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Emissions vs. Travel Time: Simulative Evaluation of the Environmental Impact of ITS

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***Abstract*—We discuss the need for taking the environmental impact as a primary metric for evaluating the quality of algorithms for Intelligent Transportation Systems (ITS). In many studies, the travel time, or its minimization, has been used to demonstrate the advantages of Inter-Vehicle Communication (IVC) solutions combined with dynamic rerouting. Such evaluations are frequently based on simulation experiments. Recently, much progress has been achieved in this domain by coupling network simulation with road traffic microsimulation. We now investigate the relationship between different metrics used for the evaluation, in particular the environmental impact represented by gas consumption and emissions versus the travel time, highlighting cases where both metrics are conflicting.**

***Index Terms*—VANET, ITS, Traffic Simulation, Network Simulation**

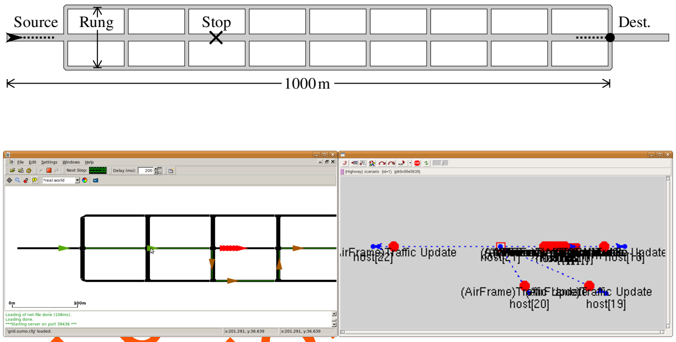

Figure 1. Baseline scenario used in the evaluation: a single trunk road is connected to two slower parallel roads by a number of rungs

I. Introduction

The research domain of vehicular communication is clearly dominated by approaches optimizing the traffic flow of vehicles. Intelligent Transportation Systems (ITS) support this optimization as vehicles can rely on Inter-Vehicle Communication (IVC) in order to inform each other about possible areas of congestion or about recent accidents [1], [2]. According to the collected information, the current route of the vehicle can be evaluated. Intelligent navigation techniques allow to pass problematic zones or streets in order to optimize the route on the fly. It needs to be noted that there are other applications of IVC such as safety solutions, but these are not in the scope of this paper.

In general, there are quite a few different approaches for efficient IVC. First, the type of communication needs to be distinguished: Vehicle-to-Vehicle (V2V) approaches are based on the information exchange between multiple vehicles, whereas Vehicle-to-Infrastructure (V2I) solutions rely on a pre-deployed network infrastructure, e.g. in the form of WiFi/WAVE Roadside Units (RSUs) or 3G networks. Furthermore, hybrid solutions are being developed that try to exploit any available infrastructure but which are not limited to this operation mode. We briefly review typical solutions in Section II.

A major aspect in the communications community is evaluation of the developed ITS approaches. The theoretically best case is to perform real-world experiments. However, due to two reasons, this is impracticable. First, experiments might become enormously expensive if city or even state-wide ITSs should be evaluated.

Additionally, the statistical impact of the many possible parameters cannot easily be determined without full control over at least the majority of parameters and executing an appropriate number of experiments. Therefore, performance evaluation of ITSs is most often relying on simulation experiments. In earlier work, it turned out that two issues are of special interest for such simulations. First, the scalability is an issue of many simulation models and tools. Secondly, the mobility of the vehicles needs to be carefully modeled [3].

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In this paper, we analyze the necessity of using multiple metrics for the simulative performance evaluation of ITS. Besides the classical metrics such as the travel time of vehicles, their average speed, and the variation of the speed, i.e. the "smoothness" of the trip, it is highly necessary to evaluate the environmental impact as a key metric. A baseline scenario which illustrates this aspect nicely is depicted in Figure 1. In this scenario a single trunk road is connected to two slower parallel roads by a number of rungs. We show that, in some cases, all these metrics are leading to similar results, but, in other cases, to quite diverging effects.

After a short review of the related work in Section II, we introduce the *Veins* (Vehicles in Network Simulation) simulation framework that uses OMNeT++ for network simulation and SUMO for road traffic microsimulation in Section III. Section IV illustrates the capabilities of this framework to estimate environmental metrics along with IVC related measures in a holistic way. Section V presents the simulation model and setup used for evaluations. In Section VI, we show that the environmental impact of the ITS might be negative even if the travel time is improved. Thus, the environmental impact is a key metric to be considered in the design of IVC protocols and ITS.

II. Related Work

A number of IVC protocols have been proposed in the last decade. In general, all these approaches can be categorized into three groups.

First, infrastructure based solutions rely on pre-deployed fixed communication entities such as RSUs for WiFi/WAVE based approaches [4] or base stations for 2.5G and 3G networks [5]. The second group is focusing on Vehicular Ad Hoc Networks (VANETs), i.e. ad hoc networking solutions that operate without any pre-installed infrastructure. Geographic routing [6] and periodic beaconing, as used for example in the Self-Organizing Traffic Information System (SOTIS) [7], are the best known solutions. Finally, hybrid forms of infrastructure and ad hoc approaches have been designed.

As mentioned before, simulation is assumed to play a major role in performance evaluation, because real-world experiments are limited in size and variability. IVC protocols can easily be modeled and analyzed using standard network simulators such as ns-2, OMNeT++, JIST/SWANS, or OPNET.

However, the analysis of the scenario demands for a very precise mobility model. Early approaches using the random waypoint or the Manhattan grid models were not able to represent realistic road traffic. Even optimized solutions using real-world traces or such generated by a road traffic microsimulation might lead to wrong results if the IVC does not have any impact on the mobility model [3].

Recent research pointed out a possible solution: bidirectionally coupled network simulation and road traffic microsimulation. For the road traffic microsimulator SUMO, this is facilitated via the newly-introduced TraCI interface which allows simulations to interact with, among others, the network simulators ns-2 [8] and OMNeT++ [9].

Looking at the metrics that can be measured in these simulation environments, first, all the network-related metrics like network load, packet loss, MAC layer collisions, and delays can directly be examined using network simulation tools like ns-2 or OMNeT++.

Furthermore, ITS related metrics like travel time, speed, and acceleration can easily be observed, either directly in road traffic microsimulation tools like Simulation of Urban Mobility (SUMO) or in the coupled network simulation tools.

Much less common is the ability to estimate the simulated traffic's environmental impact, e.g. measuring the gas consumption or the CO_2 emission from vehicles' mass, speed, and acceleration. Previous work on such estimating the environmental impact of road traffic management through simulations [10]–[12] is often based directly or indirectly on the 1985 report by Bowyer, Akcelik and Biggs [13]. In the following, we show how we perform such measurements using more recent findings and evaluate the impact of IVC in this respect.

III. The Veins Framework

Veins[1] is a simulation environment that is based on OMNeT++[2] for event-driven network simulation and SUMO[3] for road traffic microsimulation [9].

Realistic communication patterns of VANET nodes are modeled with the help of OMNeT++, a simulation environment free for academic use, and its *INET Framework* extension, a set of simulation modules released under the GPL. OMNeT++ runs discrete,

[1] http://www7.informatik.uni-erlangen.de/veins/
[2] http://www.omnetpp.org/
[3] http://sumo.sourceforge.net/

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event-based simulations of communicating nodes on a wide variety of platforms and is getting increasingly popular in the field of network simulation.

Scenarios in OMNeT++ are represented by a hierarchy of reusable modules written in C++. Modules' relationships and communication links are stored as Network Description (NED) files and can be modeled graphically. Simulations are either run interactively in a graphical environment or are executed as command-line applications.

The *INET Framework* provides a set of OMNeT++ modules that represent various layers of the Internet protocol suite, e.g. the TCP, UDP, IPv4 and ARP protocols. It also provides modules that allow the modeling of spatial relations of mobile nodes and of IEEE 802.11 transmissions.

Traffic simulation is performed by the microscopic road traffic simulation package SUMO. Developed by German research organizations DLR and ZAIK, this simulator is in widespread use in the research community, which makes it easy to compare results from different network simulations. Availability of its C++ source code under the terms of a GPL license made it possible to integrate into the simulation core all needed extensions.

SUMO performs simulations both running with and without a GUI and can import city maps from a variety of file formats including the freely available *OpenStreetMap* data. It thus allows high-performance simulations of huge networks with roads consisting of multiple lanes, as well as of intra-junction traffic on these roads, either using simple right-of-way rules or traffic lights. Vehicle types are freely configurable with each vehicle following statically assigned routes, dynamically generated routes, or driving according to a configured timetable.

Both simulators have been extended by modules that allow the road traffic simulation to communicate with its counterpart via a TCP/IP connection. The current version of Veins integrates with the newly-created TraCI interface to SUMO.

Using this interface, a connected network simulator is able to send a series of commands to individual vehicles, influencing their speed and routes. During the simulation, at regular intervals, the manager module triggers the execution of one timestep of the road traffic simulation, receives the resulting mobility trace and triggers position updates for all modules it had instantiated. Special mobility modules contained in vehicles' modules process and act upon these updates.

Table I
EMIT FACTORS FOR A CATEGORY 9 VEHICLE

factor		value	unit
v	vehicle speed		$\mathrm{m\,s^{-1}}$
a	vehicle acceleration		$\mathrm{m\,s^{-2}}$
A	rolling resistance	0.1326	$\mathrm{kW\,m^{-1}\,s}$
B	speed-correction to rolling resistance	2.7384×10^{-3}	$\mathrm{kW\,m^{-2}\,s^{2}}$
C	air drag resistance	1.0843×10^{-3}	$\mathrm{kW\,m^{-3}\,s^{3}}$
M	vehicle mass	1.3250×10^{3}	kg
g	gravitational constant	9.81	$\mathrm{m\,s^{-2}}$
ϑ	road grade	0	degrees
α		1.1100	$\mathrm{g\,s^{-1}}$
β		0.0134	$\mathrm{g\,m^{-1}}$
δ		1.9800×10^{-6}	$\mathrm{g\,m^{-3}\,s^{2}}$
ζ		0.2410	$\mathrm{g\,m^{-2}\,s^{2}}$
α'		0.9730	$\mathrm{g\,s^{-1}}$

IV. Estimating the Environmental Impact

In order to estimate the gas consumption and the CO_2 emissions, we integrated the EMIT model [14] of vehicle emissions with our OMNeT++ mobility model. EMIT calculates emissions depending on vehicle speed and acceleration, taking into account vehicle characteristics such as total mass, engine, and installed catalytic converter.

The EMIT model has been calibrated for a wide range of different emissions, viz. CO_2, CO, hydrocarbon (HC), and nitrous oxide (NO_x), and thus calculates for both accelerating and decelerating vehicles very precisely the emissions after passing through a catalytic converter, which is assumed to have reached operating temperature.

We are using this model to estimate the vehicles' CO_2 emissions, which scale close to linearly with fuel rate. For other emissions, EMIT applies additional preconditions and piecewise-linearly fitted correction factors to account for enrichment consitions and chemical effects in the catalytic converter.

First, the tractive power requirement at a vehicle's wheels P_{tract} is calculated using the following polynomial:

$$P_{tract} = Av + Bv^2 + Cv^3 + Mav + Mgv\sin\vartheta$$

Based on the tractive power requirement, the gas consumption can be estimated and, consequently,

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Figure 2. The simulated scenario and its graphical representations as rendered by the SUMO road traffic simulator and the OMNeT++/INET network simulator

tailpipe emissions of CO_2 calculated according to a second polynomial:

$$TP_{CO_2} = \begin{cases} \alpha + \beta v + \delta v^3 + \zeta a v & \text{if } P_{tract} > 0 \\ \alpha' & \text{else} \end{cases}$$

Because road grade is not currently modeled in SUMO, P_{tract} calculations assumed planar roads and, hence, $\vartheta = 0$. Values of α to ζ, A to C, and M were fitted to match what authors termed a *category 9 vehicle*[4], e.g. a '94 Dodge Spirit. The used values (see Table I), result in an error in CO_2 emission calculations of approx. 2.2 %.

V. Simulation Model and Setup

We suggested to use multiple metrics in order to evaluate the performance of ITS approaches. In particular, the CO_2 emission and the travel time represent perfect candidate measures. As described before, the simulation framework Veins supports both and allows to determine the respective quality of the IVC. To analyze the different behavior of both metrics, we prepared an easy to understand (but still quite realistic) scenario as shown in Figure 2.

[4]http://hdl.handle.net/1721.1/1675

A single-lane trunk road with a speed limit of approx. 28 m s^{-1} (100 km/h, 62 mph) is supported by two parallel streets with speed limits of 22 m s^{-1}, all connected in the form of a ladder.

We introduced an artificial incident, a vehicle stopping, on the trunk road and disallowed passing of vehicles. IVC takes place between the cars in order to inform each other about the blocked trunk road. If such a message successfully reaches a following car, it recalculates its path using one of the parallel streets if possible. Figure 2 depicts the scenario as well as its graphical representation in SUMO and OMNeT++.

We then modified the length of the stop in order to evaluate the appropriateness of the route recalculation with regard to the two selected metrics. Furthermore, we changed the length of the detour by modifying the rung length. The used communication protocol employed a simple beaconing approach. Without loss of generality, this protocol serves well to demonstrate the behavior of the selected two metrics. Other protocols will definitely perform better in more sparse or more dense scenarios. However, our main intention was to illustrate the differences in the behavior of the

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Table II
SIMULATION PARAMETERS

Parameter	Value
# stops	1, 3
total stop length	30..300 s
time between stops	14 s
# vehicles	101
vehicle insertion rate	$0.2\,s^{-1}$
rung length	100..1000 m
# rungs	10
road length	1000 m
speed limit, trunk road	$27.78\,m\,s^{-1}$
speed limit, rungs & detours	$22.22\,m\,s^{-1}$
mobility model	Krauss
max. speed	$70\,m\,s^{-1}$
max. acceleration	$3.00\,m\,s^{-2}$
max. deceleration	$9.81\,m\,s^{-2}$
assumed length	5 m
driver imperfection σ	0.5
channel bitrate	$11\,Mbit\,s^{-1}$
approx. transmission radius	180 m

CO_2 emission and travel time when changing the stop times and costs for longer detours. The most important simulation parameters are summarized in Table II. For each configuration, we executed five simulations runs. Each run was terminated after the last of the 101 cars left the system. Each vehicle entering the system started with 100 % of its expected traveling speed. Thus, no initial transient phase needs to be considered.

VI. RESULTS

Before we discuss the influence of the IVC on the selected key metrics, the travel time and the environmental impact, we briefly analyze the impact of the route choice on speed and acceleration of the cars. This behavior is obviously scenario dependent and directly impacts both metrics as both speed and acceleration are directly incorporated into the calculations of the EMIT model.

Figure 3 depicts the speed and acceleration of three selected cars, plotted for different times after entering the simulation. The lead vehicle stops after $\Delta t = 32\,s$. Thus, it decelerates abruptly to $v = 0\,km/s$. The following car is not able to receive an IVC message early enough to change its route and also has to stop, decelerating with about $a = -9\,m/s^2$. The third vehicle shown in the figure is informed of the incident before passing the last trunk road exit. Thus, it is able to change its route to take a detour. It can be seen to start decelerating moderately, at about $a = \pm 5\,m/s^2$,

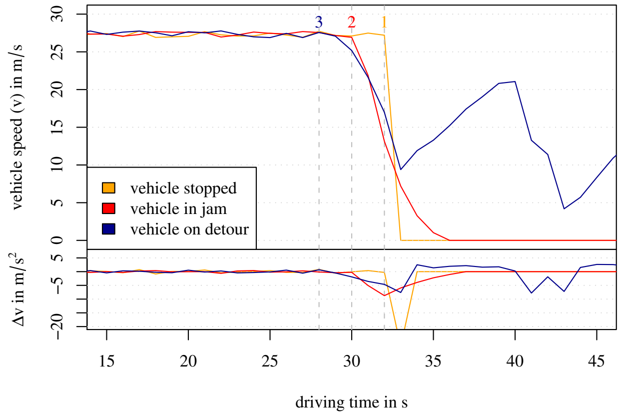

Figure 3. Impact of route choice on vehicle speed and acceleration profile

to change roads approx. 4 s before it would have reached the incident. Later it again decelerates, nearly to a stop, before entering the parallel road. It can be expected that the travel time will be increased due to the detour and, correspondingly, the CO_2 emissions will be increased as well. Following these observations, we executed a number of experiments using the configuration listed in Table II. The metrics discussed in the following are shown as boxplots. For each data set, a box is drawn from the first quartile to the third quartile, and the median is marked with a thick line. Additional whiskers extend from the edges of the box towards the minimum and maximum of the data set. Data points outside the range of box and whiskers are considered outliers and drawn separately.

In a first set of experiments, we evaluated the influence of the IVC in case of a single accident. We varied both the stop time and the length of the possible detours. Figure 4 depicts the measurement results.

As was to be expected, with IVC disabled rung lengths had almost no influence on metrics, as had stop times when IVC was enabled. Thus, a similar trend becomes visible in all the subfigures. For increasing stop times and/or decreasing rung lengths, the use of IVC improves the selected metric. If the stop is too short, the use of a detour will not be helpful. Thus, the travel time and the CO_2 emissions are only optimized by IVC for a certain minimum stop time (i.e., accident time) as shown in Figures 4a and 4c. Interestingly, the break even point is different for both metrics. The travel time can quickly be optimized even for comparably short stop times. In contrast, the CO_2 emissions are suboptimal at this point. This effect can be explained by the additional gas consumption and

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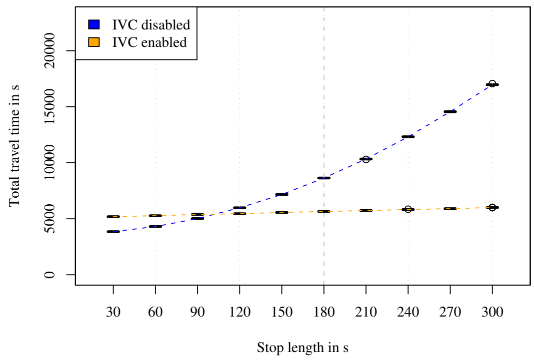
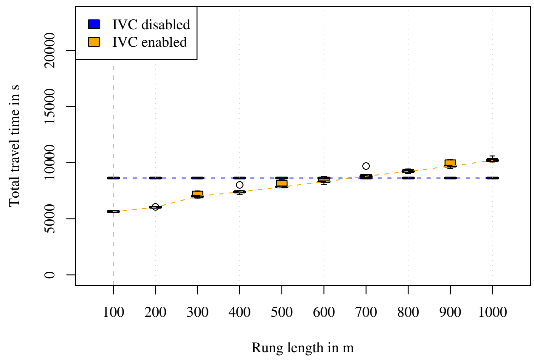
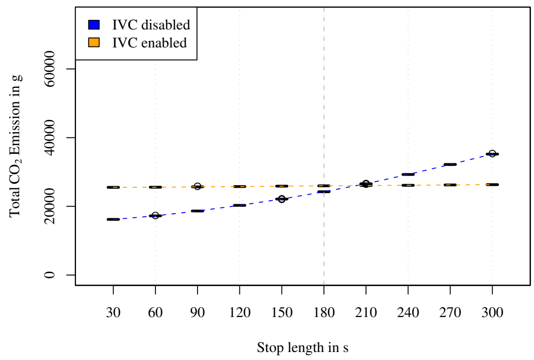


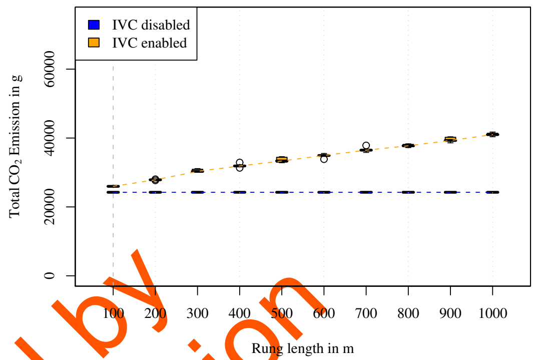
(a) . . . influence on travel time



(b) . . . influence on travel time



(c) . . . influence on emissions



(d) . . . influence on emissions

Figure 4. Influence of stop time and rung length on travel time and CO_2 emissions; lead vehicle stops once

CO_2 emissions due to the additional accelerations. Detours only optimize the emissions for much longer stop times. Obviously, the CO_2 emissions could be lower if cars would always turn the engine off for each stop. However, this is quite unrealistic for short stops. For increasing rung lengths (Figures 4b and 4d), the overhead is increased with longer detours. Thus, both the travel time and the CO_2 emissions are growing with longer detours.

In a final experiment, we analyzed the behavior of both metrics in case of repeated accidents. In this scenario, the same trends can be observed. As can be seen from Figures 5a and 5c, the advantages of IVC become noticeable only for quite long stop times. Similarly, the rung length, i.e. the overhead caused by detours, quickly influences the travel time as well as the CO_2 emissions (Figures 5b and 5d). Multiple subsequent stops also contribute to the variation of the measures.

VII. Conclusion

We discussed the need for considering the environmental impact of Intelligent Transportation Systems together with the typical "convenience" metric, the travel time, as well as other more network related metrics (which are obviously necessary for analyzing new IVC protocols). Our free simulation framework *Veins* is able to measure and to analyze several metrics related to the environmental impact including the gas consumption and the CO_2 emissions along with more traditional ITS metrics.

In this paper, we highlighted cases where these classes of metrics are conflicting. If only the travel time were to be used in the optimization process of ITSs, emission metrics are often suboptimal. Thus, much effort is needed with regard to intelligent navigation to optimize the traffic flows in case of multiple obstacles.

In future work, the used model will also be extended to encompass different vehicle classes. Additionally, the model can be extended to model more intelligent actions from the driver (or modern cars) in case of stops, e.g. turning the engine off during longer stops.

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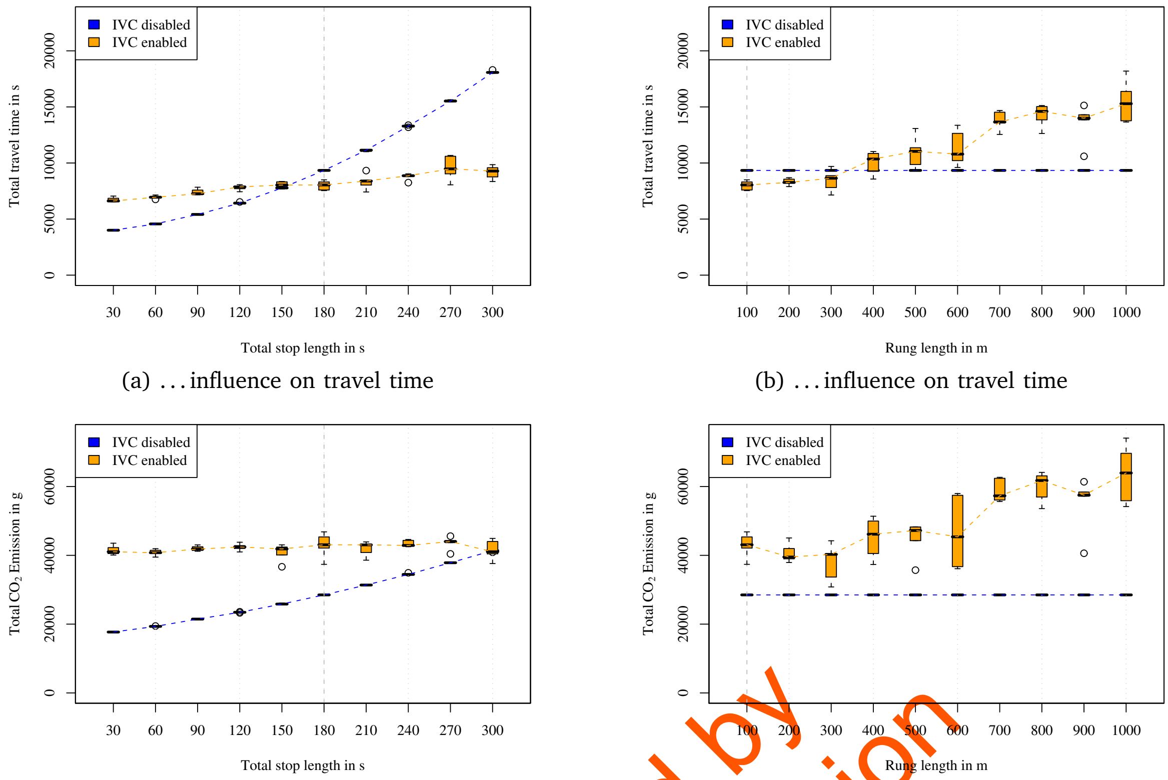

(a) . . . influence on travel time (b) . . . influence on travel time

(c) . . . influence on emissions (d) . . . influence on emissions

Figure 5. Influence of stop time and rung length on travel time and CO_2 emissions; multiple stops

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