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Traffic management based on vehicular communication at low equipment rates

Daniel Krajzewicz[1*], Robbin Blokpoel[2], Alessio Bonfietti[3], Jérôme Härri[4], Stefan Hausberger[5], Jérémie Dubois-Lacoste[6]

1. German Aerospace Center, Institute of Transport Research, Rutherfordstr. 2, 12489 Berlin, Germany, Daniel.Krajzewicz@dlr.de
2. Imtech Traffic & Infra, Netherlands
3. University of Bologna, Italy
4. EURECOM, France
5. Technical University Graz, Austria
6. Université libre de Bruxelles, Belgium

Abstract
Most applications built upon vehicular communications (V2X) target on increasing traffic safety. They often require a direct communication between at least two vehicles equipped with a communication device. Thereby, a sufficient amount of equipped vehicles is necessary for assuring these applications' functionality. Meanwhile, traffic management needs information about the state on the roads. The COLOMBO project, co-funded by the European Commission, follows the idea to support traffic management with new data, gained from vehicular communications at low equipment rates. It designs and evaluates traffic management solutions for traffic surveillance and traffic lights based on simulations. This article introduces the major achievements of the project, regarding both, the developed traffic management solutions as well as the extensions of the used simulation tools.

Keywords: traffic management, vehicular communication, simulation.

Introduction

Road traffic is a major societal topic, which directly influences the economy via the costs of transporting goods and people. It is as well responsible for a big portion of air pollution generated by the human kind. Different disciplines and actors work on increasing the efficiency of road traffic for reducing its environmental impact.

The upcoming vehicular communication technology (known as Dedicated Short Range Communication (DSRC) in the US and as ETSI ITS G5 in EU) is assumed to be one of the next major evolution steps of road traffic. This technology allows vehicles and road side units (RSUs) to exchange information via a dedicated wireless communication channel using specific messages (Cooperative Awareness Message (CAM) in the EU, Basic Safety Message (BSM) in the US). Vehicles equipped with communication devices send information about their state (GPS position, speed) periodically. Other equipped vehicles or RSUs can collect this information to generate a representation of the objects and their behaviour in their surroundings called 'cooperative awareness'. Besides CAM/BSM, further messages that inform traffic participants about specific events, such as dangerous weather conditions or an approaching emergency vehicle can be exchanged. Vehicular communication is currently undergoing a standardisation process at ISO, IEEE and ETSI.

This technology enables a broad range of applications and several of such have been standardized in the recent past. Most of these applications target on increasing traffic safety. One of their issues is the need to have a critical mass of equipped vehicles, because most of these applications use a direct communication between at least two of such. Some of the standardized safety applications warn the driver in case of hazardous events, such as a strong breaking leader vehicle or a possible collision at an approached intersection. Thereby, they work on small time scales and in small areas and being responsible for saving lives, their proper functionality is critical.

Road traffic is as well influenced by local traffic management, civil engineering that tries to use the given road infrastructure in a most effective way for coping with the increasing traffic demand. The first step of traffic management is gathering information about the state on the controlled roads. Conventionally, traffic surveillance is performed by road authorities and is used for both, strategic decisions as well as for triggering actions on tactical level (“online”). Strategic decisions use a coarse overview of a city’s or region’s traffic flows, often determined by building a demand model, first, which is afterwards used in conjunction with a macroscopic traffic assignment application to estimate the flows within the regarded area.

On the tactical level, traffic management relies on automatic traffic detection. Here, the information about the current state of a road is used for a) recognizing incidents and/or flow breakdowns, b) automatically adapt traffic lights to the current demand, c) assisting in personalized navigation. Tactical level traffic surveillance is envisioned to be critical to reach smart and sustainable mobility in future smart cities. It is expected to reduce danger on the road, reducing commuting time, traffic pollution, fuel consumption and even street wearage. Tackling these objectives is yet challenging, as traffic demand is assumed to increase, while the budgets of public authorities rather decrease. It is therefore critical to develop methods for traffic management that would at the same time extend the information about the state of the road network and reduce the deployment and maintenance costs.

The idea behind COLOMBO ([1], [2]) is to exploit vehicular communication for traffic management purposes, taking into account that the initial amount of equipped vehicles will be low. The motivation for this work is two-fold. On the one hand, traffic management should be enabled to gather and use information from existing information sources – communicating vehicles – at low costs. On the other hand, the existence of this new field of application is assumed to raise the attractiveness of the vehicular communication technology. Additionally, one may state that traffic management applications are usually less critical than the standardized vehicular safety applications, because even in case of a malfunction, no human lives are harmed. This makes the solutions be good candidates for early deployment.

Two major traffic management topics are addressed by COLOMBO, namely traffic surveillance and traffic control via traffic lights. It would be hardly possible to design, test, and implement such solutions in the real world within the project’s life time of three years. Therefore, the solutions developed in COLOMBO are conceptually designed and implemented as simulation software models, extending the iTETRIS simulation platform [3, 4]. A state-of-the-art approach for simulating vehicular communication is used, built upon existing simulation applications joining them into a single execution system. Most of these applications have been extended and improved within COLOMBO.

The remainder of this article describes the project’s achievements obtained in the first two years of the project and give an outlook on furtherly expected outcomes. It is structured as following: the first sections are dedicated to the developed traffic management solutions, namely traffic surveillance and traffic light algorithms, respectively. This is followed by a description of the developed simulation architecture and the extensions to the involved software packages done within COLOMBO are presented. Then, some aspects of the work on reducing the environmental impact of traffic are given. Further, accompanying work is presented afterwards. This article closes with a summary.

Traffic Surveillance

The first set of traffic management solutions developed by the project targets on determining “conventional” performance indicators for the state on the roads. Four different surveillance applications were designed and implemented. While all use messages exchanged via vehicular communication, they differ in the involved actors (vehicles / road side units). Two of these surveillance methods fall in a category called ‘Distributed Floating Car Data’ (DFCD). In DFCD, vehicles and smartphones are sampling traffic data, but instead of transferring the gained information to a central processing server, they autonomously compute local traffic information and transmit it directly to a road side unit. The two other methods work on collecting information sent by vehicles periodically (e.g. CAMs) by RSUs and processing them there, falling in a category called ‘Localized Floating Car Data’ (LFCD). The main objective of both distributed and local computation is not to reduce traffic on cloud systems, but to be able to work without it.

All traffic surveillance algorithms developed in COLOMBO share some features:

- Local Data Processing – a major discouraging aspect of data crowdsourcing comes from the lack of control of data once it reaches the cloud. With COLOMBO DFCD and LFCD, data remains at vehicles and at traffic lights.
- Fresh Data Processing – traffic flows are immediately and continuously monitored. Using DFCD, short delays and high reactiveness are reached through local processing and direct transmission to traffic lights.
- Low Cost – using FCD typically implies a data transfer (e.g. via UMTS) flat rate contract. Unlike FCD, the solutions developed in COLOMBO do neither need vehicles being in coverage of a cellular network, nor have a roaming contract with them.

The first COLOMBO DFCD-based surveillance method ([5], [6]) is built upon clustering vehicles for compressing the description about the traffic state. It is capable to determine traffic efficiency performance indicators without involving a road side unit. Thereby, it may be applied for monitoring parts of the road network with a sparse RSU coverage for computing the average velocity and the number of vehicles. A performance evaluation example is given in Figure 1.

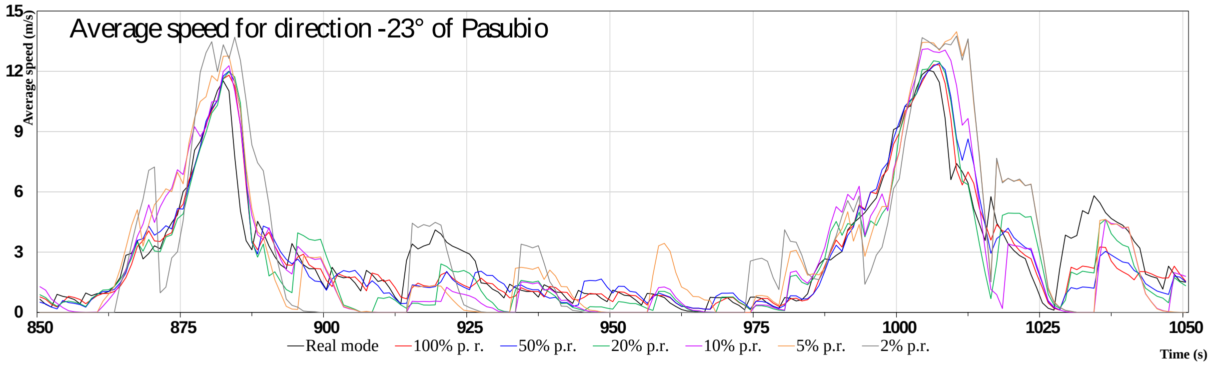


Figure 1 - Comparison of measures of the average speed at different equipment rates using the cluster-based traffic surveillance algorithm

The second DFCD-based traffic surveillance method ([7]) determines the density and speed of vehicles using the message propagation speed and may be implemented on top of n-hop communication protocols, such as Probe-Vehicle-Data (PVD), at a minor overhead on the wireless channel (~1/50 of the load created by CAMs). It delivers similar measures as the first surveillance method.

The first RSU-based approach uses only data from CAMs. Thereby, it is ready to be deployed given the current standardisation stage. It is capable to gather several commonly used performance indicators, such as the average speed, number of stops, the average waiting time, and the average travel time. A performance overview is given in Figure 2.

The fourth algorithm ([8]) builds upon the traffic flow’s dependency on traffic light control. It determines the amount of passing vehicles (traffic flow) using travel times of single vehicles as the only input. Despite vehicular communication, such an input can be gained using other (wired and wireless) vehicle re-identification methods as well.

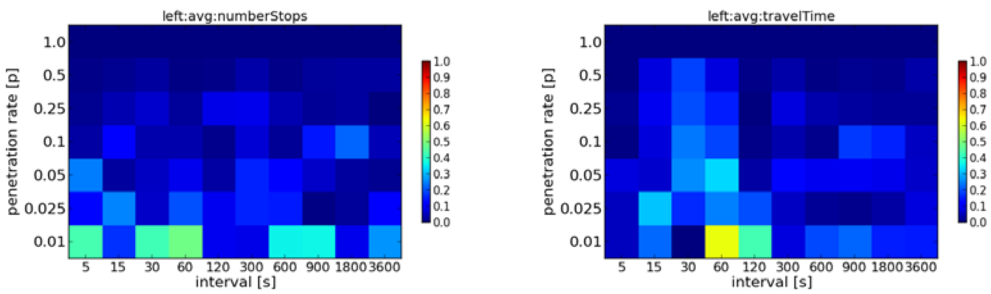


Figure 2 - Comparison of measures of the number of stops (left) and average travel time (right) at different equipment rates and for different aggregation intervals using the CAM evaluation algorithm

As written above, only few equipped vehicles will be found on real-world roads within the first years of deployment. The algorithms developed in COLOMBO take this into account assuming a low penetration rate of equipped vehicles only.

Besides determining conventional traffic performance indicators, COLOMBO delivers some new kinds of traffic information. The first of such solutions to name is a local (intersection-based) emission monitoring system. Up to now, vehicular emissions could be determined by so-called “portable emission measurement systems” (PEMS) only, which are directly attached to the tail pipe of a vehicle. This disallows to measure the amount of all pollutants emitted in a given real traffic area.

The second innovative system is a local incidents monitoring system. Different possibilities to detect incidents have been determined, classified, and their applicability has been measured using statistical approaches. To discuss what traffic anomalies detection can do and what not, the following aspects may be considered:

1. Incident detection: a road is partially or completely blocked and causes a traffic jam to develop. In this case, the speed of the vehicle(s) changes unexpectedly.
2. Small incident: a hindrance blocks a part of the road, but in this case no traffic jam develops, the vehicle trajectories simply depart from their normal behaviour. It manifests in this case by a place on the road where vehicles normally drive, but not now. The acceleration behaviour is changed slightly, but not strong enough to get detected.

3. Driving anomaly: a vehicle behaves different than the majority of vehicles in the given situation, what may include bigger lateral accelerations, strong longitudinal decelerations, a too high speed and similar.
4. A critical situation: a vehicle has to brake very strongly to avoid an accident, or to change course abruptly to avoid another vehicle or any other hindrance. This can be detected either by the acceleration behaviour, or by some traffic safety measure indicating a dangerous situation.

Besides the named scientific reports, the approaches for traffic surveillance developed in COLOMBO are reported in according deliverables of the project, available at the project's web pages.

Traffic Light Control

The second kind of a traffic management solution developed in COLOMBO is a new traffic light control algorithm, which works on data gained from vehicular communication at low equipment rates using the aforementioned traffic surveillance algorithms. Like for the surveillance algorithms, a decentralized approach is used. Every traffic light acts as an individual agent and coordination between intersections takes place indirectly via "stigmergy", an implicit, communication-free and indirect coordination mechanism which promises to be better scalable than any centralized solution.

The developed traffic light control adapts the order and the durations of phases using information collected from vehicular communications. A two-level adaptation model was realized. On the upper (macroscopic) level, a policy selection algorithm uses information about the occupancy of incoming and outgoing lanes for choosing a microscopic policy ([9]). This information is transformed into so-called pheromones, based on a metaphor developed in artificial intelligence inspired by ants. Each microscopic level policy is mapped in the pheromone space using a (Gaussian) stimulus function, as shown in Figure 3 by example. At run time, the swarm policy measures the pheromone levels in each simulation step and uses them to select a microscopic level policy. The choice is probabilistic. The parameters of the Gaussians are determined using a software configuration algorithm.

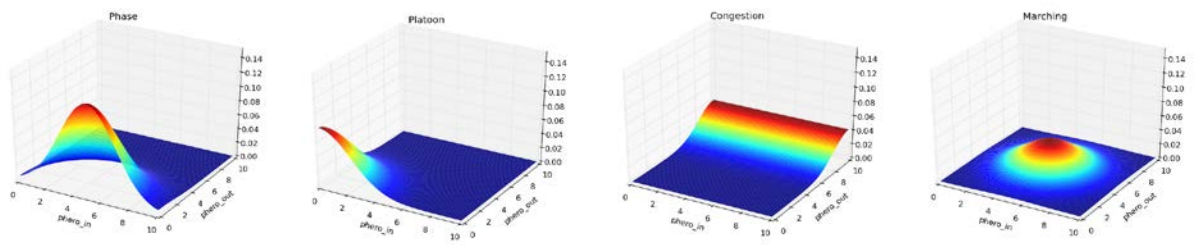


Figure 3 - Examples of stimulus functions for different micro-policies

The implemented micro-policies react on the state of the road network following an individual strategy. At the time being, four micro-policies are implemented: phase, platoon, marching, and congestion. Figure 4 shows the performance of the traffic light control that uses the swarm macroscopic policy selection and the named micro-policies for the case of a 100 % equipment rate (every vehicle is sensed).

For being applicable for low equipment rates, two methods that cope with incomplete knowledge were developed. The first one, called "eCTS" (estimated Cars-Times-Seconds) is a variation of the full-knowledge approach where vehicles are not sensed but estimated based on other available measures. The second one, "Queue length", tries to estimate the length of the queues of vehicles waiting for the green light.

After being accordingly configured, the developed traffic light system showed that it improves a traffic light's efficiency in means of waiting times for equipment rates of 10 % and above, as shown in Figure 5. At 25 % the quality of actuated traffic lights is reached. Such an actuated control usually needs traffic sensors under the road surface.

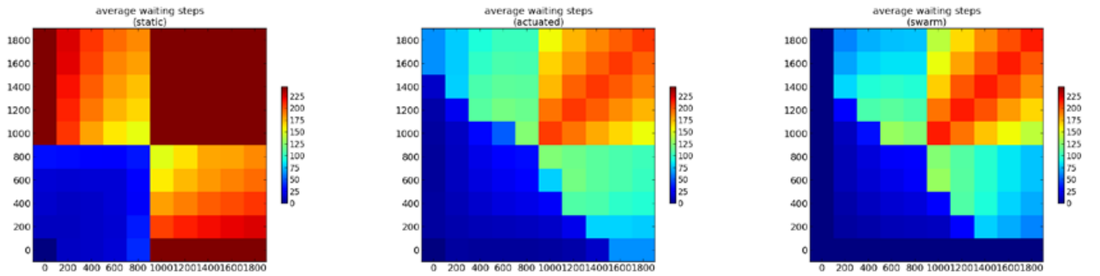


Figure 4 - Performance in means of average waiting steps for a fixed time (a), a conventional actuated (b), and the swarm (c) traffic light control at 100 % equipment rate; Values on the x- and the y-axis denote the north-south/west-east flow amounts

This given performance was gained using off-line preconfigured algorithms. One of the next extensions is an on-line optimization, which is assumed to further improve the performance.

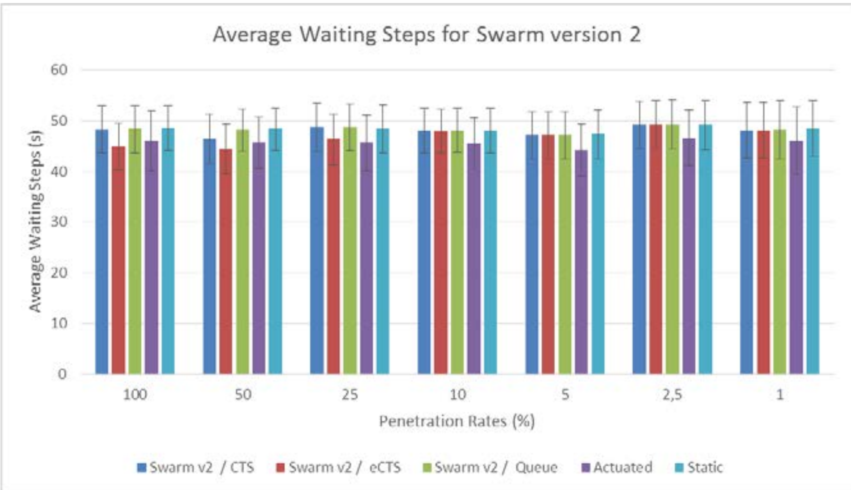


Figure 5 - Comparison of the performance of the new swarm algorithm in comparison to a fixed-time and an actuated traffic light control

The work on traffic light controls delivered as well a comprehensive comparison of national traffic light installation guide lines ([10]), including physical attributes as well as the rules for computing phase orders and timings.

Simulation Architecture

The solutions developed in COLOMBO use information obtained from wireless communication. The simulation of such systems requires tools that reproduce traffic as well as communication and that allow to include the applications under development into the simulation loop. Targeting environment-friendly solutions, proper models for emission computations are additionally needed. Finally, one of COLOMBO's goals is to generate solutions that are automatically calibrating themselves to the environment they are deployed within. This is supported by the use of automatic software configurators.

These requirements show that a complex simulation system is needed that combines models from different domains. The simulation architecture used in COLOMBO is an extension of the system developed within the project iTETRIS, a project that was co-funded by the European Commission. The iTETRIS simulation system consists of the communication simulator ns-3 ([11]), the traffic simulation SUMO ([12], [13]) and the V2X-application under evaluation. These parts are connected using the "iTETRIS Control System" (iCS). All these components are available as open source under the GPL.

COLOMBO extended this system by a new pollutant emission model and a software configuration framework as outlined in the next section. The overall simulation system is depicted in Figure 6.

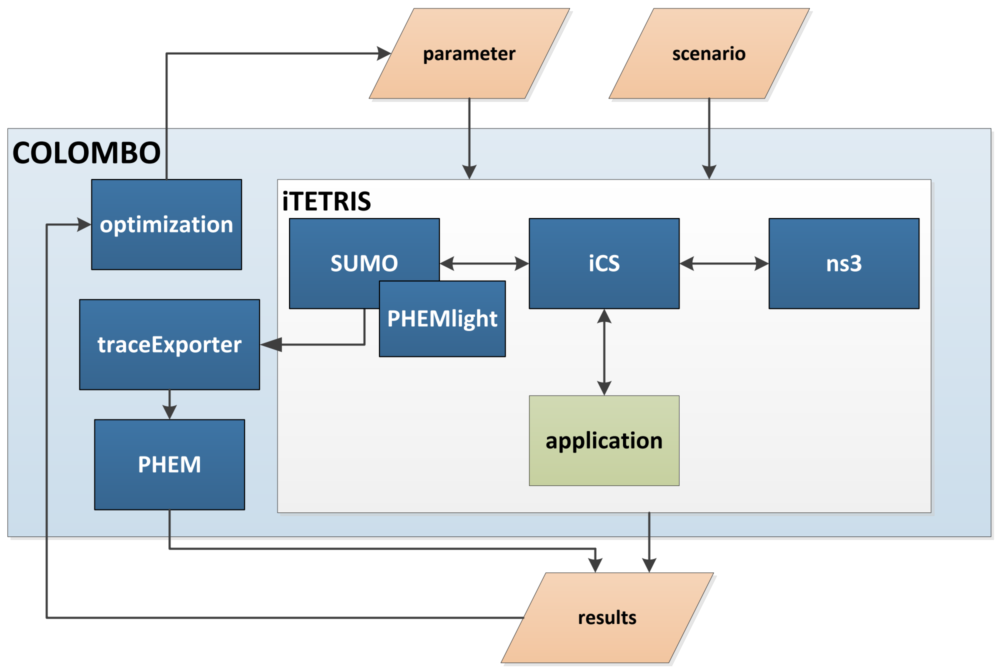


Figure 6 - The simulation architecture used and extended in COLOMBO

Several improvements to the involved simulators have been performed and will be presented in the following. These extensions are given back to the community complying with the original open source licenses.

Targeting on environment- and human-friendly solutions, COLOMBO does not consider passenger cars only, but puts a strong focus on other modes of transport, such as public transport, bicycles, and pedestrians. To enable according simulations, the traffic simulation SUMO used within the project had to be extended by models for pedestrian and bicycle traffic. Public transport was already supported. The extensions included work on different applications from the SUMO suite, including network importers, routing modules, as well as the simulation itself. The final implementation supports bidirectional pedestrian dynamics along pedestrian lanes (sidewalks), micro-routing across traffic lights, different pedestrian dynamic models, and importing sidewalk information from external network formats. It is seamlessly integrated into SUMO's multi-modal person trip model allowing to simulate persons that use different modes of transport, including walking in crowds, waiting for a public transport vehicle, using an own one, etc. Figure 7 shows one of the scenarios generated in COLOMBO that uses pedestrian traffic. More information is given in [14].

Figure 7 - The area around the “Andrea Costa” road in Bologna as simulated with pedestrians in SUMO

Several further, minor modifications to SUMO have been implemented, including extensions of the on-line interaction API and SUMO’s output facilities. COLOMBO contributions to SUMO are made available as open source as a part of the common SUMO distribution.

The other applications of the simulation suite have been extended within COLOMBO as well. The iCS middleware has experienced a major overhaul, including:

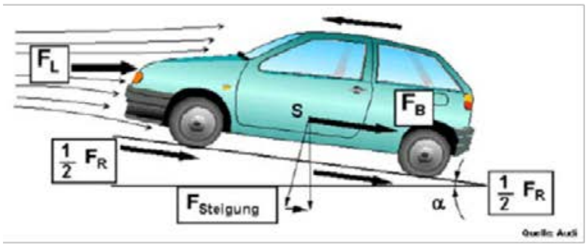
- Allowing specifying the time resolution of the simulation step with a milliseconds granularity.
- Allowing scheduling messages at arbitrary intervals in ns-3.
- Implementation of a generic data exchange between all modules (SUMO, ns-3, iCS), including retrieval of true and approximated position of all nodes.
- Adding the exchange of snr (signal to noise ratio) and lower data (transmit power, channel load, received signal strength indicator) from ns-3 to the application.
- Improving the coordination between iCS and the applications.

The project additionally releases open source scenarios for the traffic simulation SUMO ([15]). These scenarios use real-world data about the traffic demand and the traffic light programs within the respectively modelled areas.

Emission Reduction

The reduction of pollutants emitted by vehicular traffic is one of COLOMBO’s major targets. A proper investigation of this topic requires emission models of an adequate quality and granularity. For this purpose, a model named PHEMlight ([16]) has been developed based on the well-established PHEM emission model. In contrary to PHEM, PHEMlight is directly embedded into the traffic simulation SUMO. This allows to compute the emissions directly within the simulation and to write them in the needed aggregation. PHEMlight covers all relevant emission classes for the actual and future vehicle fleet composition almost completely. Comparisons with PHEM result in a minor deviation of about 5 % only.

$$P_e = (P_{\text{rolling resistance}} + P_{\text{air resistance}} + P_{\text{acceleration}} + P_{\text{road gradient}}) \;/\; \eta_{\text{gearbox}}$$



$$P_R = (m_{Vehicle} + m_{Load}) \times g \times (\mathrm{Fr}_0 + \mathrm{Fr}_1 \times \mathrm{v} + \mathrm{Fr}_4 \times \mathrm{v}^4) \times \mathrm{v}$$

$$P_{Air} = (Cd \times A \times \frac{\rho}{2}) \times \mathrm{v}^3$$

$$P_a = (m_{Vehicle} + m_{Rot} + m_{Load}) \times \mathrm{a} \times \mathrm{v}$$

$$P_{grad} = (m_{Vehicle} + m_{Load}) \times Gradient \times 0.01 \times \mathrm{v}$$

$$\eta_{gearbox} = 0.95 \quad \text{(average efficiency)}$$

Figure 8 - Computation of a vehicle's power demand in PHEMlight

PHEMlight computes the power demand of a vehicle as shown in Figure 8 in 1 Hz. The amounts of respectively instantaneously emitted pollutants are then looked up in so-called "Characteristic Emission curves over Power" (CEPs) tables, which come as additional data files. PHEMlight covers 112 distinct emission classes, divided by the type of the vehicle (heavy duty, passenger, motorcycle, etc.), the type of used fuel (mainly Gasoline/Diesel), and the Euro emission class. Some more heterogeneous vehicle types, mainly heavy duty vehicles, are divided further. PHEMlight is available as a commercial product; the implementation and two example data files are included in SUMO's free version, but the complete data set has to be licensed from the Technical University of Graz.

PHEM itself has been extended by models for engine start/stop systems, hybrid electrical vehicles (HEV), lithium ion battery-powered vehicles (BEV), and for vehicles that run on compressed natural gas (CNG) within COLOMBO.

Besides developing explicit traffic management solutions, COLOMBO works as well on more abstract methodologies to reduce the environmental footprint of traffic at two different levels. At the first level, functions for emission-optimal driver behaviour have been developed and compared to existing GLOSA (Green Light Optimal Speed Advisory) approaches. Besides determining the driving modes and, in conjunction, the respective emissions that result from the respective GLOSA speed computation algorithm, two new algorithms have been developed. These algorithms yield in lower amounts of emissions than the ones found in literature, as shown in Figure 9. This work has been accompanied by intense investigations about a vehicle's emission behaviour in dependence to the chosen speed and acceleration.

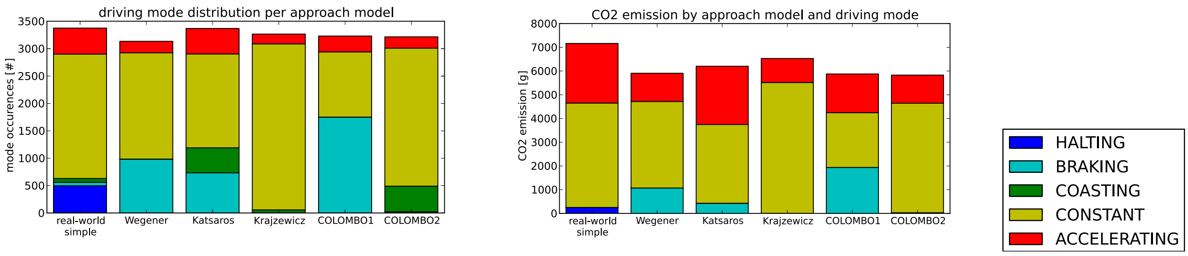


Figure 9 - left: occurrences of driving modes by GLOSA model; right: the respectively resulting CO_2 emission

At the second level, the macroscopic performance of traffic lights – may they be coordinated or standalone – in means of vehicular emissions have been investigated to formulate guide lines for traffic engineers.

Accompanying Work

Automatic Configuration

The complexity of COLOMBO's traffic light algorithms calls for an automatic configuration of the system's parameters. Within COLOMBO, state-of-the-art configuration techniques are employed and improved. They support modern optimization paradigms and are capable to perform optimizations not only in the real numbers space, but include integer ranges and sets of valid named values (sets) as well. A meta-system named "Tuning Tool Kit" ([17], [18]) for comparing different software tuners was developed within COLOMBO and released under an open source licence.

Traffic Light Evaluation

A review of 40 scientific publications performed within COLOMBO has shown that the evaluation of new traffic light algorithms lacks a common methodology. This has been targeted within COLOMBO, yielding in two distinct results. The first is a single performance indicator that joins conventional traffic efficiency measures, measures describing how drivers perceive the traffic state as well as environmental measures into a single value. It allows weighting the measures it uses for being adapted to local authorities' goals.

The second is a set of scenarios including software to execute and evaluate them. These scenarios may be applied to determine the strong and weak points of a traffic light algorithm under development. The included scenarios pose the traffic light algorithm against a set of different problems, such as changing traffic amounts, public transport prioritisation, synchronisation, etc., as shown in Figure 10. This system uses common performance indicators as defined in [19].

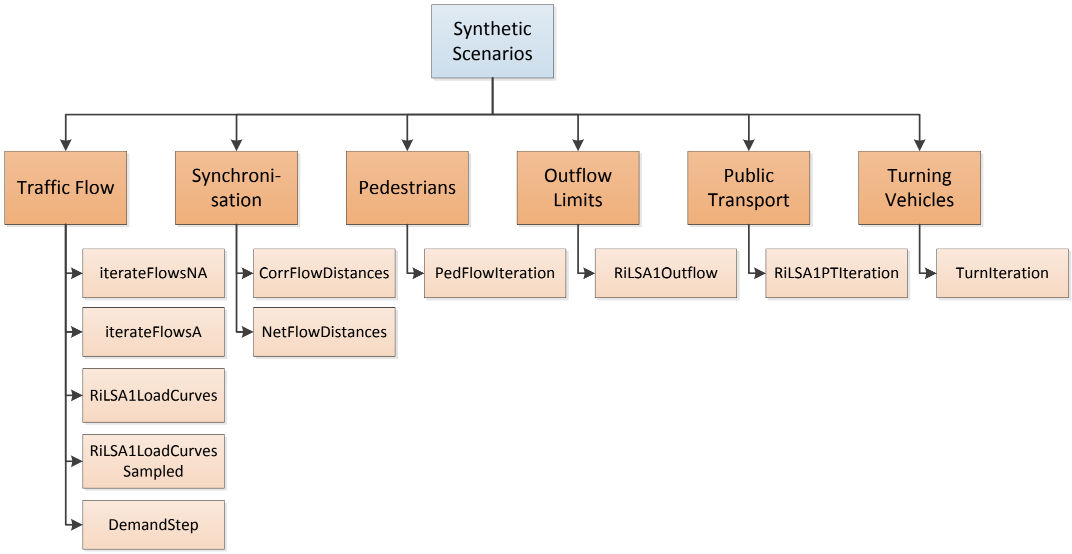


Figure 10 - Covering traffic light regulation aspects by the implemented scenario sets

Summary

This article outlined some of the achievements from the COLOMBO project. The project has developed several applications for traffic surveillance. Some of them are ready-to-use day-one applications, which, in case the enrolment of vehicular communications takes place as expected, are capable to generate commonly used traffic efficiency performance indicators.

Using them, the surrounding of an intersection could be monitored at the price of a road side unit capable to collect common CAMs. Further traffic surveillance applications based on CAMs are under development.

The developed traffic light algorithms have been shown to improve an intersection's throughput starting with equipment rates of 10 % and start to outperform actuated traffic lights, which need additional hardware under the road surface, at about 25 %. Further work, including the systems' on-line tuning as well as improvements in the surveillance algorithms, is assumed to improve the performance.

These achievements have been obtained using an existing simulation system that was extended within the project. Most of the extensions performed on open source software have been given back to the research community and were or will be included in future releases of the respective software.

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