlin

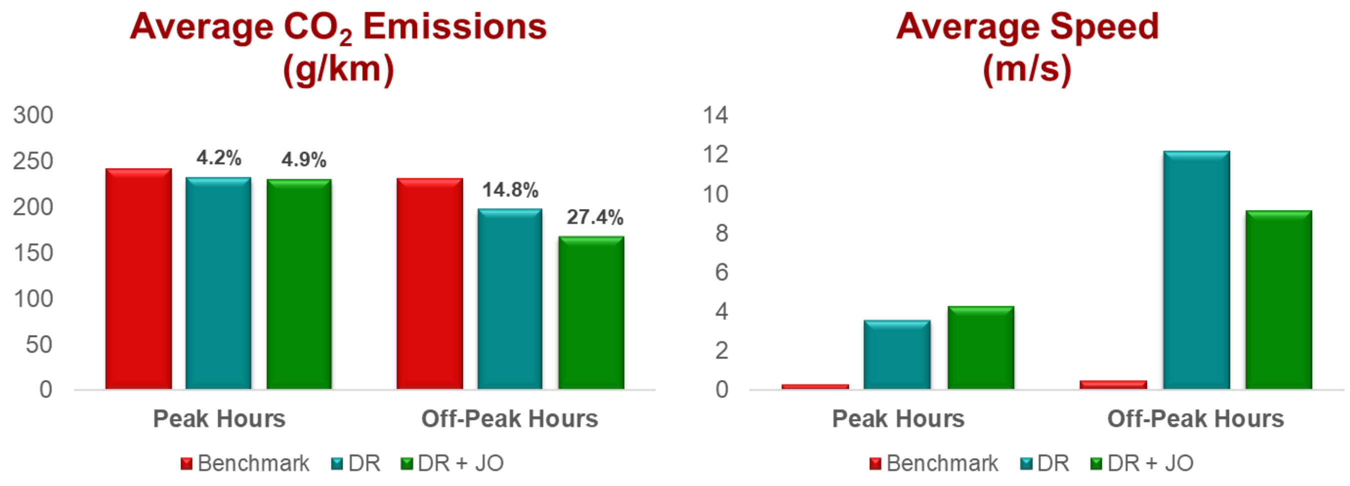

Figure 34: Bremen

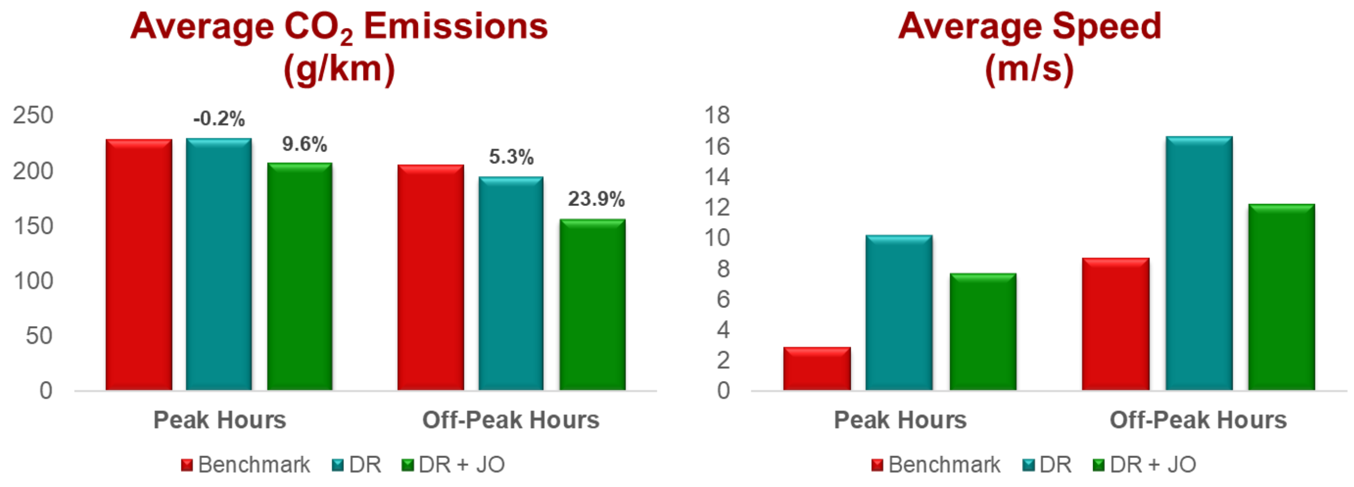

Figure 35: Cologne

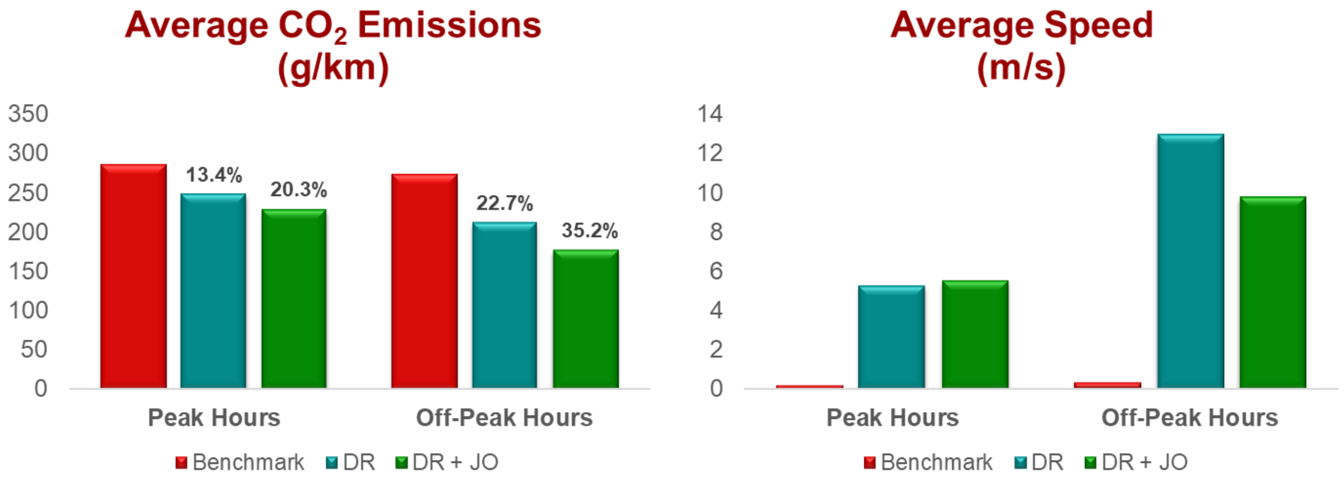

Figure 36: Frankfurt Am Main

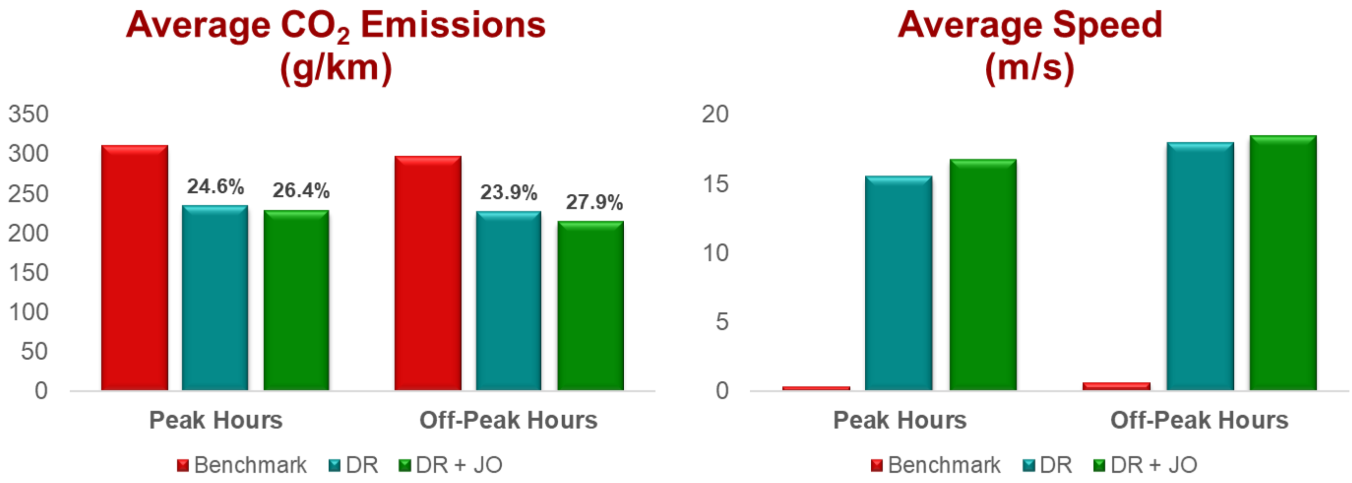

Figure 37: Munich

A.2 Tier 2 – Small Cities

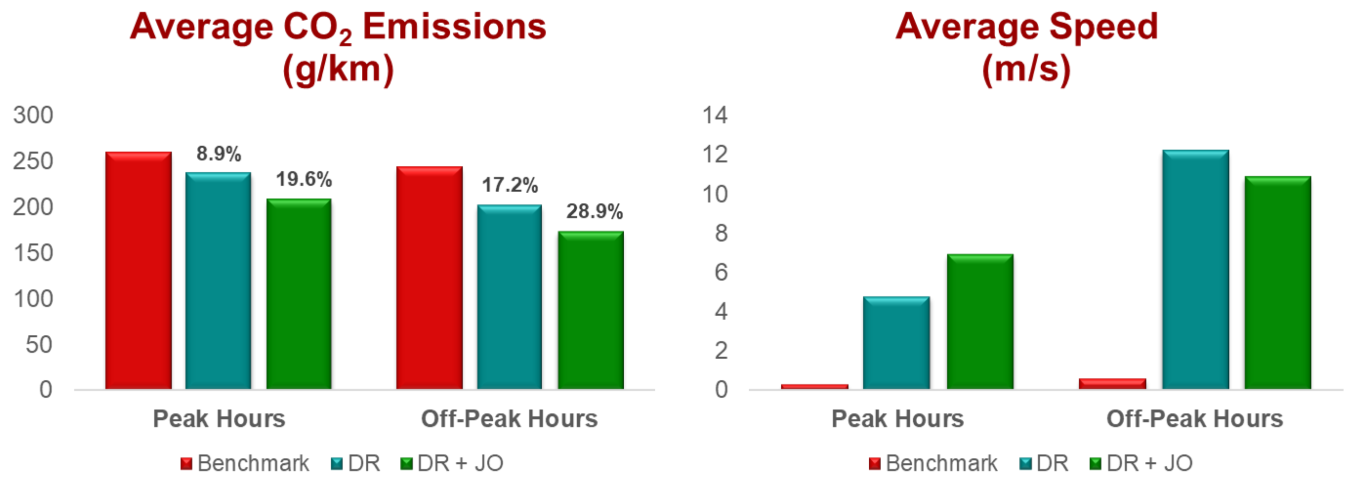

Figure 38: Aachen

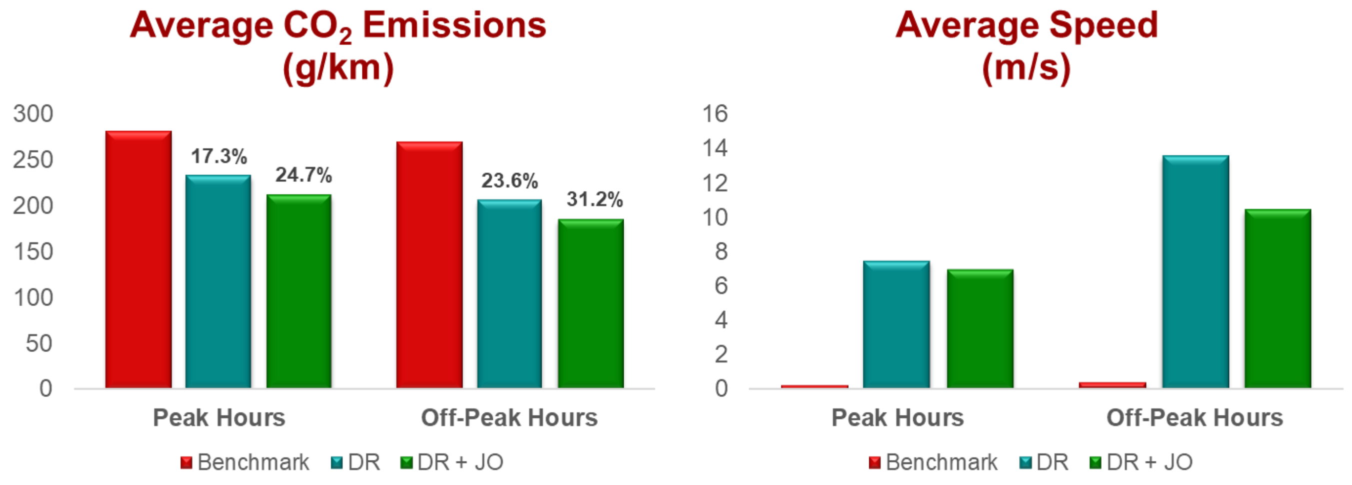

Figure 39: Freiburg im Breisgau

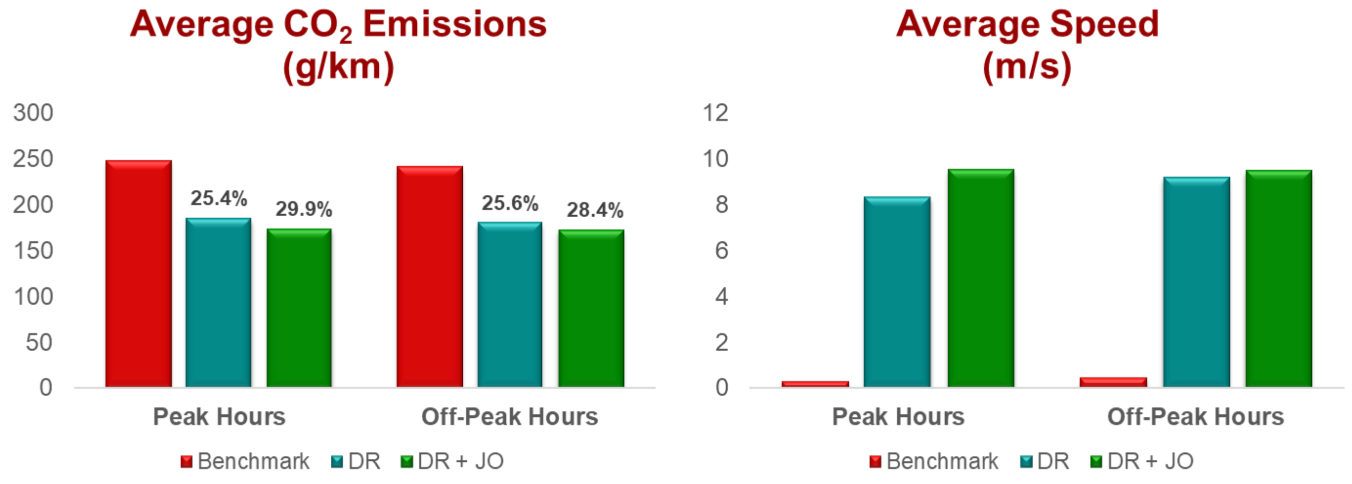

Figure 40: Kaiserslautern

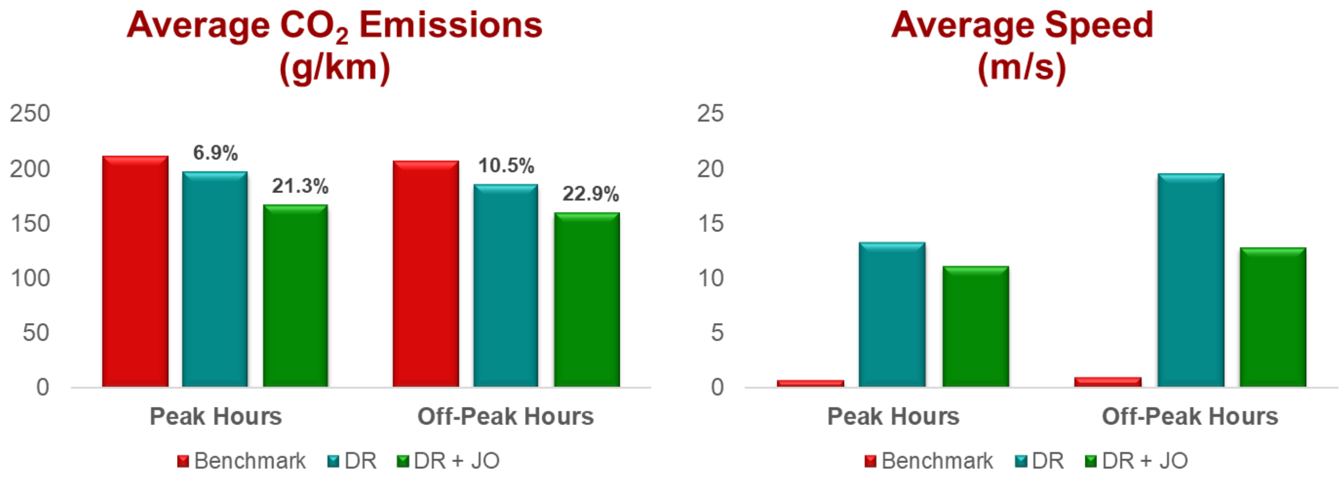

Figure 41: Lübeck

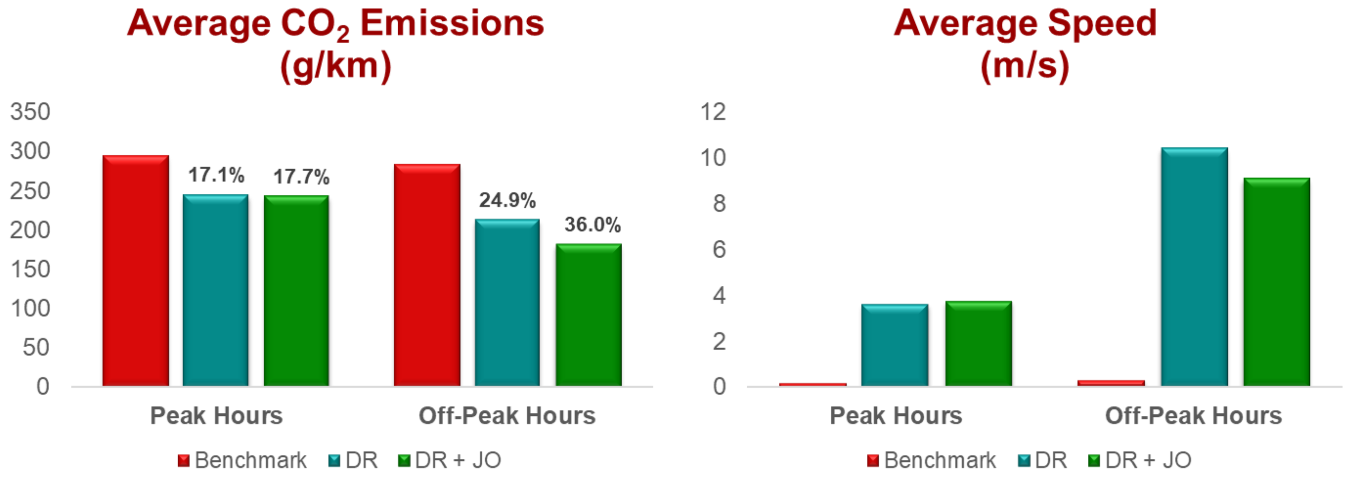

Figure 42: Mannheim

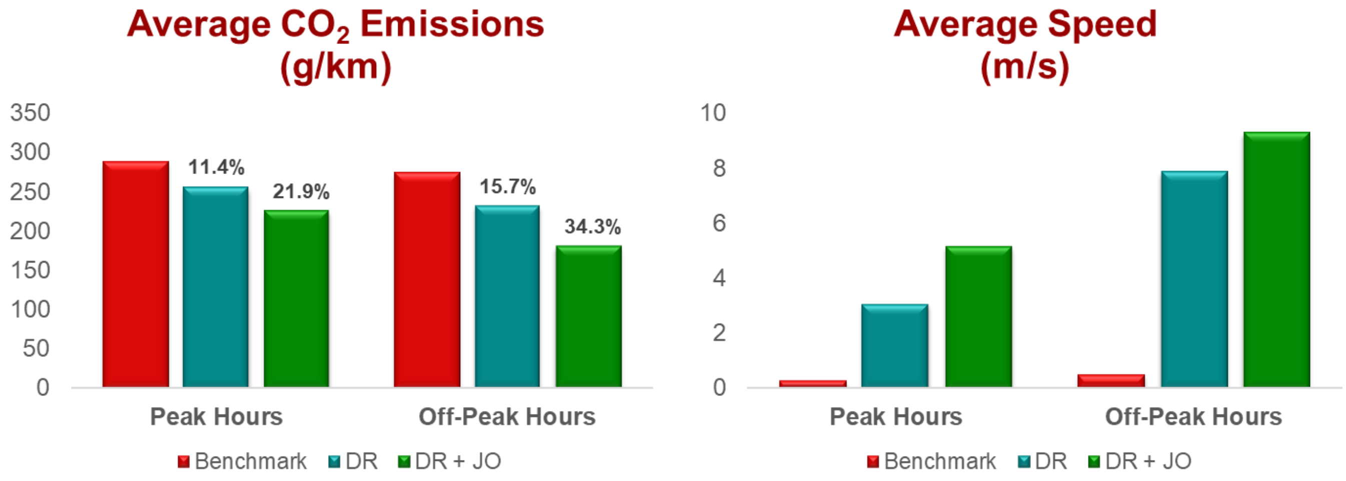

Figure 43: Offenbach am Main

A.3 Tier 3 – Rural Areas

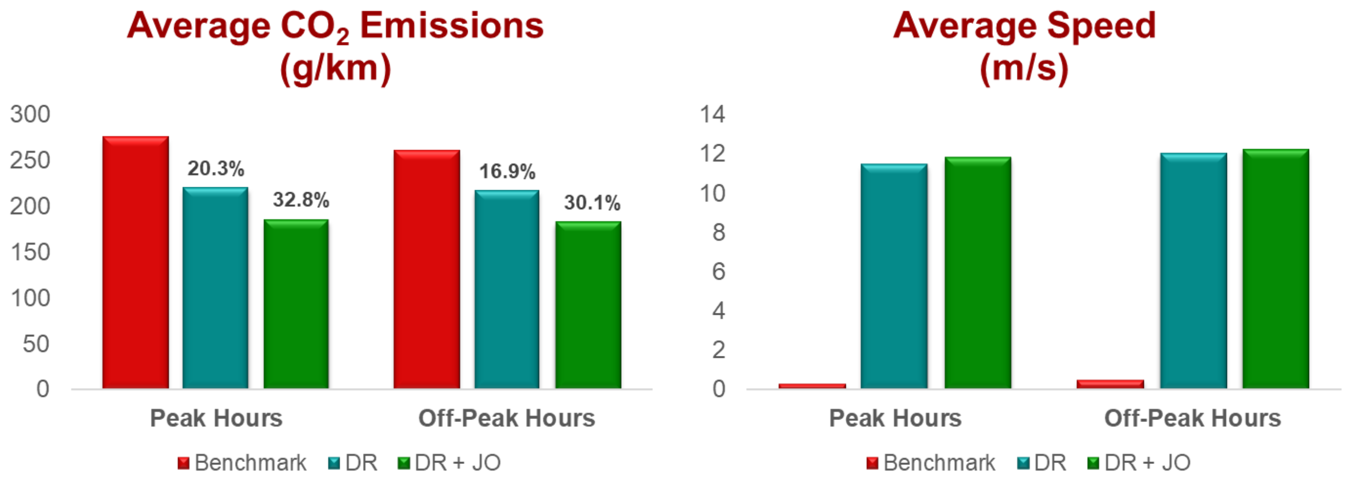

Figure 44: Ansbach

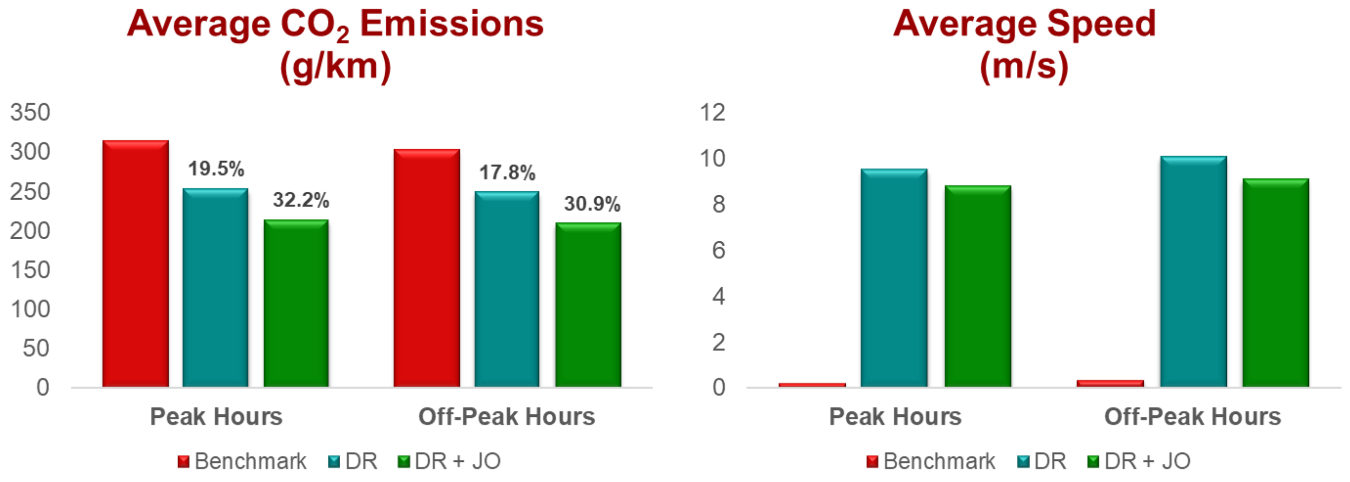

Figure 45: Brühl

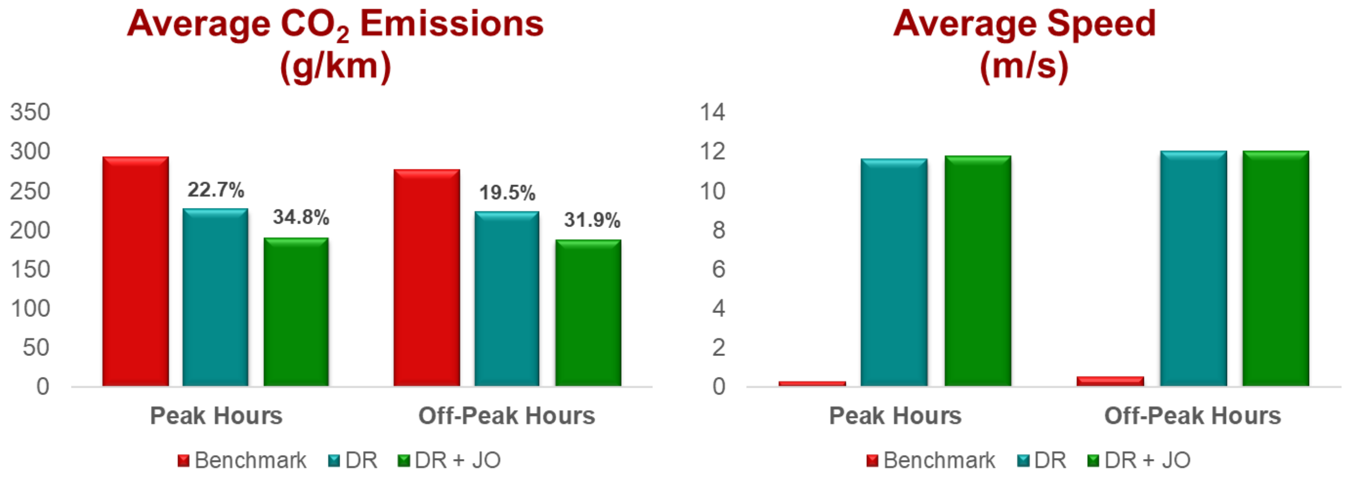

Figure 46: Fulda

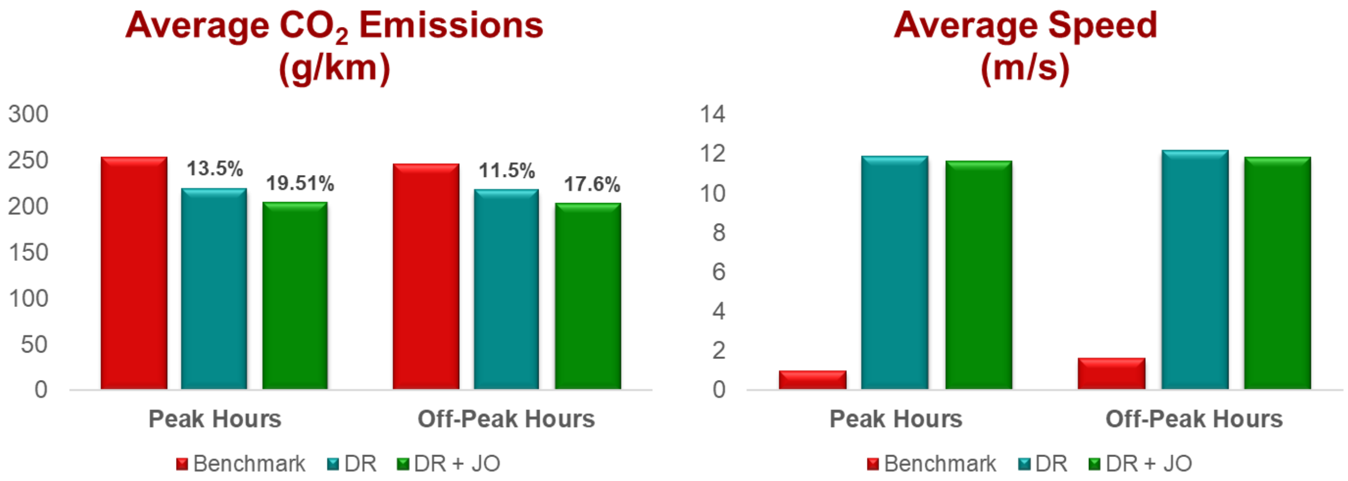

Figure 47: Merzig

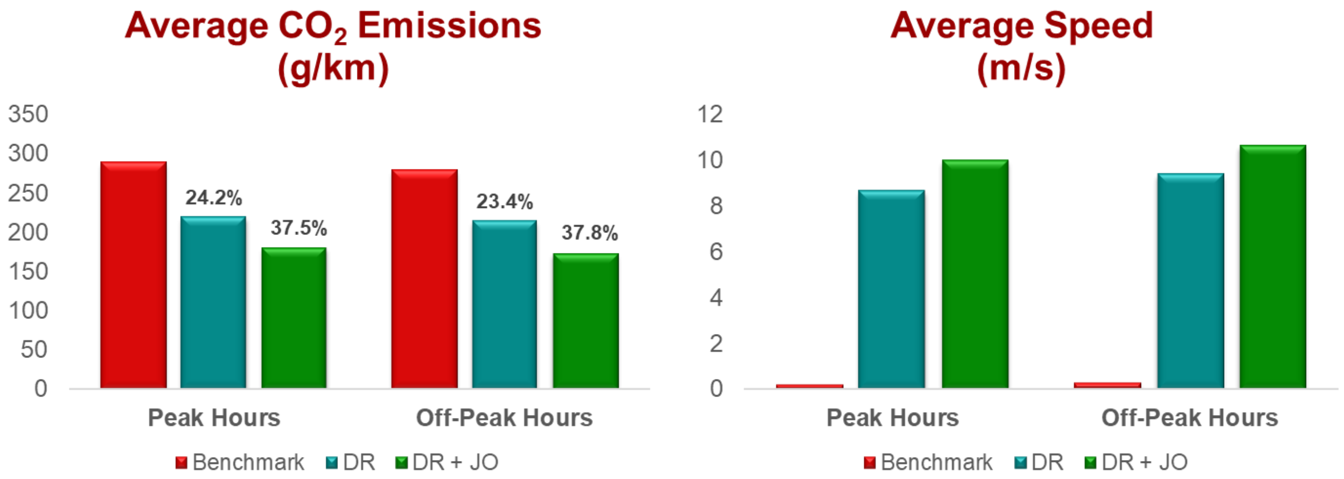

Figure 48: Schwerin

Appendix B – Emission Models

There are various types of emissions produced by vehicles, exhaust emissions (CO2, Carbon monoxide, harmful dust particles, nitrogen oxide), emission particles from tyre and break wear that further leads to air pollution and influences the climate conditions. Exhaust emission from the vehicles is mainly dependent on the following factors:

- Number of vehicles
- Vehicle engine type
- Amount of fuel consumption
- Travel time of the vehicles
- Traffic congestion

To calculate the accurate emission rate, microscopic traffic simulation model is integrated with the emission estimation model. However, traffic simulation model needs inputs parameters from the vehicles that is linked with emission factor. Therefore, two methods can be used to collect the vehicle data, data from the chassis dynamometer or the use vehicle dynamic models to calibrate the vehicle performance measures. This input data can be in the form of vehicle speed, driving pattern, vehicle category, cylinder size, fuel. Although, engine speed and power are considered as main vehicle performance measures as it directly influences the emission rate. The microscopic traffic models can generate various traffic situation and can define the trajectories for the vehicles. The output data from the vehicle dynamic model considering the vehicle trajectories from the traffic model is considered as input to the emission estimation model to obtain the emission measures [18].

For the perfect emission measurement, the emission estimation model should have the accurate emission factor. In order to achieve the faultless emission estimation, the vehicle performance measurement should be updated according to the vehicle type. These emission models are categorized depending upon the parameters affecting the emission factors and its usage and data obtained. Depending on these classifications, the emission estimation models are further used [19].

The emission models (refer Table 11) are validated with real world on road vehicle test emissions and further improved depending on the developments in the vehicle.

Table 11: Comparison of emission models

	COPERT[7]	MOVES[8]	ARTEMIS[9]	HBEFA[10]
Model Category	Average speed	Cyclic variable and modal	Average speed, cyclic variable, and modal	Traffic situations, cyclic variable, and modal
Emissions calculated	Air pollutions, CO_2 emissions, non-regulated pollutants, polycyclic aromatic hydrocarbons, persistent organic pollutants and Particulate matter (PM) emissions	Standard emissions and GHG emissions	Transport emissions	Transport emissions
Vehicle types	Passenger cars, light duty vehicle, heavy duty vehicles, mopeds and motorcycles	Passenger cars, light duty vehicle, heavy duty vehicles	Passenger cars, light duty vehicle, heavy duty vehicles, rail, air and ship transport	Passenger cars, light duty vehicle, heavy duty vehicles, buses, coaches and motorcycle
Input factors	Average speed	Vehicle speed, acceleration, and road gradient	Average speed, vehicle speed, acceleration, and road gradient	Kilometres travelled / driving situation, vehicle speed, acceleration, and road gradient
Validation result	Deviate from the real emission performance	Better emission results due to the real-world traffic pattern	Realistic emission results due to the real driving condition	Realistic emission results due to the real-world traffic pattern
Operated Area	Urban, rural and highways	Geographical scale, national regional inventories, specific locations	National inventories, Street level (local condition)	Traffic Situation

NOTE: By default, SUMO uses the HBEFA model.

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[7] COPERT - Calculation Of Air Pollutant Emissions from Road Transport

[8] MOVES - Motor Vehicle Emission Models

[9] ARTEMIS - Assessment and Reliability of Transport Emission Models and Inventory Systems

[10] HBEFA - Handbook of Emission Factors for road transport