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The Impact of Traffic-Light-to-Vehicle Communication on Fuel Consumption and Emissions

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***Abstract*—"Smart" vehicles of the future are envisioned to aid their drivers in reducing fuel consumption and emissions by wirelessly receiving phase-shifting information of the traffic lights in their vicinity and computing an optimized speed in order to avoid braking and acceleration maneuvers.**
Previous studies have demonstrated the potential environmental benefit in small-scale simulation scenarios. To assess the overall benefit, large-scale simulations are required. In order to ensure computational feasibility, the applied simulation models need to be simplified as far as possible without sacrificing credibility.
Therefore this work presents the results of a sensitivity analysis and identifies gear choice and the distance from the traffic light at which vehicles are informed as key influencing factors. Our results indicate that a suboptimal gear choice can void the benefits of the speed adaptation. Furthermore, we present first results of a scale-up simulation using a real-world inner-city road network and discuss the range in which we expect the saving in fuel consumption to be in reality.

I. Introduction

As communication technology continues to become more and more affordable, an increasing number of everyday objects participates in today's interconnected world. In the future, the interaction of physical objects is envisioned to facilitate new services that improve our everyday lives. One aspect of this "Internet of Things" is the wireless communication from and to vehicles, aiming at increasing comfort and safety of the driving experience as well as at reducing fuel consumption and emissions to mitigate the environmental impact.

An instance of such an application is *traffic-light-to-vehicle communication (TLVC)*. Thereby the traffic light periodically broadcasts its scheduling information over the wireless medium to the vehicles in its vicinity. From this information, vehicles compute their required speed in order to hit a green light and offer this information to their drivers who can in turn adapt their speed accordingly. Similar to a "green wave", the idea is to avoid stopping at red lights, thereby saving fuel.

Recently, TLVC has received an increasing amount of attention due to the fact that it promises beneficial effects for individual drivers even at low penetration rates of the new communication technology. Thus, the application might motivate drivers to buy dedicated communication units and hence might become a door opener for other vehicular communication applications, e.g. cooperative intersection collision warnings, that require very high equipment rates of vehicles.

While field tests so far have focused on a technical proof of concept, simulation is still the means of choice for an estimation of the achievable large-scale benefits of TLVC, at least until large-scale field tests are available.

To the best of our knowledge, existing simulation studies have focused on road segments with one or more traffic lights and used statistical projections to estimate the overall benefit. However, it is not clear whether, in a system as complex as vehicular traffic, unknown effects might reduce the projected benefits in reality. Therefore, large-scale simulation studies are required to evaluate the overall benefit of TLVC.

Large-scale simulations in general require a trade-off between the level of simulation detail and computational complexity. Reducing complexity without sacrificing the credibility of simulation results is a challenging task, especially in the case of TLVC due to its large and complex parameter space, ranging from traffic-light scheduling to engine characteristics, radio-wave propagation and driver behavior.

For this reason, the objective of this work is to provide a systematic exploration of the parameter space. That is, to identify key influencing factors on fuel consumption and emissions and the degree of their influence. Furthermore, we present first results of a scale-up simulation using a real-world inner-city road network.

In the following, we first review the related work. Then, we discuss the simulation components required to evaluate the environmental impact of TLVC. Section IV analyzes the impact of two key influencing factors on fuel consumption and emissions we identified: gear choice and information distance. Finally, we present first scale-up simulation results and conclude the paper.

II. Related Work

As indicated above, the majority of previous studies on the environmental impact of TLVC has been based on simulations. Small-scale real-world implementations have demonstrated the

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technical feasibility of the system [1]–[3], but, to the best of our knowledge so far there are no real-world measurements regarding fuel consumption and emissions publicly available. In the following, we review existing simulation studies on the environmental impact of TLVC with respect to different aspects of our work.

1) Simulation framework: To evaluate the impact of TLVC, at least two simulation components are required: vehicular traffic and communication. Some studies rely on self-developed tools [4], others couple existing dedicated simulators [5]. However, due to the high level of detail of existing dedicated simulation tools and the communication overhead between the different simulators, the latter approach does not scale well for a large amount of vehicles. Therefore, we take a third approach by integrating a communication module into a microscopic traffic simulation tool. Emissions and fuel consumptions are evaluated in post processing (cf. Section III).

2) Emission model: The majority of previous studies included environmental impact assessments. Most of them relied on mathematical formulae, calibrated for average personal cars, to compute fuel consumption and emissions [5]–[9]. Others used more detailed emission models [4]. However, none of these studies addressed aspects like cold/warm start, gear shifting and different vehicle and emission types, which we cover in our evaluation. Especially the aspect of gear choice is of relevance since advice on efficient gear shifting can reduce fuel consumption by up to 20% [10].

3) Communication: Like the aforementioned real-world implementations, [5] and [9] chose IEEE 802.11 as the underlying communication technology. Other studies assumed a sensor network to distribute the information [7] or indirectly computed speed advice from historic cell phone data [11].

These examples illustrate that, in order to assess the environmental impact of TLVC, it is not so important *how* vehicles receive the traffic-light information as long as they *do* receive it. Therefore, [4] and [6] abstract from the communication aspect and assume vehicles to be informed about the traffic light scheduling at a certain distance from the traffic light by an unspecified technology.

This point of view brings up two questions. First, is the communication system capable of disseminating the required information? This question is answered by the authors of [5], who modeled the entire protocol stack from physical to transportation layer in the network simulator ns-2 and found communication in the considered context to be "uncritical" in terms of bandwidth demand and robustness.

Second, at which distance from the traffic light do drivers have to be informed and does it make a difference if some vehicles get the information later because of transmission errors? Our work takes up the latter question by a sensitivity analysis of the information distance.

4) Speed adaption: The modeling of how drivers approach the traffic light when TLVC is available is a key issue in the assessment of the considered application. Corresponding algorithms are described in [4]–[7]. In our study, the focus is not on newly optimizing traffic-light approaching behavior, but on an in-depth analysis of the environmental impact. Therefore, we implement driver behavior similar to [6].

5) Scale-up: To the best of our knowledge, previous simulation studies have focused on isolated road segments with one or more traffic lights [4]–[9]. [6] statistically projected results from sample crossings to city dimensions. However, this mathematical approach does not answer the question if in an entire network of streets and traffic lights, the environmental effects of conflicting streams of vehicles might diminish the overall benefit. In a first step towards large-scale simulations to tackle this problem, we evaluated TLVC in a real-world road network.

6) Fuel-saving potential: [4] finds fuel consumption to be lowered by up to 47% for a traffic-light scheduling based cruise control algorithm when evaluating 9 traffic lights in a row and having vehicles consider the phases of the subsequent traffic lights. [6] states a maximum of 35% and an average of 14% for a single road and traffic light. Providing hard figures on how much fuel/emissions can be saved is difficult, since simulation results depend highly on the simulation setup, models and implementations used as well as on the way of evaluation. For example, when analyzing a single road and traffic light, the ratio of fuel saved depends on the length on the evaluated road segment. Thus, it is not the objective of this paper to provide hard figures, but to identify key influencing factors and to quantify the degree of their influence. The paper will conclude by discussing a range in which we expect the fuel saving potential to be in reality.

III. Simulation Components

To evaluate the environmental impact of TLVC by means of simulation, at least the following four components have to be modeled: Vehicular traffic, communication from traffic lights to vehicles, driver behavior (speed adaption) and finally fuel consumption and emissions.

Since especially the accuracy of the latter is of major importance when evaluating the environmental impact, we chose a highly detailed emission model derived from real-world measurements whose accuracy fits the demands of vehicle development. It calculates fuel consumption and emissions from vehicles' velocities, positions and other parameters in a resolution of 1 Hz. We generate these *driving cycles* using a microscopic traffic simulator, in which we integrated the speed-adaptation algorithm as well as a communication model. In the following, we describe the applied simulation components in greater detail.

A. Fuel Consumption and Emissions

PHEM (Passenger car and Heavy duty Emission Model) is an instantaneous emission model, i.e. it calculates fuel consumption and emissions from vehicles' instantaneous changes in speed and acceleration. Using a resolution of 1 Hz, PHEM maps the calculated momentary state of the engine to data from real-world measurements, taking into account a multitude of parameters, e.g. the slope of the road, engine and vehicle type, warm/cold start and gear shifting. Being based on physical

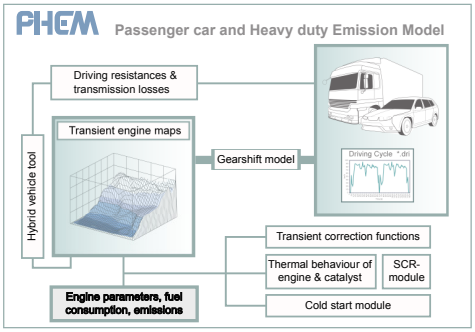
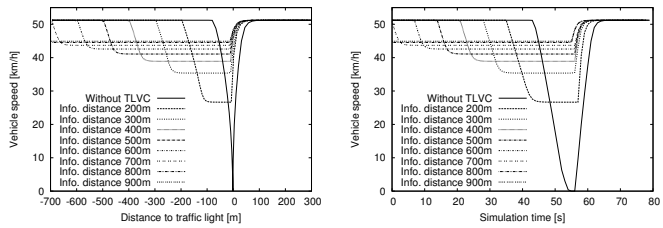


Fig. 1. Schematic illustration of the PHEM emission model



(a) W.r.t. distance to traffic light (b) W.r.t. simulation time

Fig. 2. Speed adaptation for different information distances (sample vehicle)

parameters only, PHEM allows to realistically evaluate new, unmeasured driving patterns without further measurements.
The underlying data base has been derived from real-world measurements of more than 1000 vehicles, compiled into average vehicle categories representing passenger cars, light duty and heavy duty vehicles with Otto and Diesel engines from European emission standard EURO 0 to EURO 6.
PHEM has been developed and improved in different projects, e.g. the EU FP 5 project ARTEMIS [12] and the Handbook Emission Factors for Road Transport (HBEFA) [13]. A schematic overview of the model is given by Figure 1.

B. Vehicular Traffic

VISSIM [14] is a microscopic simulation program for multi-modal traffic flow modeling. That is, each entity of real-world traffic, e.g. cars, buses, trains, bicyclists, pedestrians, etc., is represented by an autonomous entity within the simulation with individual behavior and characteristics. In this work, we use VISSIM to generate driving cycles of individual vehicles with and without TLVC.

C. Communication

As already discussed, previous studies found the evaluation of the environmental impact of TLVC to not require a detailed modeling of the communication aspect in terms of packet reception rates and bandwidth usage. Assuming that traffic lights change their scheduling less frequently than the scheduling information is broadcast, the loss of packets is also uncritical since vehicles can use a countdown to the phase change once they have received the information.
We therefore argue that the communication aspect under the given evaluation objective can be reduced to the distance from the traffic light at which the scheduling information is first received by the vehicle, in the following denoted as *information distance*. We model this aspect in the simulation by assuming vehicles to be informed about the scheduling of the upcoming traffic light when they pass the corresponding information distance. Thereby we assume a perfect communication system with a precise information distance. Since in reality wireless channels are not perfect, we additionally blur the information distance using a Gaussian distribution to compare the results. Thereby the standard deviation of the Gaussian distribution is set to 50.021, which ensures that a distance in a range of 100 m around the specified information distance is selected with a probability of 0.95 (cf. Figure 4a). In the following, we denote these communication models as the *perfect* and *fuzzy* model, respectively.

IV. Evaluation for a Single Vehicle and Traffic Light

The objective of the simulation study presented in this section is to identify key influencing factors on fuel consumption and emissions and to quantify the extent of their effects. In order to study the maximum benefit for an individual vehicle, we choose a single-road scenario with one vehicle and one traffic light, excluding potential factors of influence unlikely to yield a positive effect, e.g. other vehicles.
In the following, we first describe the simulation setup and evaluation methodology and define the notions used in the analysis. Then, we discuss the results for two key influencing factors we identified, gear choice and information distance.

A. Simulation setup and Evaluation Methodology

1) Road segment: Randomly evaluating typical street lengths of different international cities on Google Maps, we found road segments between traffic lights to rarely exceed 700 m. Therefore and in order to evaluate different information distances, we chose a road segment length of 1 km, 700 m before and 300 m after the traffic light. Figure 3 provides a schematic overview of the scenario.
Note that, since vehicles with TLVC approaching a red light save the highest amount of fuel in the proximity of the traffic light [6], the relative benefits of TLVC would be higher for a smaller road segment. However, the general tendencies are not subject to this effect.

2) Traffic light and communication: The traffic light placed on the road has a cycle time of 44 s, consisting of a red phase of 20 s, a yellow-red phase of 1 s, a green phase of 20 s and a yellow phase of 3 s (cf. Figure 4b). When the vehicle passes the configured information distance (cf. Section III-C), we assume it to be informed about the start and end of the upcoming two green phases. Thereby we use both the perfect and fuzzy communication model introduced in Section III-C to determine the information distance. We evaluated information distances from 100 m to 1000 m.

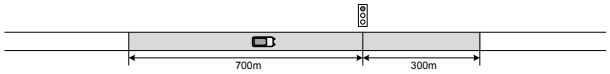


Fig. 3. Evaluated road segment

3) Driver behavior: In order to evaluate the maximum benefit for an individual vehicle, we assume perfect *driver compliance*. That is, the driver approaches a red light at full speed, even if it will only just switch to green when he arrives. To model coasting, we configured the deceleration of the vehicle to be approximately 1 m/s^2. We cross-checked this value against driving-simulator traces of the traffic-light approaching behavior of real drivers [15].

4) Vehicle types: In this study, we evaluate personal cars with EURO 4 Otto and Diesel engines. Since our objective is to evaluate a typical car in an urban environment, we assume warm starts.

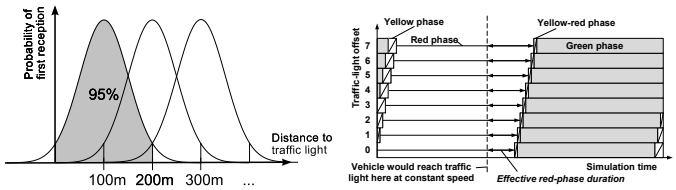
5) Evaluation metrics: Carbon dioxide (CO_2) and monoxide (CO), mono-nitrogen oxide (NO_x) and particulate matter are among the emission types with the highest impact on the environment. Since CO_2 emissions can be calculated from fuel consumption using a linear function, we limit our evaluation to fuel consumption, CO, NO_x and particulate matter.

6) Gear-shifting model: PHEM allows the user to either use one of its built-in statistical gear-shifting models or manually define the gear to be used per simulation second. In this single-vehicle analysis, we chose the latter method in order to ensure a fair comparison of the driving cycles with and without TLVC.

To analyze whether gear-shifting plays a significant role in fuel consumption when TLVC is available, we evaluated identical VISSIM driving cycles with and without speed adaptation for different preferred gears. In this context, *preferred gear* denotes the gear which the driver predominantly uses unless he has to stop or slow down below a certain threshold. We chose the threshold to shift to gears 3 and 2 to be 30 and 20 km/h, respectively.

7) Averaging: The amount of fuel and emissions saved when the TLVC is available depends on how much the vehicle would have had to reduce its speed without TLVC. The latter, in turn, depends on when the vehicle arrives at the traffic-light. As illustrated by Figure 4b, we therefore define the *effective red-phase duration* as the time interval from the moment the vehicle would pass the traffic light during the red phase if it did not reduce its speed at all until the end of the red phase. For example, if the vehicle without reducing its speed would pass the traffic light at simulation time 25 s and the traffic light's red phase was from simulation time 15 s to 35 s, the effective red-phase duration would be 10 s.

In order to evaluate a multitude of possible combinations of vehicle speeds and traffic-light phases, we chose 50 random vehicle speeds following a normal distribution such that 95% of the values are within the interval [45,55] km/h. For each of these speeds, we varied the traffic-light scheduling in steps of 1 s, resulting in 44 simulation runs per random speed. For



(a) Fuzzy communication model (b) Effective red-phase duration

Fig. 4. Evaluation methodology

each vehicle speed and traffic-light offset, we evaluated the scenario with and without TLVC and averaged with respect to the effective red-phase duration. The concept of traffic-light offsets is visualized by Figure 4b.

Note that we exclude the cases from averaging in which the informed driver violates a red light because the traffic light switches too late for him to react, while the informed driver reduces his speed and stops the vehicle. These instances show that TLVC can help to improve traffic safety, but for the fuel-consumption analysis, we did not consider it a fair comparison.

B. The Influence of Gear Choice

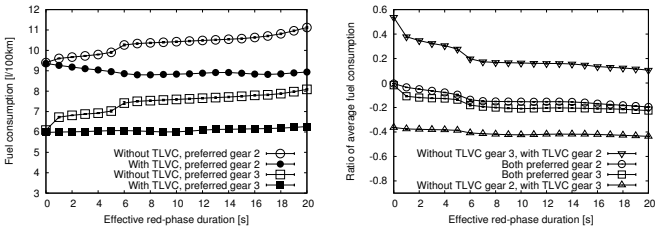
The choice of gear has a significant impact on fuel consumption and emissions [10]. This section compares the impact of TLVC with the effect of the gear choice in our setup.

Figure 6 illustrates the effect of the choice of the preferred gear (cf. Section IV-A6) on the resulting fuel consumption ratio for a sample vehicle[1]. Each individual plot consists of three parts: vehicle speed, fuel consumption and chosen gear, each with respect to the simulation time. Additionally, each chart contains the information distance used and the resulting ratio of fuel consumption with and without TLVC averaged over the evaluated road segment.

Following the individual plots in horizontal direction, we compare identical VISSIM driving cycles for different choices of the preferred gear. In the left column of plots (Figure 6a) the vehicle uses predominantly gear 3 when TLVC is not available and predominantly gear 2 when TLVC is available. In the right column (Figure 6b), the preferred gears are interchanged: The informed driver predominantly uses gear 3, while the uninformed driver's gear choice does not exceed gear 2.

Note that the speed curves for the vehicle with TLVC in the first row (information distance 200 m) differ slightly, even though the underlying VISSIM driving cycle was the same. This effect results from the emission model PHEM which adapts the achievable acceleration to the chosen gear, resulting in the vehicle accelerating slower than specified in the driving cycle when gear 3 is chosen.

Comparing the resulting ratios of fuel consumption in horizontal direction for each information distance, the effect of the chosen gear becomes apparent: While in the left column fuel consumption is reduced by up to 43 %, the right column yields an *increase* of 14 % to 24 %. That is, the impact of a suboptimal gear choice outweighs the beneficial effects on fuel consumption achieved by TLVC.



(a) Average of absolute value (b) Average *ratio*

Fig. 5. Gear choice vs. average fuel consumption[1]

Note that, if in both cases the preferred gear is 3, the simulation yields a reduction in fuel consumption of 16.2 %, 20.2 % and 20.8 % for information distances of 200 m, 400 m and 600 m, respectively. While the latter are in line with the identified fuel saving potential found in other studies (cf. Section II), the results presented in Figures 5 and 6 demonstrate that the choice of gear is of significant importance when evaluating the environmental impact of TLVC.

Figure 5 illustrates the influence of gear choice and speed adaptation on the average fuel consumption in our setup with respect to the effective red-phase duration (cf. Section IV-A7). Considering Figure 5a, we observe that for both preferred gears 2 and 3, TLVC can effectively reduce the average fuel consumption to the level of driving with constant speed, even for longer effective red-phase durations. That is, in terms of fuel consumption, the speed-adaptation algorithm performs as if there were no red light. However, comparing the difference in the average fuel consumption between gears 2 and 3, we observe that the amount of fuel saved with a higher preferred gear exceeds the effect of TLVC. That is, in our setup, a driver not aware of the traffic-light scheduling and predominantly using gear 3 saves more fuel than a driver preferring gear 2 and using TLVC.

Figure 5b shows that a fair comparison of the benefit of TLVC requires the same preferred gear to be used in both cases. Otherwise, ratios of fuel consumption between -40 % and +60 % can be observed.

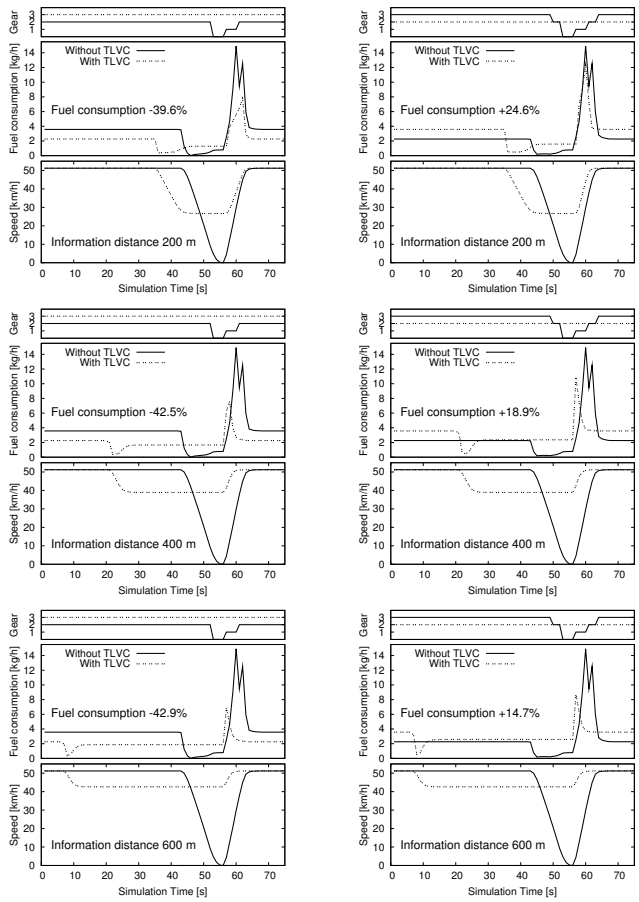
C. The Influence of the Information Distance

In our setup, v is on average 50 km/h and t is 87 s (the vehicle is informed about the upcoming two green phases). Therefore, the maximum information distance is about 1200 m. However, we observed the decrease in average fuel consumption on our evaluated road segment became negligible for information distances greater than 600 m. Considering Figure 2, this effect can be explained by the fact that for high information distances, the adapted speed of the vehicle does not change significantly on the evaluated road segment.

[1]Average for personal cars with an Otto EURO 4 engine, information distance 600 m, perfect communication model

[2]Exemplary personal car with an Otto EURO 4 engine, speed 51.2 km/h, effective red-phase duration 7.19 s

[3]Figures 7a-7d: Personal car with an Otto EURO 4 engine, preferred gear 3 with and without TLVC; Figures 7e-7h: Personal car with a Diesel EURO 4 engine, preferred gear 3 with and without TLVC.



(a) Without TLVC preferred gear 2, with TLVC preferred gear 3 (b) Without TLVC preferred gear 3, with TLVC preferred gear 2

Fig. 6. Gear choice vs. fuel consumption[2]

Therefore, we limit the following evaluation to information distances up to 600 m.

Figure 7 illustrates the effect of different information distances on fuel consumption and emissions, assuming a preferred gear of 3 with and without TLVC. The left column of plots (Figures 7a, 7c, 7e and 7g) depicts the average total value of the different metrics evaluated on the selected road segment with respect to the effective red-phase duration. The right column (Figures 7b, 7d, 7f and 7h) illustrates the average reduction per metric comparing the driving behavior with and without TLVC. Black symbols illustrate the results for the perfect communication model with a precise information distance, while white symbols represent the results for fuzzy communication model using the corresponding information distance as the mean of the Gaussian distribution.

Note that we omit the results for an information distance of 100 m here, since due to the assumption of coasting, the driver without TLVC takes his foot off the gas pedal at close to 100 m and the effect of TLVC is negligible.

Figures 7a and 7b illustrate the effect of the information distance on the average fuel consumption of a personal car

with an EURO 4 Otto engine. The results for Diesel engines are very similar and therefore not shown here. The considered graphs illustrate that the benefit of increasing the information distance from 200 m to 400 m is greater than the resulting benefit from an increase from 400 m to 600 m. As already mentioned, the positive effect for information distances greater than 600 m is even smaller.

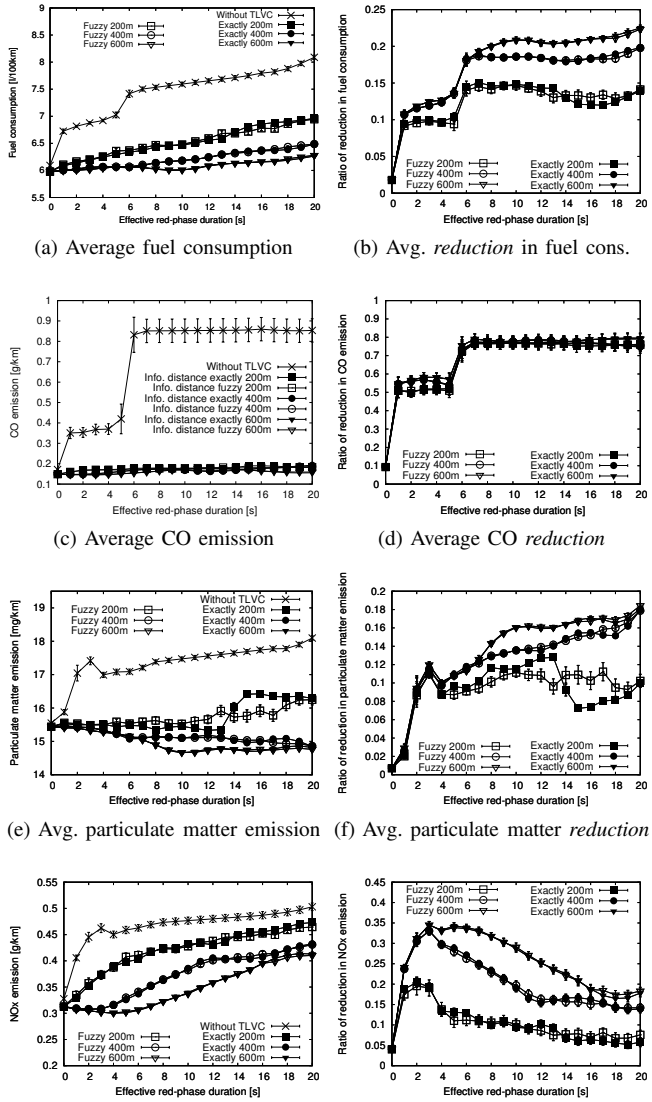
Depending on how long the vehicle would have been affected by the red phase, average fuel savings of up to 22 % can be observed in our setup. Note that the "knee" in the curve without TLVC between 5 s and 6 s can be explained since in our setup, the corresponding traffic-light offset results in vehicles having to fully stop at the traffic light for effective red-light durations greater than 6 s, requiring additional fuel to overcome the inertia of the matter.

The second "knee" between 13 s and 15 s in the curve corresponding to an information range of 200 m results from the underlying gear-shifting behavior. While for effective red-light durations of up to 13 s, the driver does not have to slow down below 20 km/h and therefore does not shift to gear 2, a speed reduction below 20 km/h becomes necessary after effective red-light durations of 14 s, resulting in a usage of gear 2 for parts of the evaluated road segment.

Figures 7c and 7d show that the CO emissions of a personal car with an Otto engine can be reduced by up to 80 % if the speed-adaption algorithm is applied, independent of the information distance. Thus, for CO emissions, the most important factor is to avoid stopping at the traffic light. For a personal car with a Diesel engine, CO emissions are negligible.

Figures 7e and 7f show the reduction in particulate matter for different information distances for a personal car with a Diesel engine. Due to the negligible amount of particulate matter emissions of Otto engines, the corresponding results are not shown here. The results indicate that for the considered Diesel engines, particulate matter exhaustions can be reduced by up to 18 %. Furthermore, we observe benefits from an increase in information distance. Still, the most important factor appears to be the avoidance of a full stop. Analogously to the discussion on fuel consumption, the observed "knee" in the curve for 200 m information distance results from gear choice.

Finally, Figures 7g and 7h illustrate the effect of the information distance on NO_x emissions for a personal car with a Diesel engine. The NO_x emissions of Otto engines are similarly reduced but are negligible in their absolute value. We observe that NO_x emissions are not reduced in the same way as the other metrics discussed and grow linearly with increasing effective red-phase duration. This effect can be explained by the fact that NO_x emissions depend on the acceleration of the vehicle. For increasing effective red-phase durations, vehicles have to increasingly reduce their speed and accelerate again. However, the results indicate that TLVC has a beneficial effect on NO_x emissions, ranging from 5 % to 35 %. As already mentioned, the white symbols in Figure 7 correspond to the fuzzy communication model. We observe that the results with perfect and fuzzy communication are



(a) Average fuel consumption (b) Avg. *reduction* in fuel cons.

(c) Average CO emission (d) Average CO *reduction*

(e) Avg. particulate matter emission (f) Avg. particulate matter *reduction*

(g) Average NO_x emission (h) Avg. NO_x *reduction*

Fig. 7. Information distance vs. fuel consumption and emissions[3]

close to identical, with the exception of the fuel consumption and particulate matter curves for 200 m information distance. This deviation can again be explained considering the chosen gears. Since the fuzzy communication model can result in smaller information distances than the perfect communication model, on average vehicles have to reduce their speed more than with an exact information distance. Thus, they reach the gear-shifting threshold to gear 2 more frequently than when the perfect communication model is applied, which is reflected in the average environmental impact.

V. Evaluation for Multiple Vehicles and Traffic Lights

While the focus of the previous section was to evaluate the maximum environmental benefit from TLVC for a single vehicle and traffic light, this section presents first results of

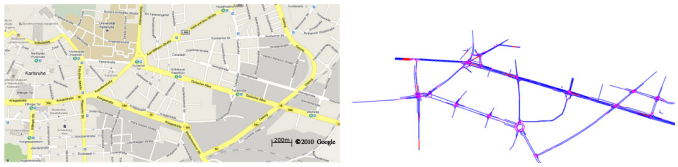


Fig. 8. Model in VISSIM (right) of an extract of Karlsruhe's inner city (left).

a scale-up simulation study using a model of a real-world network of urban streets. In contrast to an isolated road segment with a single vehicle where an optimal traffic-light approaching behavior is feasible, a multitude of influencing factors can diminish the achievable environmental benefits in a road network. For example, preceding vehicles might interfere with an optimal speed adjustment. In addition, distances between subsequent traffic lights might be too short for an efficient speed adaptation.

In the following, we first describe the simulation scenario and setup. Then, we present and discuss the simulation results.

A. Simulation setup

1) Scenario: The scenario evaluated in this section models an extract of the inner city of Karlsruhe, Germany (cf. Figure 8), covering an area of approximately 1 km × 3 km. It consists of 15 crossings equipped with traffic lights, distributed over the area such that vehicles pass up to six traffic lights in a row. We calibrated traffic densities and vehicle flows against real-world measurements of evening rush hour traffic. Expressed in figures, this means that 850 to 950 vehicles traverse the scenario during the evaluated 500 s of simulation time. The relatively high traffic density justifies our choice of the traffic-light scheduling. While in reality the considered traffic lights adapt their phases dynamically with respect to the arriving traffic, they more or less fall back to a static scheduling for high traffic densities. In our scenario, we therefore calibrated the traffic lights according to their real-world fall-back schedule if no measurement data are available.

The considered vehicle fleet consists of personal cars, 40% with Otto and 60% with Diesel engines ranging from EURO 0 to EURO 4 in increasing ratios.

2) Communication: As in the previous section, we used the perfect and fuzzy communication models introduced in Section III-C. That is, vehicles are again informed about the upcoming traffic light's upcoming phase as soon as they pass the determined information distance determined by the applied communication model. Furthermore, we evaluated five different radio-equipment penetration rates of vehicles: 0 %, 25 %, 50 %, 75 %, and 100 %.

3) Driver behavior: In contrast to the single-vehicle analysis, we now do not assume perfect driver compliance which we do not consider to be realistic. That is, drivers do not fully trust the system and reduce their speed when the traffic light still shows red and the vehicle has passed the minimum distance to come to a stop in front of the traffic light. Our speed-reduction algorithm takes into account the green phase of the upcoming traffic light, but not the phases of the subsequent ones.

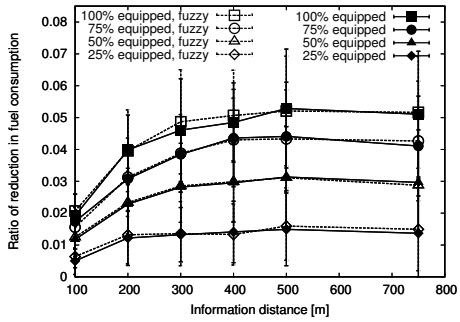


Fig. 9. Average fuel saving ratio in the scale-up scenario

4) Gear choice: Although Section IV-B outlined the significant influence of gears on fuel consumption, in this study, we do not assume vehicles to automatically choose their gears in an optimal way, since to our impression this would exceed the border to automatic driving. Instead, we rely on statistical gear choices suggested by PHEM, derived from empirical data.

5) Parameter space and averaging: Our simulation study considers all possible combinations of the considered ratios of radio-equipped vehicles, information distances, and communication models. For each configuration we ran 50 independent replications, altogether summing up to 2,450 individual simulation runs. For each simulation run, we first allowed the network to fill with vehicles for 300 s before evaluating the simulation for 500 s.

B. Simulation results

Figure 9 illustrates the simulation results with respect to the *reduction* in fuel consumption comparing the scenario with and without TLVC (y-axis) and the (average) information distance (x-axis). As in the previous section, black and white symbols represent the perfect and fuzzy communication model, respectively. Again, the two communication models yield very similar results, so that the graph shows four groups of curves, differing in the ratio of radio-equipped vehicles.

The first thing that catches one's eye when looking at the graph is that, at 6 % to 8 %, the evaluated ratio of fuel savings is significantly lower than in the single-vehicle analysis. Note that we do not claim this value to be the "true" saving ratio to be expected from a real-world deployment of TLVC. In fact, the graph may rather serve as an orientation point, since in reality, a multitude of influencing factors may shift the absolute values upward or downward.

For example, we used a rather basic speed-adaption algorithm not considering other vehicles or the scheduling of subsequent traffic lights. An advanced algorithm is likely to yield positive effects on fuel consumption. Furthermore, an optimized gear-shifting model considering traffic-light phases could further improve fuel efficiency.

However, there are also factors that may diminish the achievable benefit. In our setup, we assumed static traffic light schedules, so that the real time horizon of phase shifts known

to the vehicle is relatively long. In reality, however, most traffic lights adapt their phase shifts dynamically based on sensor measurements. Therefore, the time horizons of phase shifts available to the vehicles would most likely be significantly shorter than in our setup.

This list of pros and cons is certainly not comprehensive and estimations which effects might cancel out each other can hardly be given. However, we do expect that the tendency given Figure 9 will not change significantly.

Furthermore, we consider the following tendencies of the graph to be realistic: First, an increased penetration rate of the TLVC application results in higher fuel savings. Second, there is a saturation point regarding the information distance from where no additional benefit is achieved (in our setup, it is at approximately at 500 m). Third, to evaluate the environmental impact of TLVC, it is sufficient to model the communication aspect as a fixed information distance, since the results for the two communication models do not differ significantly. Note that, for different evaluation objectives a different modeling detail of the communication system is likely to be required, e.g. when investigating how vehicles can determine the correct traffic-light phases for their respective lane.

VI. Conclusions

Traffic-light-to-vehicle communication (TLVC) has the potential to reduce the environmental impact of vehicular traffic by helping drivers to avoid braking and accelerating maneuvers at traffic lights. However, equipping traffic lights with communication technology requires significant financial expenditures. Thereby, credible large-scale simulation studies are an important means to assess the return on investment.

Since large-scale simulations, in turn, require a trade-off between simulation detail and computational cost without sacrificing the credibility of the results, in this work we use a detailed emission model to identify key influencing factors on TLVC and evaluate the level of detail required for the different simulation components. Furthermore, we present first simulation results for a real-world road network.

In our simulation setup for a single vehicle and traffic light, TLVC reduces fuel consumption by up to 22 % and CO, NO_x and particulate matter emissions by up to 80 %, 35 % and 18 %, respectively. Furthermore, we identify gear choice as a significant influencing factor to the extent that a suboptimal gear choice can void the positive effects of TLVC. Therefore, future applications might benefit from combining speed advice based on TLVC with gear-shifting advice. For vehicles with an automatic transmission, advanced cruise-control algorithms could optimize both speed and gear choice based on TLVC.

As a second key influencing factor, we discuss the *information distance*, i.e. the distance at which vehicles are first informed about the traffic light's phase shifts. Our evaluation shows a saturation point at about 500 m to 600 m, after which the achievable benefits become negligible compared to the technological effort (e.g. multi-hop communication). In addition, our simulation results indicate that, to assess the environmental impact of TLVC, the communication aspect of the simulation can be reduced to a fixed information distance. We emphasize that this result only holds for the given simulation objective. However, for upcoming simulation studies, this result can help to reduce computational overhead that would not further improve insight.

Finally, our road-network simulation yields a reduction in fuel consumption of only up to 8 %. This significant difference to the result of the single-vehicle analysis indicates that the results of isolated vehicles may not be mathematically projectable to a street network, emphasizing the need of large-scale simulations of the environmental impact of TLVC.

Our evaluation indicates that driver behavior, e.g. gear choice and compliance, plays an important role in the beneficial impact of TLVC on the environment. A future deployment of TLVC could thus benefit from further studies how to present the speed choice advice to drivers in order to enable and motivate them to drive "green".

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