SEVENTH FRAMEWORK PROGRAMME

PROJECT FINAL REPORT (Public)

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4.1 Final publishable summary report

Part I: Executive Summary

Traffic control systems should cope with the ever increasing demand by determining the situation on the road network and by controlling traffic flows. Emerging cooperative techniques like vehicle-to-infrastructure communication increase the knowledge about road traffic participants and open new channels for delivering information to these participants. However, most cooperative systems require large penetration rates in order to assure their functionality, making the first steps towards their deployment unattractive.

COLOMBO overcomes this hurdle by delivering a set of modern, self-organizing traffic management algorithms designed for being applicable even at low penetration rates, asserting their usability from the very first deployment days on. COLOMBO focuses on two traffic management topics: traffic surveillance and advanced traffic light control algorithms. Herein, cost-efficiency and the reduction of vehicular emissions are the project’s key objectives. Both results lay the foundations for new, cost-effective and comprehensive way to measure and handle traffic. The results of COLOMBO include prototypes for incident and emission monitoring at intersections, for traffic state estimation based on fragmented data collected in low V2X equipment rate scenarios and for the self-organizing traffic control algorithm SWARM. A key aspect in the COLOMBO investigations is the use of advanced optimization techniques for tuning the parameter sets of the traffic control algorithms.

As one of the most noticeable results of COLOMBO, even at very low V2X penetration rates around 1% SWARM can already perform as well as or better than state of the art adaptive traffic control algorithms which rely on a high number of costly inductive loop vehicle-detectors. This finding is the conclusion of extensive simulation runs for realistic traffic scenarios of congestion hot spots in a European city. Evaluations of key performance indicators that measure the waiting time, number of stops per vehicle at the intersection and the emission of pollutants substantiate this statement. The COLOMBO results give a promising outlook on the future of traffic control solutions: they will feature improved performance at a cost that is an order of magnitude reduced compared with the state of the art of today.

Many of the COLOMBO results are available to the research community as open source simulation software, simulation scenarios and publicly available publications and reports. The open source version PHEMlight of the Passenger Cars and Heavy Duty Emissions Model (PHEM) and the SWARM traffic control algorithms have been integrated into the open source Simulation of Urban Mobility software (SUMO). A tuning toolkit suitable for parameter tuning of traffic light control algorithms with the open source Iterated Race (irace) software for Automatic Algorithm Configuration was designed. The COLOMBO solutions have been implemented as iTetris Control System (iCS) applications in the COLOMBO Overall Simulation System (COSS). Other COLOMBO solutions such as Green Light Optimal Speed Advice (GLOSA) algorithms or data fusion and incident detection are implemented as SUMO-extensions, standalone applications or simply python scripts that communicate with SUMO over its TraCI interface. COSS is provided as part of the COLOMBO educational toolkit as a virtual machine. The educational toolkit is meant as an introduction for interested parties in the research community to start using, testing and evaluating the COLOMBO software solutions with little effort.

These results have been achieved in tight cooperation of the project partners Graz University of Technology contributing PHEM, the German Aerospace Center DLR issuing SUMO, the University of Bologna who devised SWARM, the Université libre de Bruxelles which maintains irace, and the Graduate School and Research Center in Communication Systems EURECOM.

Part II: Project Context and Objectives

Most research done on V2X solutions for traffic management applications concentrates on inter-vehicle communication, which only shows its benefits when assuming a large percentage of equipped vehicles. However, there is a chicken and egg situation: Vehicle manufacturers are hesitating to provide V2X features in their passenger cars as long as there is no benefit for the customer to pay for. On the other hand, road traffic technology providers are not willing to bear the risk of investing money into the development of a traffic control solution that relies on a cooperative technology that may develop into a dead end. This situation can be solved either by legal regulations or by using bridge technologies that work well in the period of transition to high V2X equipment rates. Within COLOMBO both aspects were addressed.

Prior to raising legal regulations, the society needs to know what the positive impact of the new technology is in the future. COLOMBO provides answers to some of the related research questions. On the other hand, COLOMBO provides simulation tools that enable independent researchers in the scientific community to re-evaluate the COLOMBO findings, to do their own investigations, and to find answers for other research questions not yet foreseen by the COLOMBO project consortium. The project context of COLOMBO was to do research in V2X based traffic control, traffic state estimation and traffic surveillance.

In the context of traffic surveillance, investigations were made on (ii) the collection of traffic state information from equipped vehicles by infrastructure facilities, so called Road Side Units (RSUs) and also (ii) on cooperation approaches between the few equipped vehicles, by means of data gathering, fusion and dissemination. One assumption was that the physical and deterministic aspect of traffic flow allows extrapolations of traffic state even if based on a low traffic sampling rate. Therefore, COLOMBO was supposed to deliver an analysis and simulative demonstration of the possibilities to determine traffic state using information from V2X-communication at low penetration rates, by considering self-organisation, machine learning and cooperative approaches. The objective was to do investigations on the detection of traffic flows, traffic incidents and environmental effects.

Vehicles can be classified into three categories: class A – non equipped, class B – equipped with a personal digital assistant (PDA/Smartphone/Navigation system) and class C – with full V2X sensing capabilities. One of the challenges was to experiment on different rates of A/B/C classes and to design self-organizing dissemination, collection and fusion algorithms capable of determining the traffic state and an estimation of its accuracy.

In particular, COLOMBO had to deliver the design and simulation-based prototypes of:

- a cooperative traffic state evaluation system, based on traffic state extrapolations, data gathering and fusion, including cooperative data dissemination between vehicles and RSUs,
- a local emissions monitoring system, and
- a local incidents monitoring system.

Furthermore it was planned to make realistic and synthetic simulation scenarios publicly available including hotspots within European cities where the systems could be tested in a simulation environment.

The overall objective of the work on the Self-Organizing Traffic-Light Control System SWARM was to design and implement a self-organizing, adaptive, distributed and monitoring-aware approach to traffic light control. The control system would acquire information from the V2X based traffic state estimation system developed within COLOMBO taking into account the reliability of the obtained information. On the basis of the acquired information, the traffic light control system chooses the best policy to be enforced and receives feedback on how this policy influenced traffic. The system is targeted to be used for low penetration rates (down to 1%) of equipped Class C vehicles and for low penetration rates of equipped RSUs. However, due to the self-organizing feature of the system, it was assumed to be extremely flexible to a wide range of penetration rates. Extensive simulation based tests on the system robustness at varying penetration rates were planned to be performed.

In particular, it was planned that within the investigations in the context of traffic control within COLOMBO the following tasks were fulfilled:

- Define a set of policies each specifically designed to cope with a particular traffic condition (low, medium, high traffic density, congested traffic) as well as for pedestrian crossing, bicycles, public transport and emergency vehicles.
- Design a dynamic policy selection algorithm based on input from the distributed monitoring. The policy selection should take into account the reliability of the information coming from “mobile sensor” fusion.
- Interact with the traffic surveillance systems developed within COLOMBO and automatically configure the local policies parameters and the policy selection algorithm.
- Test the resulting system on the SUMO simulator to measure the impact of low penetration rates on the policy selection algorithm.

The self-organizing traffic control algorithm SWARM switches between different so called micro-policies each designed to control traffic fairly optimal in a certain traffic state. The algorithm includes many micro-policy algorithms and the corresponding parameter sets. Therefore, the parameter set of SWARM comprises a high number of parameters. The algorithm performs best when the values of these parameters are chosen to be optimal with respect to some target parameters (e.g. average waiting time of vehicles, the number of stops per vehicle or the averaged per vehicle emissions). The process of automated selection of optimal parameter vectors is called parameter tuning.

Within COLOMBO, for the configuration and the parameterization of various sub-systems and also the overall final system, recent techniques from automatic algorithm configuration were applied.

Of particular relevance in this context are the automatic offline configuration of the decision rules that are applied by the traffic lights and the online calibration of parameters. The performance optimization also can take into account different performance measures, for example, the impact of traffic light policies on waiting times and on emissions. More in particular, it was planned to supply tools to (i) offline optimize the emergent behaviour of the traffic light system by defining and tuning decision rules that are applied by traffic lights and (ii) provide algorithmic solutions for the online adaptation of the decision rules’ parameters while the system is actually running to adapt parameters in dependence of the current traffic situation.

When tuning a traffic control algorithm for optimal emissions of pollutants, one needs to quantify emissions. Therefore, a software solution for fine-grained, high-quality measurements of the environmental impacts of the solutions within COLOMBO had to be developed. It was planned to employ the vehicle longitudinal dynamics and emission model PHEM and connect it to the other systems developed in COLOMBO via the traffic simulation SUMO. For this coupling with PHEM the simulation SUMO had to be opened for providing speed trajectories to PHEM. Additionally, as a major scientific advance, a feedback to SUMO was to be established for taking into account vehicle acceleration limitations stored in PHEM's databases.

For predicting future impact, PHEM had to be extended by models of the vehicular population in the year 2020. Additionally, evaluations on optimising traffic at intersections towards being ecologically friendlier had to be performed. Both, driver behaviour, as well as the interdependencies between traffic control and pollutant emission were to be investigated. Further COLOMBO objectives were to develop an emission-optimal driver model and guidance on traffic lights development.

In particular, research within the topic of emissions monitoring included the following tasks:

- Extend the PHEM vehicle database by future vehicles in order to resemble the vehicle population in the year 2020
- Develop a PHEM version that can be integrated in microscopic traffic models (PHEMlight)
- Establish a connection between the involved traffic simulation SUMO and PHEMlight
- Develop an emission-optimal driver behaviour for controlled intersections
- Support the work on ecologically friendly traffic light algorithms
- Deliver a guidance on how to develop ecologically friendly intersection controls

Furthermore, a generic, well-defined approach for evaluation and benchmarking of the traffic light control algorithms had to be developed, including its software realisation. Consisting of a set of well-described traffic scenarios, as well as efficiency and environmental performance metrics, the ambition of this approach was to be portable to other traffic simulation packages, allowing to be reused in later development of new traffic light algorithms. The objective was to take into regard different rates of penetration with communication and sensors, proving the COLOMBO Systems capabilities to work under low penetration rates.

The tasks in this context can be summarized as follows:

- The integration of the COLOMBO into a single execution system
- The implementation of needed interfaces for interaction with the algorithms developed in the other work packages
- The enhancement of the simulator by models for pedestrian crossings and cyclists for improving its quality
- The development and implementation of a generic approach for evaluating traffic light systems

The key objectives of COLOMBO can be summarized as follows:

1. Develop synthetic and real world scenarios especially for benchmarking traffic state estimation, incident detection and traffic control algorithms at signalized intersections.
2. Develop an evaluation scheme that allows computing performance indicators for a given algorithm in the scenarios.
3. Strain the open source tools in use for simulation (SUMO), optimization (irace), emissions calculation (PHEM) and integration (iCS).
4. Develop, tune and benchmark solutions for traffic light control, traffic state estimation, incident detection and emissions monitoring and reduction.
5. Integrate selected solutions in a single executable system – the COLOMBO overall simulation system COSS

Part III: Main Scientific and Technological Results and Achievements

Work Package 1 - Low Penetration Rate Cooperative V2X Traffic Surveillance

Work package 1 is concerned with the development of self-organizing solutions for traffic surveillance, which gather data from on-board vehicle devices, such as vehicular communication (V2X) (class C) or PDAs (class B). The work includes:

(i) V2X traffic surveillance and their evaluation considering low penetration of V2X (class C) vehicles;
(ii) Alternate technologies proposals to compensate low penetration of V2X class C vehicles with class B vehicles (Smartphone, Bluetooth);
(iii) Traffic anomalies detection based on V2X, including the impact of low V2X penetration on the reliability of the traffic surveillance;
(iv) Local emission modelling considering V2X class C vehicles to locally estimate the emission impact of traffic flows, including the evaluation of the impact of low penetration of V2X class C vehicles on the performance of the local emission.

Over the project lifecycle, we first proposed different V2X-based traffic surveillance approaches considering 100% penetration rate, and then evaluated the impact of low penetration of V2X on the surveillance systems. Two directions have then been followed: (i) propose alternate technologies equipped by class B vehicles to compensate low penetration of V2X (Class C) vehicles, (ii) leave the compensation to be corrected by the COLOMBO SWARM-based traffic light algorithms.

The V2X traffic surveillance systems developed in this work package could then be used to feed traffic state information to the traffic anomalies detection as well as local emission modelling. The work of this work package is linked with WP2, considering the close ties between traffic estimation and traffic control.

The tasks of work package 1 include:

- the development of simulation scenarios,
- investigations on V2X based traffic state estimation (TSE),
- the development of an automated incident detection (AID) system on the basis of cooperative vehicle data
- analyses of traffic alert dissemination methods, and
- to deliver an emissions monitoring system (EMS).

Scenario development

The first work in this WP was the generation of different scenarios in which all developed solutions could be tested and evaluated. The scenario implementation into the software framework itself was accomplished in WP5.

All scenarios describe the spatial (e.g., road network), temporal (demand load curve), regulatory (speed limits), technology (penetration rate, vehicle propulsion), and behavioural (driving style) parameters which are exogenous.

They were derived either completely from the real world - like the different Bologna and iTetris networks and the Monza corridor – or “synthetically” as idealised examples of common junction / network configurations. Therefore three junctions from the German “**Ri**chtlinie für **L**icht**S**ignal**A**nlagen” (guidance for traffic light systems) were taken as the RiLSA junctions #1, #2, #4 with an initial peak hour traffic demand and static fixed time control (Figure 1). The traffic on each ingoing and outgoing lane is regulated by a *satellite* traffic light. For instance, in urban scenarios, where the flows are platooned by traffic lights, each *satellite* is controlled with an actuated policy. In interurban scenarios, the *satellite*s could be fixed to green lights (emulating a free flow).

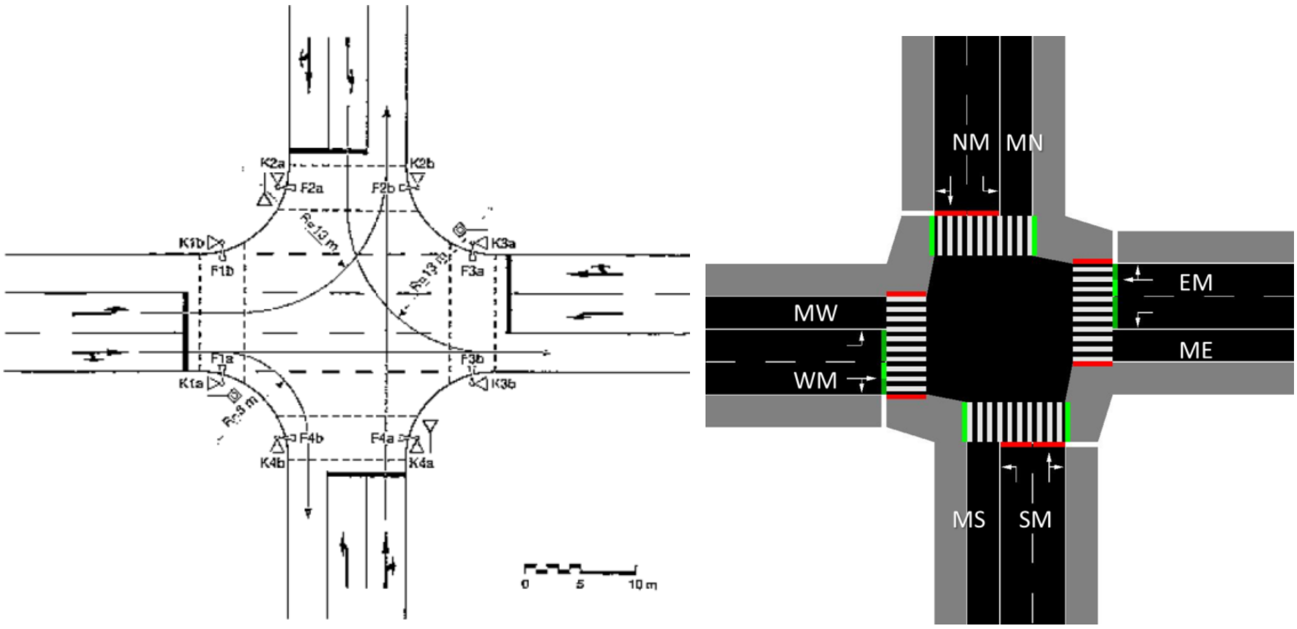

Figure 1: RiLSA network (left) and SUMO model with the edge names (right).

To investigate also fluctuations in this demand two methods were implemented: “Brute force” by simply iterating chosen parameters like the demands of both streets between a lower boundary and the capacity (or further) in equidistant steps of, e.g., 10 veh/h. The second method was an ad-hoc traffic generator based on realistic daily load curves (Figure 2). The 24h load curve was also compressed into 1h to reduce computational time.

Additionally, a fully-actuated TLC and a commercially available adaptive TLC (namely ImFlow of project partner IMTECH) were made available for scenario subsets. The technological parameter of penetration rates was set to 100%, 50%, 25%, 10%, 5%, 2.5%, and 1% for dedicated V2X, and to 30% for Bluetooth[2] where applicable. These different configurations are obtained not by modifying the number of simulated cars, which would provide unrealistic results, but labelling a set of cars as shadow cars (vehicles that do not have to be considered by our system on a particular penetration ratio).

[2] Although Bluetooth may benefit from a larger penetration rate (up to 70% in current vehicles and smartphones), only a part of them may actually be capable and configured to support traffic detection.

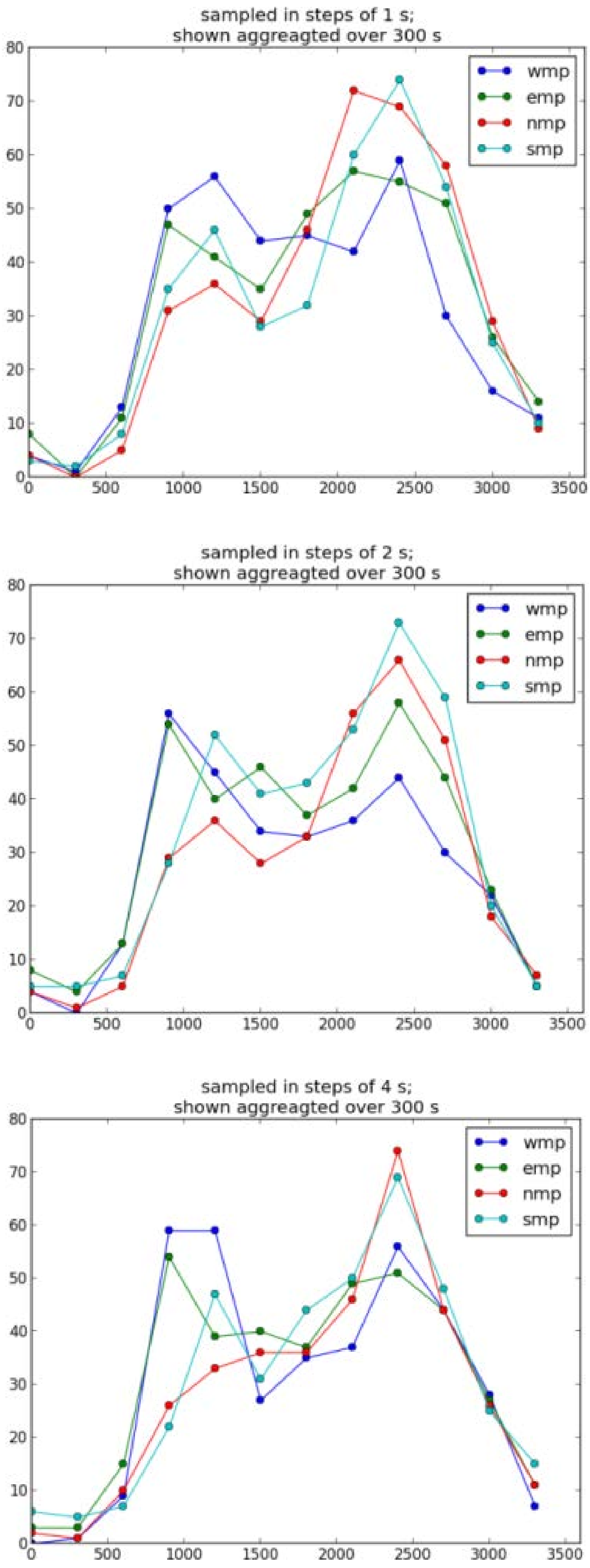

Figure 2: Sampling examples as obtained from the demand generator.

Based on the single RiLSA intersection two more structurally different scenarios were built: the Corridor and the Grid. The corridor is composed by three controlled traffic lights in a row, while the Grid has a 2 x 2 design. Figure 3 depicts the three models.

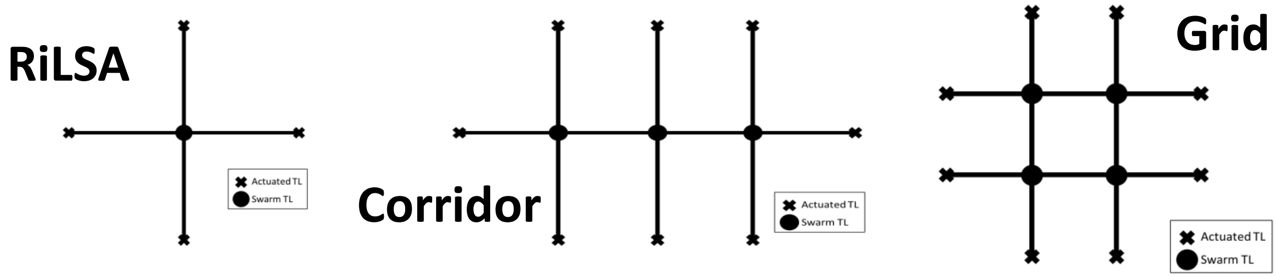

Figure 3: Synthetic but realistic scenarios.

In Figure 4 the scenario network of a part of the Monza road network (near Milan, Italy) is shown. The Monza network was based on contact with the municipality. The network layout was taken from OpenStreetmaps and the traffic demand is based on counts from the municipality. These counts were per 15 minutes over the period of 07:00 to 09:00 AM. This granularity enabled to model the natural increase and decrease of traffic volumes during the typical rush hour. The off peak scenario has no counts available, but the general traffic engineering rule of thumb to use 60% of rush hour volumes was applied. To create platoon dispersion, three passenger vehicle classes (slow, medium and fast) and a truck class were defined.

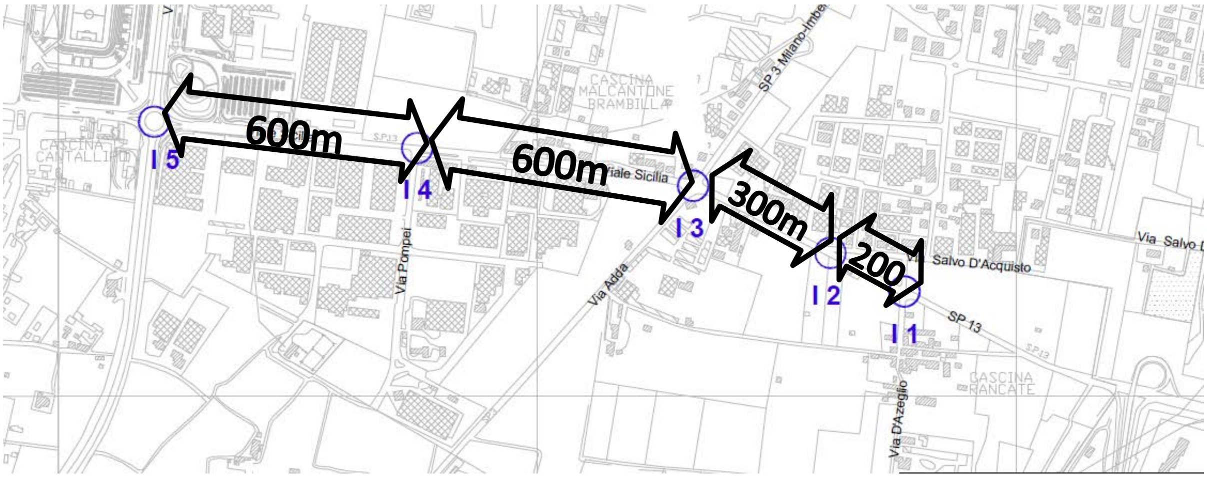

Figure 4: Overview of the Monza network.

V2X-based Traffic State Evaluation

Rather than relying on centralized (cloud-based) *Floating Car Data (FCD)*, COLOMBO proposed the concept of **Decentralized Floating Car Data (DFCD)**, aiming at benefiting from the dedicated communication capabilities of V2X-equipped vehicles (class C), even at low penetration rate, fusing them with Bluetooth/WiFi equipped vehicles (Class B) to extract, and locally consolidate the required traffic data for COLOMBO's traffic light control.

V2X-equipped vehicles supporting the ETSI ITS communication system can cooperatively exchange their position/speed information, instead of transmitting this to the cloud for traffic data consolidation. COLOMBO aims at consolidating traffic data locally either directly by vehicles, or by local RSUs.

Five approaches have been proposed by the different COLOMBO partners during the course of project for traffic surveillance:

- **Clustering-Map-Matching-based** – RSU fusion input from Class C (V2X) and Class B (WiFi-Direct) GPS position data, and uses map-matching techniques to enhance the lower positioning information from Class B vehicles.
- **Data-Dissemination-based** – RSU estimate traffic flows from the relationship between multi-hop dissemination delay and traffic density, and fusion input data from Class C (V2X) having high dissemination capabilities with Class B (Bluetooth) supporting reduced dissemination capabilities.
- **Bayesian-Network-based** – a RSU models inputs from Class C (V2X) and Class B (Bluetooth) detectors as a Bayesian network in order to efficiently fusion inputs of varying quality.
- **Probe-Vehicle-data-based** - RSU receives and tracks vehicles speed through the exchange of ISO Probe-Vehicle-Data (PVD) messages, and extrapolate missing samples.
- **Aggregation-based** – a RSU evaluates the impact of the aggregation period in the level of precision of the COLOMBO traffic surveillance, emphasizing the trade-off between real-time and accuracy.

COLOMBO D1.2 and D1.3 present a detailed description of their properties and performance. We provide here the main traffic surveillance results of the different approaches.

Cluster-based Fusion for Traffic State Estimation

The vehicles that participate in the traffic monitoring algorithm can have a complete communication package (Class C) or only a limited capability provided by an application running on a PDA (Class B). These different vehicle types differ not only in their communication capabilities, but also in the precision on the sensors used to collect the positional information. As the precision of the Cluster-based Traffic State Estimation described in [COLOMBO D1.2, 2014] significantly depends on the vehicles to precisely know their locations, heterogeneous position information (various GPS quality of V2X vs. smartphones) is expected to play a critical role.

To locate a vehicle near an intersection, when GPS shows errors, map matching may be employed. We used the positional information in different ways: the vehicle direction allows us to estimate which road a car is currently travelling on (cf. Figure 5); its position can also be correlate with a map to find the edge that it is using.

For cross-comparison with the different traffic surveillance methods proposed in COLOMBO and WP1, the RiLSA scenario has been used (Figure 1). We reported traffic surveillance data in terms of *speed (m/s)*, which is one critical indicator required by COLOMBO Swarm traffic light control in WP2. We first display the absolute values, before providing a summarizing table of the Root Mean Square Error (RMSE) of the V2X traffic surveillance system.

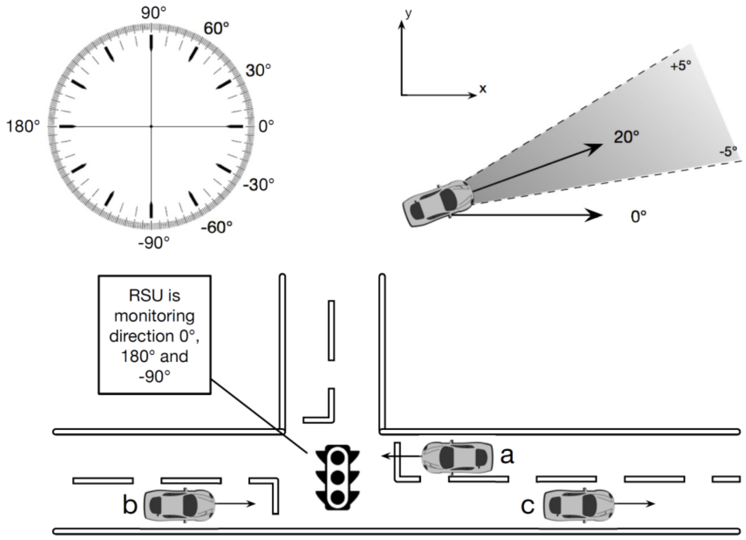

Figure 5: Definition of monitoring direction and direction compliance with an error margin.

Figure 6 shows the average speed of the vehicles estimated by the protocol. We can observe that the average speed is less influenced by the penetration rate used, with results that more closely resemble each other. Only for the lower penetration settings there are significant deviations from the mean shape, since the lower number of cars used to get the average worsen the overall result.

Table 1 provides a performance (RMSE) summary of the V2X traffic surveillance at gradual penetration ratio. We can observe that a low V2X penetration tend to worsen the performance of density estimations, which it tends to reduce the RMSE. This is an illustration of the limits of RMSE metric, as although it indicates a lower error at 1% compared to 100%, the speed curves at 1% follow significantly less the true traffic trends compared to higher penetration. Yet, this can still be compensated by traffic light control as described in the WP2.

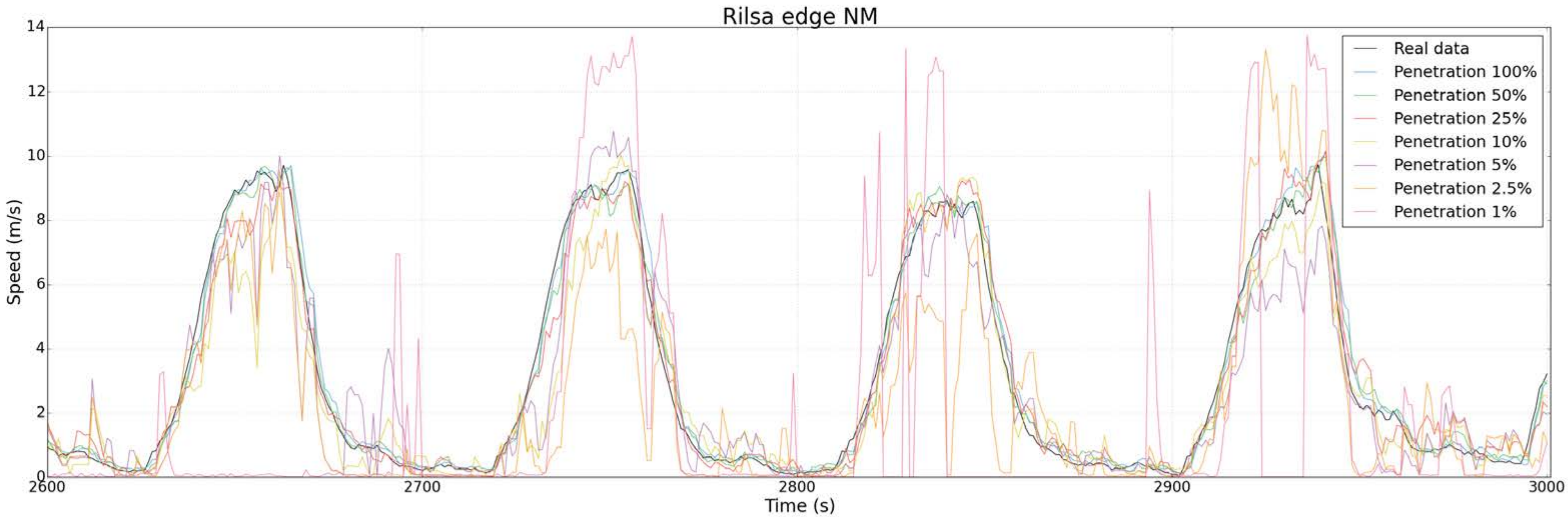

Figure 6: Average speed vs time [simulation steps] in the edge NM of RiLSA.

The described V2X traffic surveillance shows its capabilities to report traffic density or speed that is fairly accurate at high penetration. The RMSE increases while penetration decreases but curves follow similar trends, which is already good information for traffic light control. Also, the COLOMBO Swarm algorithms will also be able to internally compensate for low penetration to adapt its traffic cycles.

Table 1: Root mean square error (RMSE) of the V2X traffic surveillance.

Penetration rate	Total Cars #	Cars # edge NM	Cars # edge SM	Speed edge NM	Speed edge SM
100%	0.73	0.32	0.36	4.55	4.61
50%	11.85	2.40	3.13	4.46	4.28
25%	17.79	3.62	4.57	3.98	3.85
10%	21.84	4.45	5.57	3.59	3.30
5%	23.16	4.69	5.89	3.47	3.14
2.5%	23.81	4.83	6.05	3.97	3.52
1%	24.17	4.91	6.15	3.89	3.62

Dissemination-based Fusion for Traffic State Estimation

Similarly to the fact that Traffic Flow theory is based on three fundamental diagrams, one of which being illustrated in Figure 7, data dissemination is also based on one major fundamental diagram. Depicted on Figure 8, it shows the relationship between the delay in multi-hop dissemination wireless networks and the network density. The denser it is, the lower is the delay. DissFlow has been designed on the proposal to revert this relationship and compute network (urban road) density from multi-hop dissemination delay.

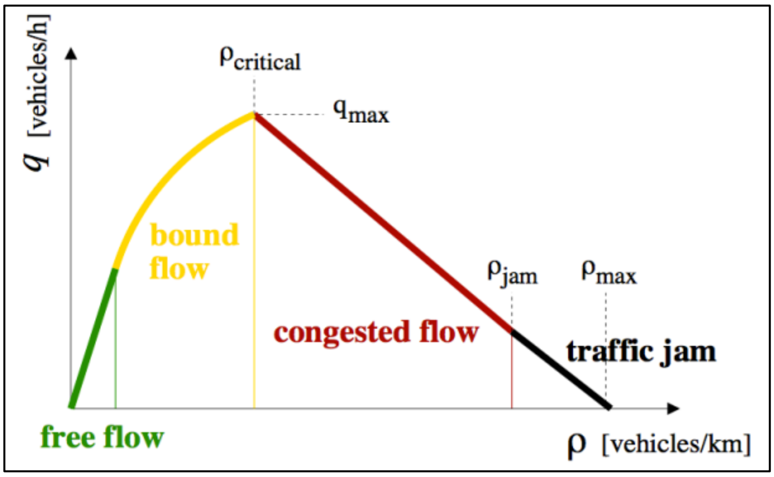

Figure 7: Fundamental Diagram of Traffic Flow.

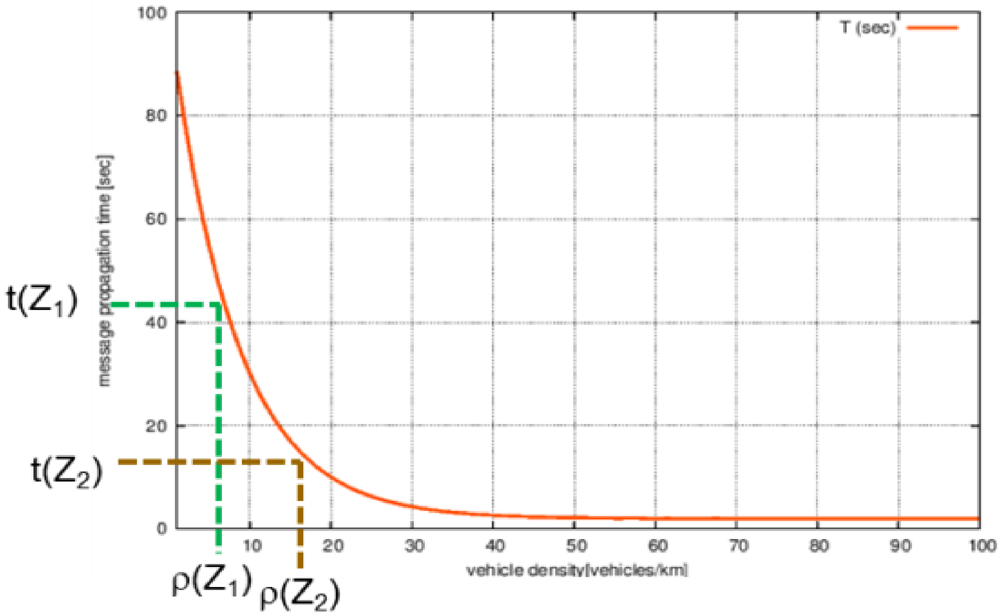

Figure 8: Fundamental Diagram of Data Dissemination.

The DissFlow protocol let RSU designates vehicles located at specific distances to disseminate a Traffic Surveillance Data message (TSD) back to the RSU, which measures the dissemination delay and extract traffic density and speed. A key aspect of DissFlow is therefore its dissemination algorithm, which should be able to support various traffic density, and also different technologies. It should be noted that unlike the definition of Class C and class B vehicles differing by their sensing capabilities and GPS positioning, our definition of the Class B and Class C vehicles defer only by the communication technology available and not on their capabilities to know their position. In this work, we assumed Class B vehicles to be equipped with Bluetooth technology, and the major difference with Class C (V2X) vehicles is a shorter transmit range (15m) compared to 100m of Class C (2X).

The performance of DissFlow for traffic speed estimations is evaluated by RMSE depicted in Table 2 for class B and Class C individually.

Table 2: Traffic speed for Class B and Class C individually, considering various penetration rates.

	100%	50%	25%	10%
Class C (V2X)	5.13	4.65	3.65	2.98
Class B (Bluetooth)	3.35	2.70	2.18	2.31

We then report the fusion of traffic speed estimates between Class C (V2X) and class B(BT) vehicles. As for density estimates, we can also clearly observe the beneficial factor of using alternate technologies for traffic speed estimates available at a higher penetration rate in order to compensate for low penetration of V2X technology.

This benefit is not only visible in Table 3, where a typical fusion between Class C (V2X) available at 10%, and Class B (BT) available at 30% provides a reduction of the RMSE of both technologies considered individually, as well as on Figure 9.

Table 3: Traffic speed - fusion between Class B and Class C vehicles.

Class C & Class B	50%-50%	25%-25%	10%-10%	10% - 30%
	3.351	3.35	3.37	2.48

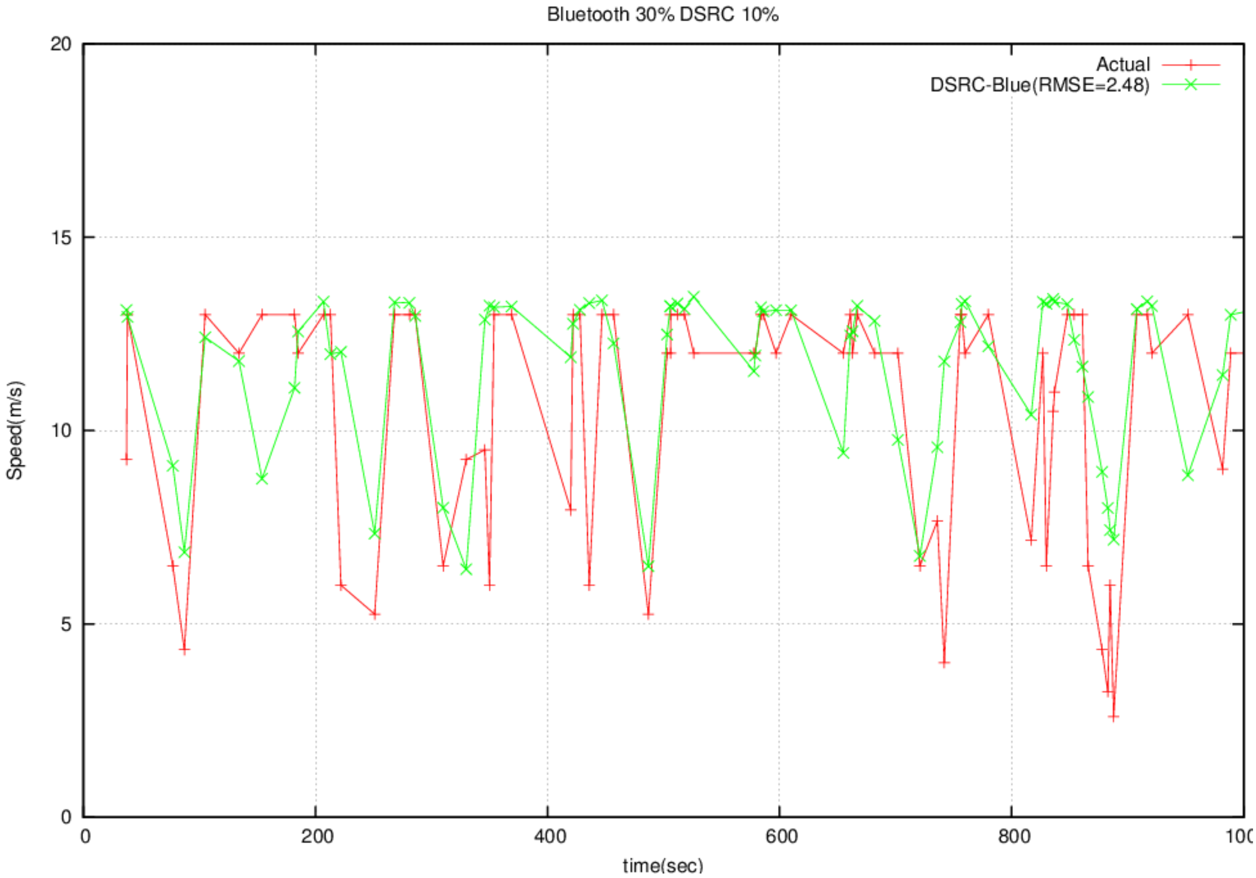

Figure 9: Traffic Speed - Fusion between class B & class C vehicles.

It may finally be noted that the overhead created by the dissemination of TSD messages creates approximatively 30bytes/second/vehicle, which relates to 1/50 of CAM overhead.

Combination of V2X and Bluetooth data by Bayesian Network Data Fusion

Determining traffic state from cooperative vehicle data at low penetration rates is a challenging task. Within COLOMBO we combined the V2X technology with a standard Bluetooth detector. Bluetooth devices of smartphones and hands-free devices have penetration rates between 3 and 50% in European cities. Bluetooth has been tested and used for traffic detection for years.

We merged V2X and Bluetooth data to obtain high quality speed estimations. On the one hand, V2X provides accurate speed data, but suffers from low penetration rate. On the other hand, Bluetooth is an occupancy detector, and is not capable of providing high quality speed estimations. Consequently, there are two opposed sensors, which shall be combined. Further, there is a lot of incomplete data, which need to be combined properly. We investigated the concept of Bayesian Networks (BN), for data fusion in this context.

The overall BN, which is capable of combining Bluetooth and C2X data to obtain the best estimate of speed, and which was developed in COLOMBO is shown in Figure 10. It consists of several nodes for modelling the underlying traffic process, i.e. the true physical speeds V of the vehicles; sensed speeds V_C2X and V_BT, the mean speed of the detected preceding vehicle V_BT'; and the speed difference ΔV.

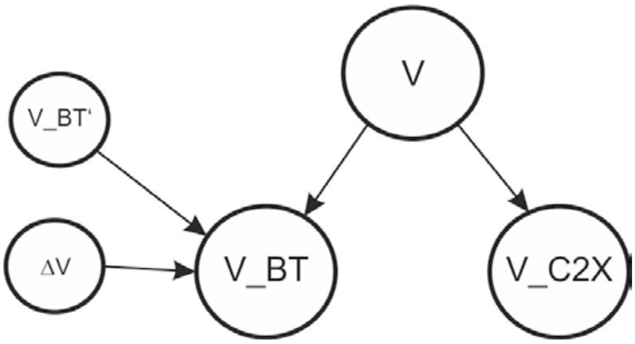

Figure 10: BN for merging C2X and Bluetooth data.

Processing the BN in Figure 10 yields an a-posteriori distribution of the speed estimation given the evidences by the sensors, which can be writes as follows:

$$P(V|V_{BT}, V_{C2X}, \Delta V, V_{BT}') = \alpha \cdot P(V) \cdot P(V_{BT}|V, \Delta V, V_{BT}') \cdot P(V_{C2X}|V) \cdot P(\Delta V) \cdot P(V_{BT}')$$

Solving the fusion equation and applying an adequate estimator allows to improve the speed estimation results. The fusion method was implemented and tested with SUMO on the RiLSA scenario (Figure 1). Table 4 presents the RMS error values for speed estimation on the different arms at different penetration rates.

Table 4: RMS error for speed estimation at different V2X penetration rates.

	Root mean square error for speed estimation [m/s]			
penetration rate	northern arm	eastern arm	southern arm	western arm
1%	2.3	4.5	1.7	5.1
2%	2.2	4.5	1.8	4.7
5%	2.3	4.0	2.0	4.3
10%	2.3	3.7	2.1	3.8
20%	2.2	3.1	2.2	3.1
50%	2.2	2.3	2.1	2.4
100%	1.8	1.8	1.6	1.9

Driving Anomalies Detection

Apart from expected behaviour of vehicle drivers, there might occur intended or unintended deviations from these patterns, herein called driving anomalies or atypical behaviour. They could lead to hazardous situations and in the worst case to road accidents. From the viewpoint of traffic safety a detection of such driving anomalies on a disaggregated level is desired. Amongst others, the Surrogate Safety Assessment Model (SSAM) is widely adopted. However, related to the COLOMBO assumption of low equipment rates, the task is pretty much reduced to traffic incident detection and to the safety measures based on trajectories.

There are numerous parameters that can be used to assess if the behavior of a road user is as usual or not. As well, the number of approaches published in literature is high. Within COLOMBO, we made studies on the performance of the PDMap approach developed by the project partner DLR. PDMaps are area histograms reflecting the expected behavior of road users (see for example Figure 11).

Figure 11: PDMap of the vehicle count on test site (Red: frequency is high, Green: frequency is low).

For the experimental investigation, a scenario data set of trajectories of real vehicles was used. These trajectories were collected using a dedicated video surveillance system and generated by means of an advanced image processing method that allows tracking vehicles over a range of more than 100m resembling well the real world V2X data to be expected at different V2X equipment rates in the future. GPS signal errors have been modelled by superimposing modelled noise of the position signal using a Gauss-Markov process.

The 3h video stream of a road scene was recorded at the sub-urban L625 road between Braunschweig's districts Bienrode and Waggum where it has a level crossing with a single-track railway line. Road block events occur frequently there for about 60s on the level crossing every time a railroad train passes.

The quality of detection has been measured (Table 5) by calculating true and false positive and negative values (for details see COLOMBO D1.3). The system exhibited notable robustness against noise added for simulating the position distortion of the GPS signal. Tests for different penetration rates, as expected, show an almost linear decline of the true positive detection rate at lower penetration rates. Large traffic jams and long lasting events can be detected well at low V2X penetration rates, while small events are less likely to be monitored. This corresponds to the needs of a traffic light controller or a road operator. Future work will concentrate on fusing the information about single atypical trajectories in order to determine the type of incident.

Table 5: Detection rates for incidents at different V2X equipment rates for trajectories with GPS noise added calculated per incident.

	penetration rate						
	1	0.5	0.2	0.1	0.05	0.02	0.01
TP	100%	80%	48%	26%	8%	10%	0%
FP	0%	0%	0%	0%	0%	0%	0%
TN	100%	100%	100%	100%	100%	100%	100%
FN	0%	0%	0%	0%	0%	0%	0%

Local Emissions Monitoring

The advantage of V2X communication for local emission monitoring is that a speed profile generated for every equipped vehicle can be directly used for the estimation of the emissions. The problem is only that it will take a long time until all vehicles will be equipped with V2X communication. To overcome this problem this work presents an approach which combines the detailed speed information from V2X communication with the data from induction loops to estimate the local vehicle emissions.

The local emission monitoring approach was tested using the traffic simulation SUMO and using the emission simulation module PHEMlight developed during the COLOMBO project. Each monitoring approach was simulated 10 times spanning 7 hours. The emissions were calculated every 5 minutes. The simulation was run with different penetration rates of equipped vehicles: 1%, 10%, 20%, and 50%.

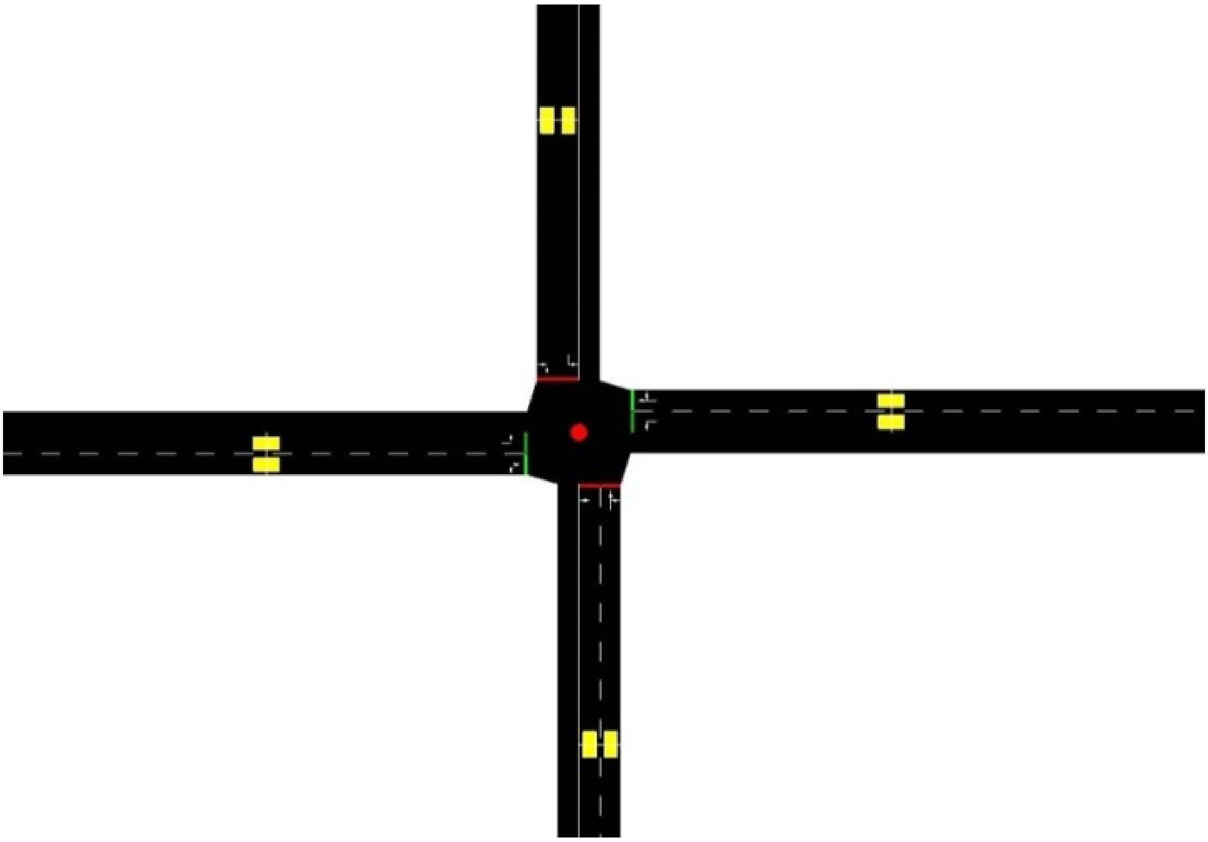

Figure 12: RiLSA scenario in SUMO with induction loops (yellow) and RSU (red).

Emission Monitoring Methods

Two methods have been proposed and evaluated to compute emission models:

- **Simple model**: From the CAM data fields speed a time-speed series can be computed. The emissions of the equipped vehicle can be calculated by feeding this time-speed series into the emission model PHEMlight which runs as an application inside the RSU.
- **Cluster Model**: To overcome the uncertainties of the basic approach the hypothesis is introduced that vehicles with a similar speed profile produce similar emissions. The basic approach was extended by a clustering of the speed-time series of the equipped vehicles. The road side unit stores the computed speed-time series of every equipped vehicle in the communication range.

Regarding the basic model, the simulation results show that even with a low penetration rate of 1 % the relative error of the estimated emissions is around 5 % after 1 hour of simulation and emission collecting time (see Figure 13). The relative error is decreasing with higher penetration rates, this effect can be expected because with a higher penetration rate the knowledge about the produced emissions is also larger.

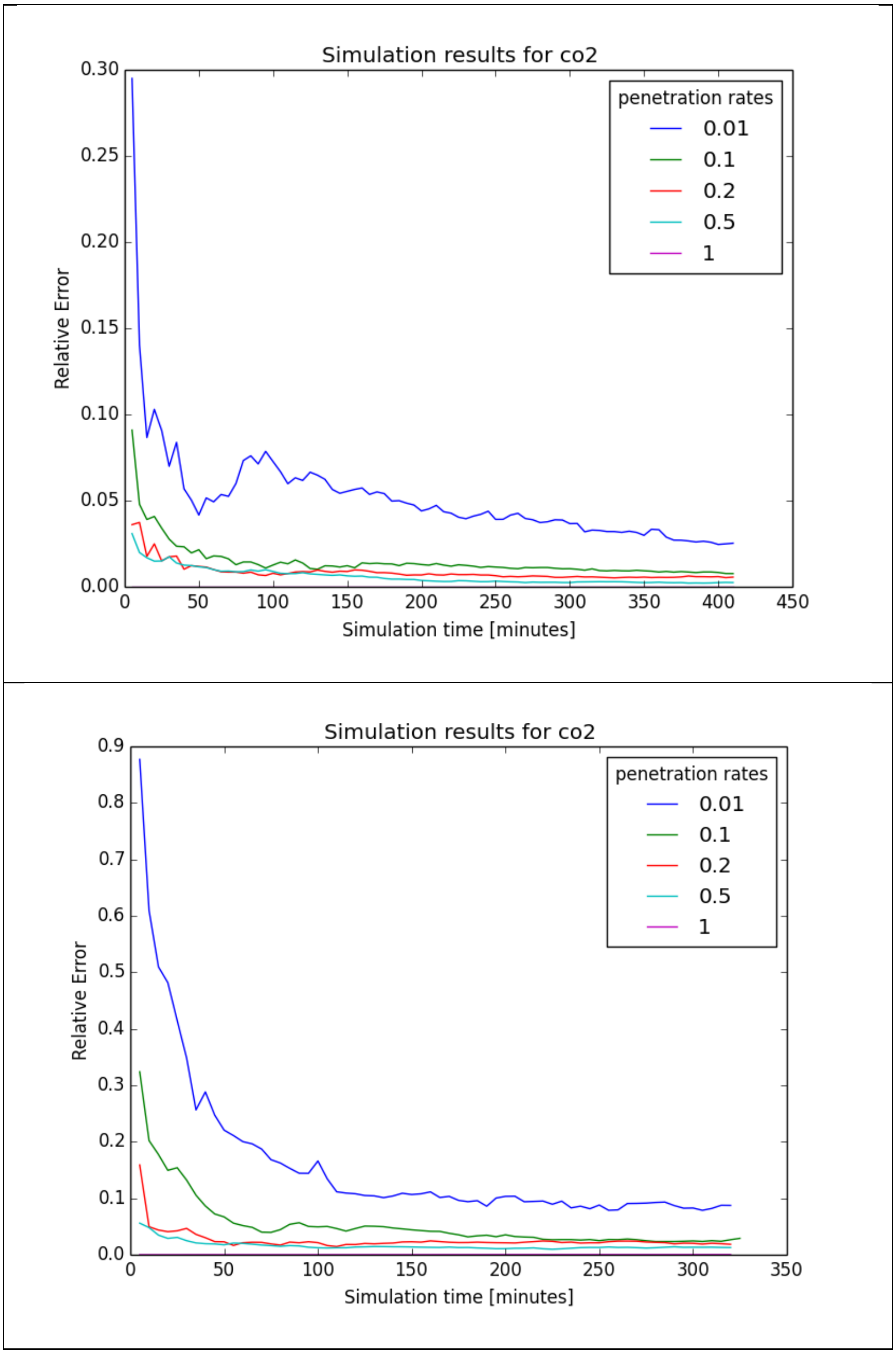

Figure 13: Relative Error of the estimated emissions over time (above) and with different vehicle types (lower).

Regarding the clustering model, the emission clusters are mapped onto the induction loops or street of the network. According to the assumption that the GPS positions of the CAMs are not accurate enough to know the exact lane and loop a vehicle is driving at, this mapping distinguishes only between the approaching streets, but not the lanes. The errors for the emission calculation with the clustering approach can be seen in Figure 14. The errors are slightly higher than the results for the basic approach but are still relatively good.

When comparing the result for the simulation with different vehicle types the clustering approach performs much better than the basic approach (cp. Figure 13).

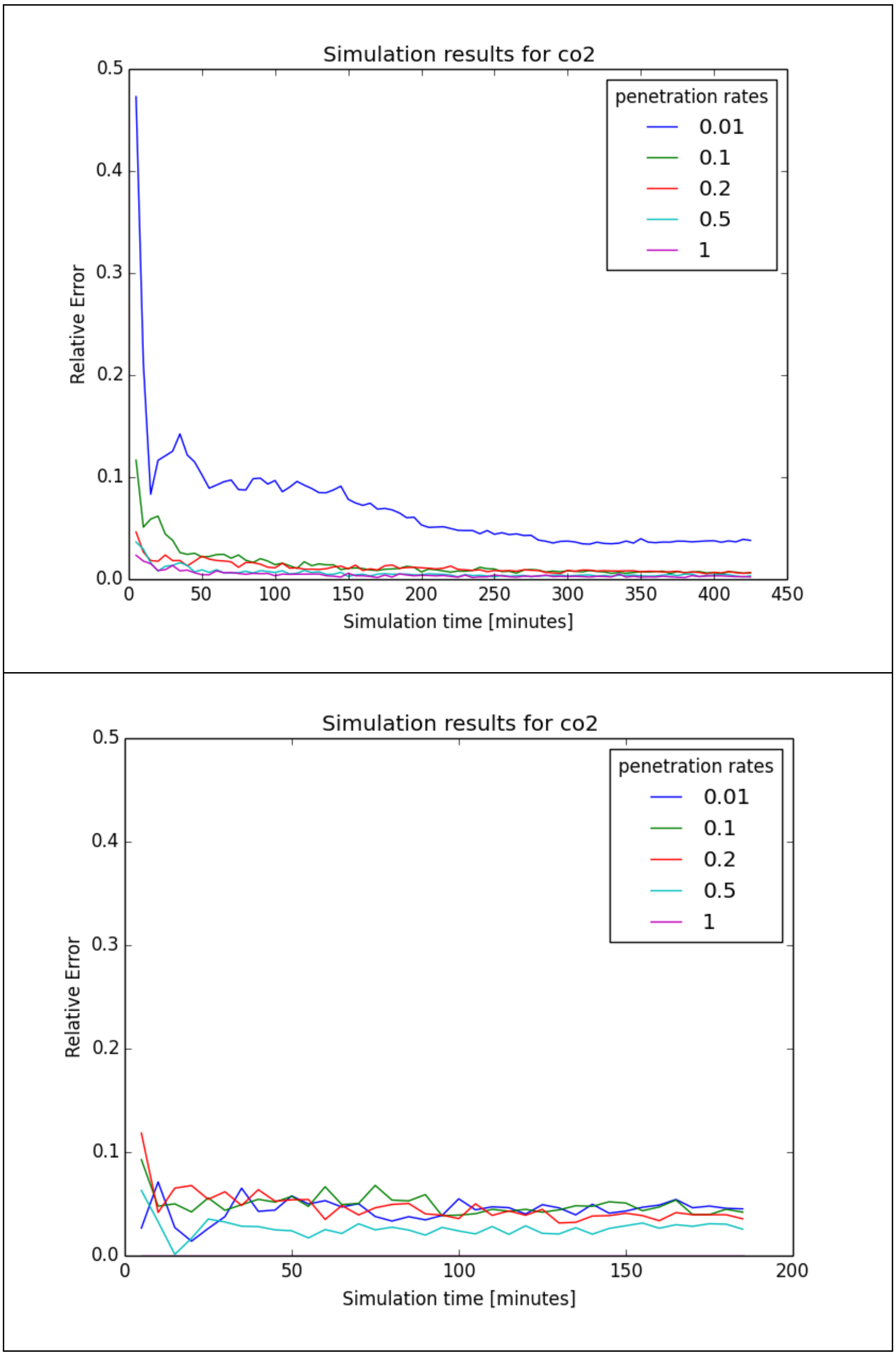

Figure 14: Relative Error of the estimated emissions over time for the clustering algorithm (above) and with different vehicle types (lower).

The basic idea of the local emission monitoring was to use the vehicle counts from induction loops and combine this information with the speed profile of equipped vehicles. The simulation results show that the algorithm can be used for emission monitoring. Even with low penetration rates of 1% the error can be as low as 10%.

Work Package 2 - Self-Organizing Traffic-Light Control System for low Penetration Rates

Introduction

In this section we briefly recall the system developed within the Work Package 2.

The main goal of Work Package 2 it to design a self-organizing traffic light control algorithm that is able to sense the traffic condition and automatically select the policy which best fits the current traffic. The algorithm is structured into two levels: the macroscopic level consists in an algorithm (called SWARM) that, using the information on the current traffic condition, chooses a proper low level policy. The microscopic level is therefore modelled through a set of policies that could take short-term decisions: when the green light should go on and off and on which lanes, the duration of the green period and so on. The selection of a microscopic policy depends on the sensed traffic condition. Given the uncertainty in the definition and measurement of “high” vs “low” traffic, we use the natural metaphor of pheromone to abstract the traffic conditions. Each microscopic level policy is mapped in the pheromone space using a stimulus function. A stimulus function specifies how to compute the current level of stimulus for every policy a traffic light controller is able to execute, with respect to pheromone levels: the more desirable the policy, the higher the stimulus. The selection of a microscopic policy is probabilistic: the higher the stimulus function for a policy, the higher the probability that the policy will be selected.

During the project lifecycle the system has been extended in several aspects:

- We have improved the pheromone computation making it more accurate and robust w.r.t. low penetration rates:
    - we use the speed and the acceleration instead of the number of vehicles;
    - we compute the dispersion pheromone which indicates if the traffic is not homogeneous among the roads of an intersection.
- We enhanced the stimulus function and the micro-policy selection.
    - Since a policy could be efficient for different traffic condition, instead of using a single Gaussian as stimulus function, we use a family of Gaussians.
- We introduced a chain change safe procedure (called decay threshold method) to avoid chain change deadlocks with very low penetration rates.
- We extended the controller to take into account pedestrian and bicycles management and give precedence to the public transports and emergency vehicles.
- We developed a realistic traffic generator based on real daily load curves.

The experimental results show that the developed system is viable, efficient, and robust to low penetration rate on both synthetic and real scenarios.

Self-organizing Traffic Lights

Our proposal abandons the traditional static approach: as implied before, the system decides when it is time to switch to the next phase on the basis of the sensed traffic conditions and not necessarily according to a clock. This makes our system able to react to changes in the traffic density both on the input and on the output lanes of the controlled junction. Communication with the neighbouring traffic light controllers is done indirectly through stigmergy, a form of self-organization, exploiting the natural metaphor of the pheromone and without explicit knowledge of the existence of other controllers.

Every traffic light controller of our system is a simple agent that controls one or more intersections and operates independently of all other controllers. It relies only on local information coming from the lanes that form the controlled intersection, which are distinguished between incoming and outgoing lanes. This principle is taken from autonomous agents' theory, where each agent relies only on local information since there is no central coordination, neither by choice nor by force.

The reason why we choose to forgo a centralized control is that it would be computationally too expensive and difficult to optimize. A centralized system would also need to predict the traffic behaviour, which is known to be a hard task since the traffic is a complex system. Moreover, a decentralized system capable of self-organization is simpler to implement and is more reactive to rapidly changing conditions.

We conceive a traffic light system as a self-organizing system such as depicted in Figure 15. The system works in a continuous loop like every classic digital control system: sensing, evaluation, action. In particular, information is acquired from sensors, elaborated and used to feed stimulus functions that probabilistically select one out of a set of rule-based policies, specifically defined for different traffic conditions, the one to be executed for the next time span.

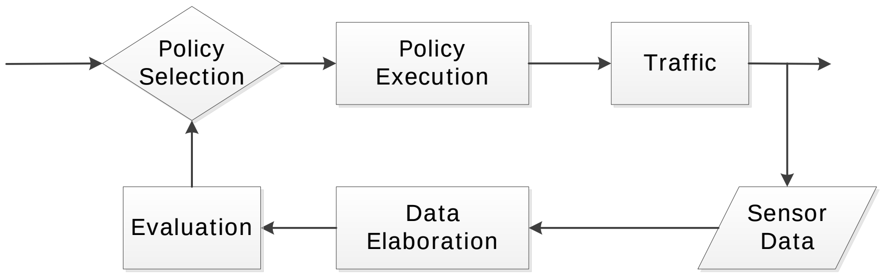

Figure 15: Self-organizing traffic light system.

The concept of static timing and phases for traffic lights is abandoned: a traffic light does not change according to any clock but after sensing. This gives traffic lights the capability to react with the smallest possible delay to traffic density changes in incoming and outgoing lanes. In comparison to conventional phase cycles, a reactive control based on sensor-aware decisions allows a larger flexibility in giving green for certain vehicle flows across the intersection.

Measuring Traffic - Pheromone Level

There is some uncertainty in the definition of "high" vs. "low" traffic and on how to measure it, because it depends on the number of lanes and their width, the geometry of the intersection, and the vehicles' paths. The measure of the traffic should be rather insensitive to very short peaks, like a singular platoon, but should react rapidly to more persistent traffic changes where we expect a burst in traffic from a single direction that will last for fifteen to twenty minutes.

For these reasons, an abstraction of the level of traffic is used, using simulated **pheromone levels.** In nature, pheromone is an olfactory trail left by some animals like ants on the path they walk. This pheromone is additive: the more ants walk on a path, the higher the level of pheromone. Pheromone also evaporates over time, allowing ants to use it as a guidance to choose their direction: the shorter the path from home to food, the less the pheromone evaporates and the higher the level.

In this project, pheromone levels are used to calculate the level of traffic: cars driving down a lane or waiting at a red traffic light leave a virtual pheromone trail. It will quickly sum up if a significant increase of the traffic volume happens, and will evaporate in a short time when the number of cars decreases.

In the system we use three pheromone levels:

- pheromone for the incoming lanes (pheromone_in, or φ_{in})
- pheromone for the outgoing lanes (pheromone_out, or φ_{out})
- dispersion of the pheromone among the approaching lanes (pheromone_dsp, or φ_{dsp})

Since the controller has to be robust to low penetration rates, instead of using the number of cars, the pheromones are computed on the average speed. In particular the pheromone value depends on the speed and on the acceleration of the equipped vehicles.

The pheromone is computed with the following equations:

$$f_l(k+1) = \beta f_l(k) + \gamma v(l,k);\ f_l(0) = 0$$

$$v(l,k) = \frac{MaxSpeed(l) - \ MeanVehicleSpeed(l,k)}{\frac{dMeanVehicleSpeed(l,k)}{dk}}$$

Note that, using only the speed and not the acceleration (which is the derivative of the speed) the pheromone value could be not accurate. For instance, the average speed of a small number of vehicles decreases faster than the average speed of a large number of vehicles approaching a red traffic light. By using the average speed as the source for the pheromone value this behaviour would result on a higher pheromone value when less vehicles are stopping compared with a larger number.

We therefore use the absolute value of the derivative of the average speed as an indicator of how quickly the speed changed. With this value, we can penalize a faster change in speed in the computation of the pheromone so that the faster the speed changes, the slower the pheromone value will follow.

Since the system is discrete, we make use of a discrete derivative, computed as the difference between the average speed at two subsequent time instants divided by the interval between them (since the protocol uses time steps of a fixes length of one second, the division is always by 1).

Figure 16 depicts the pheromone value (shown in red) and the real number of cars (in black) over time. Note that the pheromone value indeed follows the number of cars.

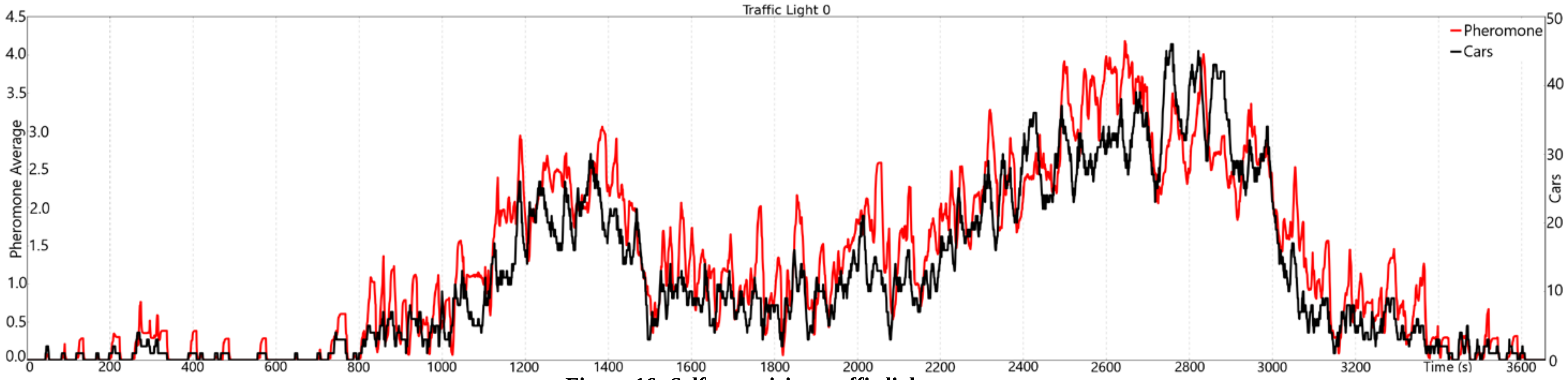

Figure 16: Self-organizing traffic light system.

Stimulus functions and Policy selection

The stimulus functions, or stimuli, are functions associated with the microscopic level policies used to probabilistically determine which policy is more appropriate according to the current traffic conditions. They map their associated policy in a the pheromone_in x pheromone_out x pheromone_dsp (i.e. φ_{in} x φ_{out} x φ_{dsp}) space. This mapping is determined experimentally or via automatic parameter tuning and is used by the SWARM policy to probabilistically select the proper policy given the pheromone on the incoming lanes (φ_{in}), the pheromone on the outgoing lanes (φ_{out}) and the pheromone dispersion over the incoming lanes (φ_{dsp}).

The idea behind the stimulus function is that the more desirable the associated policy the higher the stimulus should be, given the current pheromone values.

The shape used for the stimulus function is obtained by considering the maximum value of a family of Gaussians. The use of more than one function allows the definition of multiple areas in the pheromone space (i.e. different traffic conditions) where the policy performs best, centring each Gaussian on a different area. As stated before, the parameters of the Gaussians are computed off-line via ad-hoc experiments or automatic parameter tuning. The same policy can perform well in different traffic conditions depending on the characteristics of the controlled intersection, so the associated stimulus function may have different parameters for different agents.

The stimulus function must be normalized over its domain. This formulation makes the stimulus function similar to a probability density function, which is important since it expresses the level of specialization of a policy: we want high stimuli in the neighbourhood of specialization and a rapid decrease outside it.

With very low penetration rate configurations some of the microscopic level policies may reach a deadlock situation in which there is no chain change. This issue arises whenever the system could not detect any existing vehicles (due to the low penetration rate) on a lane served with red light. The unseen vehicles may wait for green light for a long period of time.

We solved this issue introducing a dynamic traffic threshold, called decayThreshold, working as a trigger for the chain selector. The threshold is based upon an exponential decay, which increases the probability of triggering the chain change.

Experimental results

We made synthetic benchmarks on the RiLSA, Corridor and the Grid scenarios (Figure 3). Figure 17 and Figure 18 show the results of these experiments. Each column represents the average waiting steps in [s] over a set of 100 diverse simulations for different simulation setups.

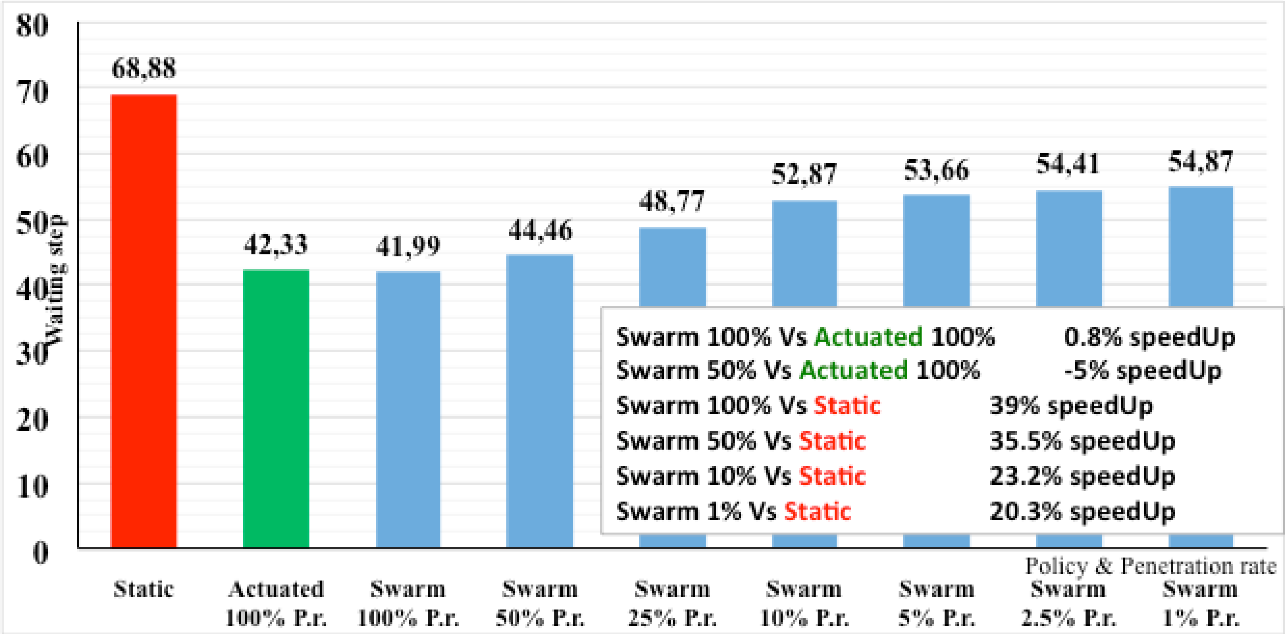

Figure 17: Corridor results.

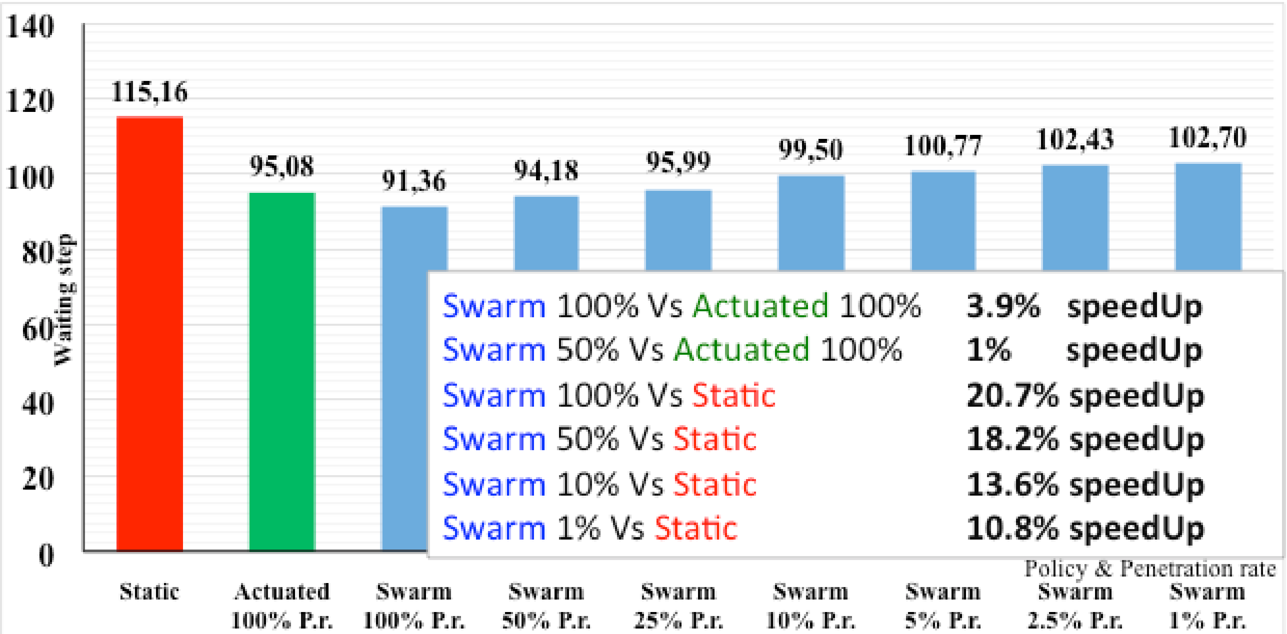

Figure 18: Grid results.

The results show that with penetration rates of more than 25% the SWARM system is comparable with the actuated (which has always full knowledge). Moreover our system outperforms the static policy even with very low penetration rates (i.e. 1%).

We conclude that the SWARM traffic light controller is efficient with regard to the average waiting time of the vehicles at an intersection and robust to low V2X penetration rates.

Work Package 3 - Automatic Algorithm Configuration and Tuning

The goal of work package 3 was to support the configuration and the parameterization of the various sub-systems, in particular, the SWARM traffic light control algorithm by recent techniques from automatic algorithm configuration. Automatic algorithm configuration techniques have previously shown to offer significant benefits in the design and development process of optimization algorithms and the COLOMBO project was the first attempt to transfer these techniques to the automatic configuration of traffic light algorithms.

The task of algorithm configuration and parameter tuning is a ubiquitous task in the development of modern optimization and control algorithms. In fact, the performance of all such algorithms depends crucially on the setting of specific parameters. In automatic algorithm configuration, parameters may refer to any choice to be made either in the algorithm design, for example, which of different algorithm strategies to use, or in the final fine-tuning of numerical parameters. Automatic algorithm configuration makes this parameterization task more automatic by transferring it to the computer instead of using the traditional manual development. The overall application cycle of automatic algorithm configuration methods (called also configurators) is shown in Figure 19. The configurator receives as input the definition of the parameters of the software to be tuned including their name, the type of parameter (e.g. categorical, ordinal, integer, continuous) and the possible values the parameters can take. With specific configurations, that is, assignments of values to all relevant parameters, the configurator calls the software to be tuned. The performance of the software is estimated by actually applying it to some instances of the target problem and returning the observed costs of the solution to the configurator. The configurator then generates new candidate configurations and the process iterates until some termination criterion of the process (such as a maximum computation time) is satisfied. When applying this scheme to the tuning of traffic light control software such as the SWARM algorithm, the evaluation of the SWARM configurations is done by simulation. As the configuration objective any measure such as average waiting time or the amount of emissions may be used. Of main importance for this process to work is also is that the simulation is realistic and provides correct estimates.

The work package 3 was structured into three main tasks. In a first step, we have reviewed the literature on automatic algorithm configuration and developed a tuning tool kit into which we have integrated the main existing automatic algorithm configuration methods. The tuning tool kit provides a common interface for the user of configurators, and takes care of the underlying details necessary to use different configurators in a transparent way. This is necessary, as the available ones use different formats for input files and interfaces to the software to be configured. One of the tasks of the tuning tool kit is to generate these necessary interfaces from one common description making easier the use of different configurators and easing comparisons among them.

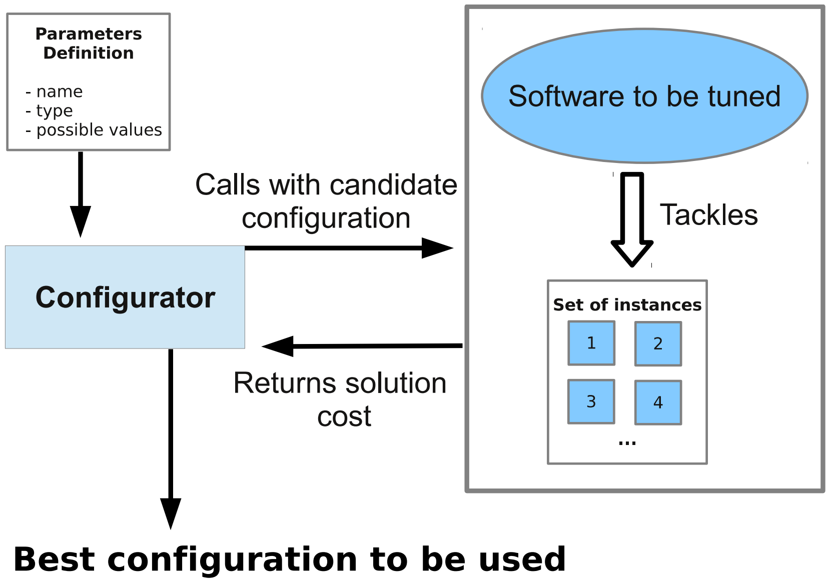

Figure 19: Summary of the interaction between configurator and software to be tuned.

A second step was concerned with the configuration methods including their comparison and improvement, the adaptation of these methods to the configuration tasks arising in the COLOMBO project, in particular, the configuration of the SWARM software, and the execution of the configurators and experimental tests of the tuning performance.

We have compared several available configurators on some benchmark tuning tasks and identified irace as the most promising of these methods for our purposes. After a detailed analysis of the behavior of irace, we have introduced a number of improvements to it such as various functionalities that make easier its usage as well as major algorithmic improvements. The algorithmic improvements mainly include a new handling of the best configurations found during the automatic configuration process, led to the new irace elite method and also a major update of the irace software (available at http://iridia.ulb.ac.be/irace).

To perform the actual configuration of the SWARM algorithm, we have adapted irace to the configuration of the first versions of the SWARM software, which had 46 parameters to be set. In fact, the use of the automatic configuration was seen as crucial due to the large number of parameters of the control software and the impossibility of setting all these parameters manually. The initial, exploratory experiments were done using a reduced setup where only one hour of traffic was simulated at a single crossing. Computational results for this setup using different penetration rates of equipped vehicles has shown that the automatic configuration tools could obtain consistently very high performing parameter configurations. While initial experiments were performed with a rather large tuning budget of 20000 simulation runs, qualitatively the same results could be obtained even with a much smaller budget of only 5000 simulation runs.

These results also suggested that the further extensions of the SWARM software with a much larger number of parameters may be feasible. In fact, the most recent versions of the SWARM algorithm with more than 100 configurable parameters were successfully tuned by irace on scenarios with a 24 hours traffic simulated and using 50000 simulation runs. Although the time of all these simulations on a single core of our machines (AMD Opteron 6272 CPUs running at 2.1 GHz) would result in a total computation time of ca. 60 CPU days, due to the parallelization capabilities of irace this time can be reduced to well below one day of wall-clock time, making the overall approach of automatic configuration through simulation well feasible.

In a final step, we examined the possibility of the online adaptation of the parameters of the SWARM algorithm. While initially it was considered to adapt specific SWARM parameters on a very small timescale of minutes or hours in the spirit of reactive search approaches, this idea was discarded in favour of an approach that consists in the occasional offline re-tuning of the SWARM algorithm parameters over a longer period. With long-term, we refer here to time-scales that are in the range of months or even years. In a nutshell, these longer-scale re-configurations have the intention to make the SWARM algorithm adapt to possible changes in what we call *environmental conditions* or *environmental changes*. With environment conditions or environmental changes we refer to modifications or changes of the setting in which the SWARM traffic light control algorithm works. Such environmental changes can include changes in the penetration rate of equipped cars, changes in the topology of an intersection or the traffic network, changes of the general characteristics of the traffic flows, or changes in the objectives of the control strategy such as an increased importance of environmental objectives over pure traffic flow oriented objectives. The high-level view of the proposed strategy is indicated in Figure 20.

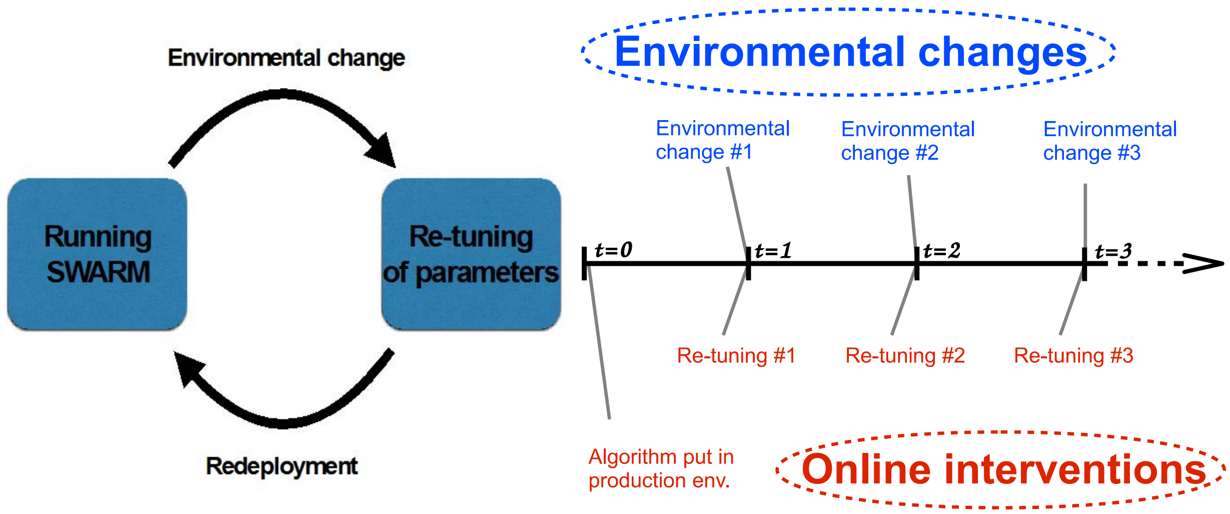

Figure 20: High-level view of the proposed approach of occasional re-tuning after (significant) environmental changes (left) and a possible time-line of interventions.

In an extensive experimental campaign we have considered the following possible environmental changes and their impact on the performance of the SWARM algorithm.

- Modifications of the penetration rate of equipped vehicles;
- changes of the network scenarios in which the SWARM algorithm is applied;
- general changes in the flow characteristics such as increases of flow densities.

The experimental study gave evidence that the proposed approach can improve significantly the performance of the SWARM algorithm over time and across the potential environmental changes. In particular, the following main trends have been observed. An increased penetration rate does not impact very strongly the performance of the SWARM traffic light controller so that re-configurations appear only to be necessary once penetration rates have increased considerably. However, a decrease of the penetration rate, for example through equipment failure, seems to significantly impact the performance of the SWARM traffic light controller that has been configured assuming a high penetration rate. When moving from one network scenario to a different one, a re-optimization of the SWARM parameters was found to be useful, although default parameter settings still obtain reasonable though sub-optimal performance. A high penetration rate makes the default parameter settings more robust with respect to changes in the network scenario. Finally, the SWARM algorithm seems quite robust with respect to changes in the traffic density of up to about 20%.

While these particular results are specific to the SWARM algorithm, we think that also many other traffic light systems, where the performance depends on the values given to some decision parameters that steer the system, may require adaptation to specific environmental changes and thus would profit from our methodology.

Overall, the usage of automatic configuration techniques to configure the SWARM traffic light control software proved to be highly successful in obtaining high quality settings and we believe that the overall simulation-optimization approach that we have followed, may be a keystone to future developments of high performing traffic light control algorithms.

Work Package 4 – Optimisation of energy consumption an emissions

The goal of work package 4 was to supply the project with an emission computation model that fulfils the project's needs. Main demand is the possibility to provide correct energy consumption and emission values for variations in instantaneous vehicle speed patterns for a representative vehicle fleet. The model has to cover future vehicle fleets also, in the means of including the possibility to compute emissions for modern combustion engines, as well as of electrical and hybrid vehicles. In addition, the emission model had to be integrated into COLOMBO's overall simulation architecture.

The first step in work package 4 was to extend PHEM[3] ("Passenger Car and Heavy Duty Emission Model") by vehicle models for the year 2020. For this task the PHEM data on gasoline and diesel vehicles from EURO 0 to EURO 6 emission legislation which were already available from former projects have been extended by hybrid electric vehicles (HEV), plug-in- hybrid electric vehicles (PHEV), battery electric vehicles (BEV) and vehicles using combustion engines but different fuels (e.g. CNG and E85). These new vehicle classes partially have different reactions on specific driving situation (e.g. brake energy recuperation) and are expected to have increasing market shares till 2020. Consequently these vehicle technologies are especially important to simulate the future effect of traffic signal control strategies which shall lead to low fuel consumption and low pollutant emissions also for the future vehicle fleet. The generation of the emission and engine maps for PHEM of these new vehicle technologies were based on on-board measurements in real word trips at TUG (HEV, PHEV and BEV) and by adapting the conventional engine maps by applying "alternative fuel factors" (e.g. CNG and E85). The PHEM model was extended by other relevant new technologies which will have a high market penetration in the future like engine start/stop systems which switch off the engine automatically during vehicle standstill phases and avoided by this the emissions during engine idling phases. The total positive effect depends on the share of idling in a driving cycle (share of idling time) but also on the percentage of vehicles equipped with this technology.

The second step was to couple the emission model PHEM with the traffic model SUMO[4] ("Simulation of Urban Mobility"). Due to the software architecture PHEM can be used for post processing the vehicle speed trajectories computed by SUMO "only", since PHEM needs information on several time steps before and after the actual computed time. PHEM needs this information to calculate the thermal status of after-

[3] http://www.ivt.tugraz.at/de/forschung/emissionen.html
[4] http://sumo-sim.org/

treatment systems, to consider effects of transient engine loads on the engine out emissions and to feed the driver model which selects the gears in the virtual vehicles. Additionally keeps PHEM long time series for each vehicle in the simulator which leads to high storage demand and long computation time. Because of these model properties it was not possible to integrate PHEM directly into the micro-scale traffic model SUMO but rather as an off-line connection where output files generated during a simulation run by SUMO are converted into inputs for PHEM. This architecture leads to a handicap when optimization loops have to be run and is in general a reduction of the user friendliness. Thus PHEMlight was developed in the COLOMBO project and was designed to be integrated into SUMO by replacing the detailed simulations from PHEM. In PHEMlight the needed time steps before and after the actual computed time where replaced by generic functions which use only information that are available in SUMO for the actual second.

The simulation tools were used in work package 4 to develop optimisation options for lower pollutant emission. The corresponding research in WP 4 concerned also emission-optimal driver behaviour for crossing a traffic light. The driving style has a significant influence on vehicle emissions and fuel consumption[5]. The results of the research can be summarised by six rules:

1. Drive as steady as possible (“cruising”) in a velocity range of 40 km/h to 80 km/h.
2. Choose the highest possible gear in order to keep the engine speed low (but above about 1.5 times the engine idling speed).
3. Drive as “anticipating” as possible in order to avoid the use of mechanical brakes as much as possible.
4. Perform decelerations in engine motoring mode (i.e. without additional mechanical braking) and using a high gear. Shift back when engine speed comes close to engine idling speed.
5. Accelerate in a moderate way using high gears.
6. Avoid stop times with running engine.

For the hybrid vehicles all above made statements are also found to be correct. Since the hybrids recuperate parts of the brake energy, mechanical braking means lower losses of energy than for conventional vehicles but still shall be avoided if possible.

[5] Fuel consumption is proportional to CO_2 emissions. Hence all conclusions discussed for emissions of CO_2 are also valid for fuel consumption.

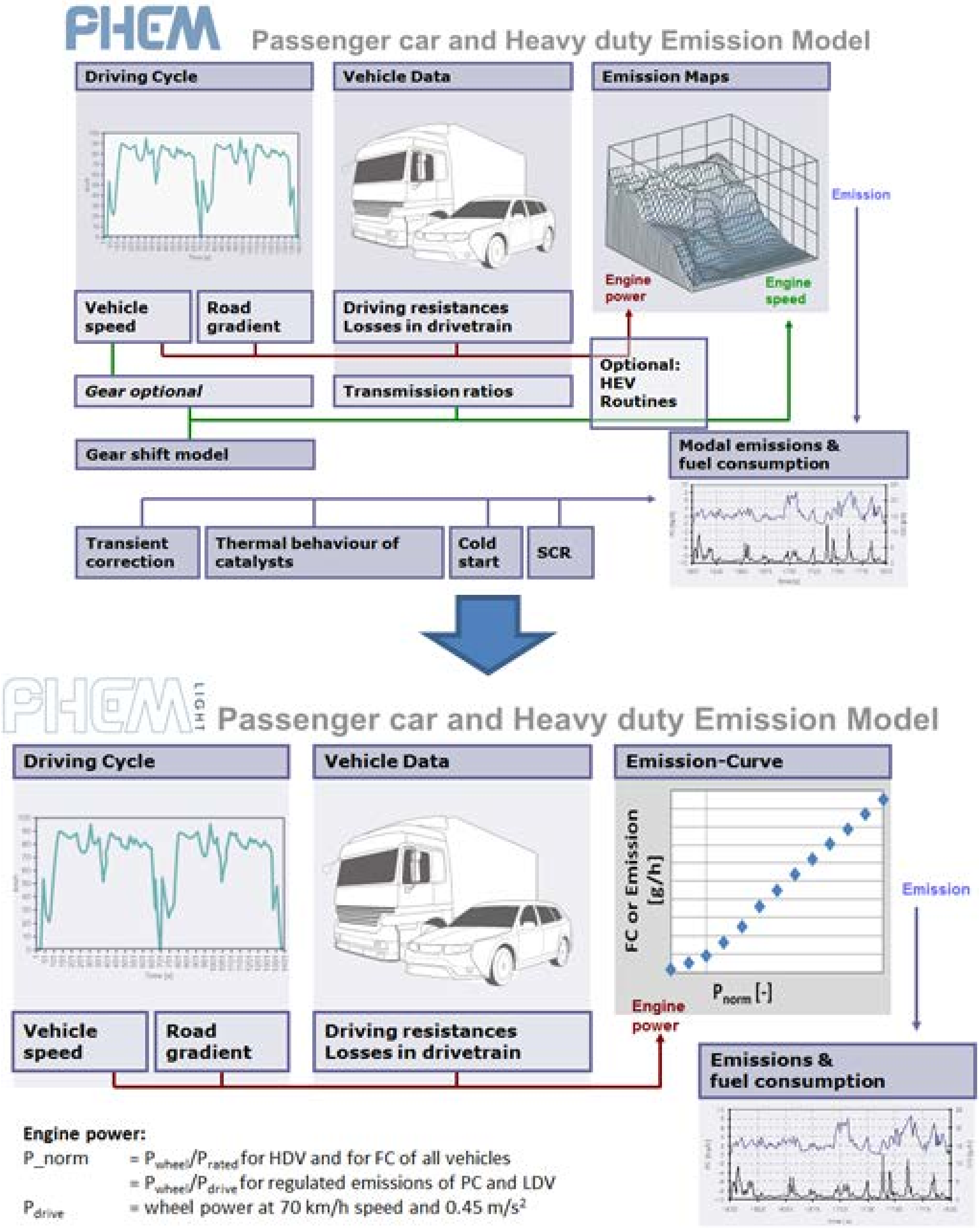

Figure 21: Model structure PHEM and PHEMlight.

The final step in the work package was to elaborate a guideline for emission optimized traffic light control (TLC). For an efficient simulation of the traffic flow and of emissions the model MONITRA (Monitoring and optimizing Traffic signalization) was developed at the TUG. MONITRA allow simple simulation runs of traffic flow and emissions on road sections with traffic light controls. The model was designed to simulate single vehicles as they accelerate, cruise, decelerate and stop to get the data necessary to integrate the PHEMlight model for emission simulation. The traffic model MONITRA is somehow a "light" version of microscopic traffic models, considering the driver behavior but no route selections. As a consequence of the simplifications the model can be set up very quickly for given road sections and also the calibration proved to be possible with low effort if measured data for the traffic flow on the road are available. The MONITRA model also includes a routine for optimizing TLC parameters for user defined target functions. The target can be a minimum in e.g. stop time, delay time, emission components, fuel consumption or weighted averages of selected parameters. As support for defining starting values for the offset between traffic lights in road networks equations were set up based on average vehicle speeds and distances between junctions.

Optimization runs with MONITRA were performed for several test cases based on real world data. Starting from state of the art base signal control plans the phase offsets are optimised by MONITRA. In the second step the selected signal control plans are fine tuned. When emissions are considered as target for optimisation approximately 10% lower emissions are obtained in the test cases compared to an optimization considering only delay times and number of stops.

The reduction potential for emissions in real applications certainly depends on the control system actually implemented. Since optimization for low emissions is typically not yet considered in controller designs, the emission reduction potential is assumed to be high. Therefore it is recommended to perform at least an analysis of possible emission reductions if local air quality problems exist or if CO_2 reduction is a political target.

PHEMlight was used for emissions calculations in the following investigations:

- development of the COLOMBO Emissions Monitoring System
- Studies on the effectiveness of Green Light Optimal Speed Advice (GLOSA)
- Evaluation of the SWARM traffic light controller in synthetic and real world scenarios

Work Package 5 – Simulation Tools and Evaluation

Work package 5 includes results the two main topics “simulation tool integration” and “evaluation”.

The developed applications of WP1 to WP4 can be tested and evaluated only in a simulated environment. This required the extension of existing simulation software tools for road traffic (SUMO), communication (ns3), and emissions (PHEM/PHEMlight), their linking via an extended middleware (iCS), the coupling with the applications as Software-in-the-Loop (SIL), and post-processing tools for the evaluation. According to Figure 22 the scenarios from WP1 are then used to feed and parameterise the COLOMBO Overall Simulation System (COSS).

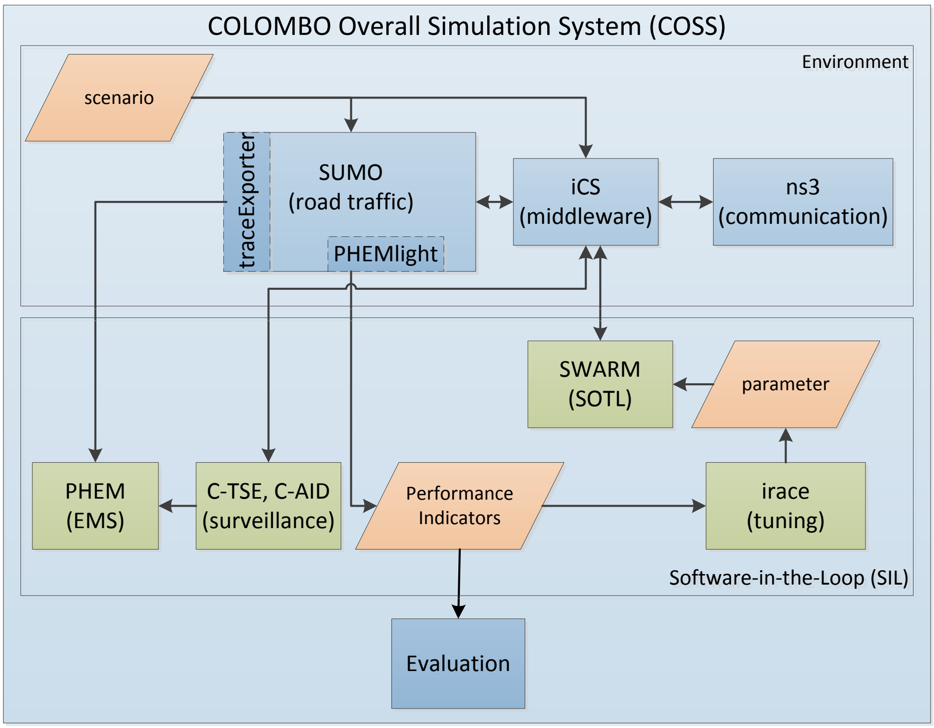

Figure 22: COLOMBO Overall Simulation System (COSS).

The following software development objectives were achieved within COLOMBO:

- The communication simulation tool ns3 was extended by key functions of WiFi direct to support smart-phone communication, RX_Container for sensed data feedback, and a sensor node for class B vehicles (D5.1).
- SUMO now includes a traceExporter to feed the external emission software PHEM (WP4). To enable emission computation in real-time a simplified derivate of PHEM was included into SUMO as PHEMlight. The previous pedestrian model was replaced by a newly developed one to represent interactions between motorised and non-motorised traffic. Also cyclists can now be modelled (D5.2). Network importer and generator tools were extended to cater for the new necessities.
- The iTetris Control System (iCS) as middleware between the different environment simulators and the applications had to be adapted to the respective connected software. Its computational performance was also achieved.
- The cooperative applications as described in WP1 to WP3 on the other hand were extended by interfaces to exchange data with the iCS middleware. An integrated SWARM algorithm implementation in SUMO was created. This implementation was needed for computational speed in the context of Software in the Loop algorithm configuration investigations.
- The irace tuning tool kit was improved and extended to handle situations in which the performance of the system to be configured will be evaluated by multiple performance measures, i.e., situations in which the configuration task actually becomes a multi-objective task.
- As the whole COSS consists of many components it was packed into a virtual machine which can be easily downloaded and used by the interested public. Parts of the COSS were also included in an educational kit together with examples.

As second part of the WP 5 the framework for the TLC algorithm evaluation was set up, containing the exact procedure and meaningful performance indicators (PIs) that address different criteria, such as traffic efficiency, environmental impacts of traffic, or road user perception and acceptance. To tackle the problem of multi-criteria decision, a single aggregated performance indicator that considers the named sub-topics was derived, too. This required the assignment of weights and grades to the indicators.

The simulation execution of the SWARM TLC algorithm took place on the Monza network. To have a fair base case optimised static fixed time TLCs with a common cycle time of 120s were computed. To compare the SWARM with more advanced commercially available algorithms an actuated TLC and IMTECH's adaptive ImFlow algorithm[6] were deployed, too. The simulated period was 120 minutes at peak time and at off-peak time (with 60% of peak time traffic volume). Each scenario was simulated 30 times and results were averaged afterwards. Determining the effect on CO_2 emissions unveiled unforeseen aspects of traffic simulation. SUMO exhibited acceleration noise due to the Krauss car following model. The respective problems could be overcome and the simulation showed a CO_2 reduction of up to 1/3 for SWARM compared with fixed time traffic control.

Generally, regarding the waiting time and number of stops, the well-tuned adaptive ImFlow algorithm is as good as or little better than the base case. The SWARM algorithm can achieve improvements - even at very low penetration rates of 1% - compared to ImFlow under certain conditions. This holds for rather simple junctions with a major and a minor corridor and 2 signal phases, as well as for complex four-armed junctions with four phases and strong flow interrelations.

At peak periods, however, this counts only for the PI "delay/waiting time", while the number of stops might increase more or less (Table 6). This can be explained by the different optimization procedures. While SWARM was tuned to minimize waiting time only, ImFlow takes both waiting time and stops in its objective function.

Table 6: Relative PI changes of SWARM 50% against adaptive TLC at Monza I1.

	Off-peak		**Peak**	
Time interval [min]	**Stops [-]**	**Delay [s/veh]**	**Stops [-]**	**Delay [s/veh]**
0-120	-3%	-34%	1%	-25%
15-30	9%	-31%	-8%	-26%
31-45	3%	-34%	14%	-19%
46-60	-1%	-36%	17%	-16%
61-75	-3%	-34%	-1%	-25%
76-90	-4%	-32%	8%	-22%
91-105	-11%	-37%	-8%	-32%
106-120	-8%	-35%	-1%	-27%

SWARM improves throughout the different penetration rates, exemplary shown for junction I1 in Table 6. The general tendency of decreasing PI values up to the penetration rate of 50% does not exclude intermediate worsening. Also the values at 100% suggest a backlash from the 50% penetration rate onwards. The interval between 50% and 100% is relatively big and without any further sampling point it is yet unclear where this contra-movement starts.

[6] Van Vliet, Koos, and Siebe Turksma. "ImFlow: policy-based adaptive urban traffic control first field experience." *9th ITS European Congress, Dublin, Ireland.* 2013.

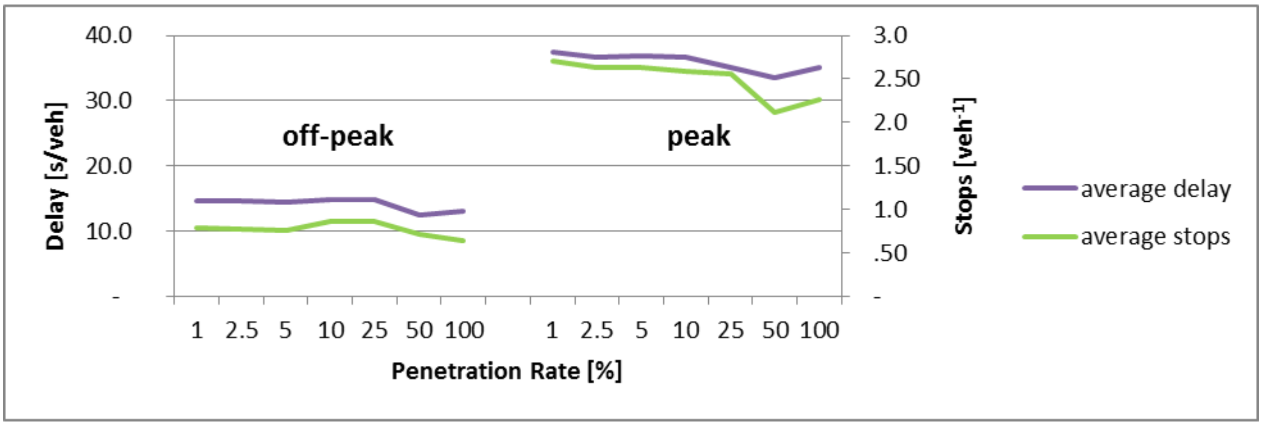

Figure 23: Interval-aggregated PIs for SWARM TLC with all penetration rates at Monza I1.

Part IV: Societal and Economic Impact

"Significant improvements in energy efficiency and environmental friendliness of transport and mobility in Europe"

The impact of the COLOMBO project mainly concerns the improvement of the efficiency and the environmental friendliness of transports in urban environments. Urbanization has been a clear trend in the past decades and this is expected to continue, with the proportion of the European population residing in urban areas increasing from 72% in 2007 to 84% in 2050. This urban sprawl is the main challenge for urban transport, as it brings a greater need for individual transport modes, thereby generating congestion and environmental problems.

Any improvement in the efficiency in the management of the traffic flows in urban scenarios has a large environmental impact, since the metropolitan mobility embodies a substantial portion of the overall impact: it accounts for 40% of CO_2 emissions and 70% of emissions of other pollutants arising from road transport. The growth of transport activity raises concerns for its environmental sustainability besides affecting the quality of life in urban environments. According to data from the European Environment Agency, transport accounted for close to a quarter (23.8 %) of total greenhouse gas (GHG) emissions and slightly more than a quarter (27.9 %) of total CO_2 emissions in the EU-27 in 2006.

COLOMBO goes in the direction of reducing emissions in urban areas by increasing the efficiency of urban transports through improvements of traffic flow, decreasing the number of stops at traffic lights and minimizing the time needed to solve congested situations.

COLOMBO has monitored the environmental aspect of the systems developed by using a very accurate emission modelling tool, PHEM and integrating this system into the SUMO simulator. Clearly, this integration has enabled an accurate estimation of emission reduction in all the tests conducted in COLOMBO and using SUMO as a base reference for traffic control and management.

Overall, results have been very encouraging: if we support the emission reduction is maintained when we go from a simulated system to a real one, we could obtain up to 33% reduction in CO_2 emissions.

For measuring the impact of the COLOMBO project on the reduction of traffic flow, we have measured also the average waiting time in queue and the throughput of traffic lights. The improvement of the efficiency of urban transport is achieved by focusing on traffic flow improvement and in particular on reducing congestions. Congestions, which are prevalent in agglomerations and in their access routes, are source of large costs in terms of delays and higher fuel consumption.

The simulation of real world scenarios validated the COLOMBO approach, achieving improvements of up to 34% of average waiting time compared to static control system and is comparable w.r.t. commercial adaptive systems. The usage of cooperative data turned out to result in larger gains for a complex network like Monza, than for simple networks like used in the beginning of the project.

One extremely interesting feature of COLOMBO that enhances significantly its impact is the extreme robustness to lack of precise information on traffic. Even at very low penetration rates, the system presents a graceful degradation in performances.

"Opening new markets for mobility, safety, energy efficiency and comfort services in Europe. Ensuring market leadership by Europe's industry in green products and services"

The COLOMBO project goes in the direction of widening the market of new ICT-based mobility and transport services by proposing innovative traffic surveillance/monitoring and traffic light control systems that exhibit the lowest-on-the-market installation, maintenance, extension and configuration costs and a short time-to-market as they are based on existing technology.

In contrast with many of the currently developed V2X applications that show their benefits at large penetration rates, COLOMBO can work with small penetration rates (down to 1%) of deployed V2X systems, and is designed to increase in performance with the growing of the penetration rate, showing the benefits of deploying V2X infrastructure and on-board systems.

The traffic surveillance system developed by COLOMBO will help traffic managers to cope with their everyday problems: being low-cost, the system allows a faster improvement of the infrastructure. In combination with the possibility to deploy it without road works, it can increase the knowledge about the state on the road network. The system can spread the coverage of the traffic that is monitored and the quality of knowledge by offering new types of data, moving from cross-section measures to a complete knowledge about vehicular dynamics across intersections and travel times between those.

Increased impact through the delivery of Open source software

Open source is increasingly relevant for research, because: "*FOSS as a development model is a very effective way to collaboratively develop software with fast take-up and improvement cycles. It is more and more used as a vehicle for the dissemination of results of ICT research projects. Those aspects are particularly important for the development of the information society, and in particular of the future internet of services, as FOSS provides open and adaptable building blocks that lower the barriers to entry to new service providers and allow them to develop and innovate faster*"[7].

In the context of EC-initiatives, the licensing of software as open source software is regarded from different point of views. Within the ICT Policy Support Programme, open source standards and reference implementations are seen as important feature[8].

Within COLOMBO, the open source traffic simulation package SUMO (http://sumo.sf.net) is used, which is developed at the DLR since 2001. SUMO was made available as open source to the public, allowing researchers not only to use the applications from the package for free, but also to modify them towards their needs. Having a functioning base for their own developments allows them to implement their ideas faster, saving development time. When made available, different approaches for certain topics – such as traffic light algorithms – implemented within the same framework are easier to compare. Making SUMO available as open source is a "success story". Researchers from different parts of the world are using SUMO within their projects, mostly in the context of Master or Diploma theses. The average daily download is currently pending between 30 and 40 downloads a day, and the amount of users communicating on the SUMO mailing list is increasing, too. SUMO is also used within several currently running EC projects, either

[7] http://cordis.europa.eu/fp7/ict/ssai/foss-home_en.html
[8] http://ec.europa.eu/information_society/activities/ict_psp/documents/ict_psp_wp2010_final.pdf

employed directly by the DLR, as in iTETRIS[9] or DRIVE C2X, or used without DLR's participation, such as in SOCRATES.

By directly extending the open source package, parts of the work done within COLOMBO allows to simulate further traffic management applications, not only to the project partners, but also to other researchers. In addition, the results can be easily verified, because both, the applications used to generate them and these applications' source code is available.

In addition to the SUMO open source simulator, other COLOMBO results are made available as open source software to public. Both, the COLOMBO System Prototype and the Automatic Algorithm Configuration and Tuning tool are delivered as open source software. The free availability of these software tools increases the chances that the solutions proposed in the COLOMBO project will be widely adopted in practice. In addition, the availability of automatic algorithm configuration and tuning tools has impact in virtually all areas where effective algorithms are repetitively used.

[9] iTETRIS was successfully closed in January 2011

Part V: Contact Details

www.colombo-fp7.eu

Work Package	Institution	Individual	Contact
	Deutsches Zentrum für Luft- und Raumfahrt e.V	Andreas Leich	Andreas.Leich@dlr.de
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WP2	ALMA MATER STUDIORUM-UNIVERSITA DI BOLOGNA	Michela Milano	Michela.Milano@unibo.it
WP3	UNIVERSITE LIBRE DE BRUXELLES	Thomas Stützle	stuetzle@ulb.ac.be
WP4	TECHNISCHE UNIVERSITÄT GRAZ	Stefan Hausberger	Hausberger@ivt.tugraz.at
WP5	Deutsches Zentrum für Luft- und Raumfahrt e.V	Andreas Leich	Andreas.Leich@dlr.de
WP6	Imtech/ Peek Traffic B.V.	Robbin Blokpoel	Robbin.Blokpoel@imtech.com

4.2 Use and dissemination of foreground

COLOMBO has made significant efforts for ensuring that the results of the project and the knowledge that it has gathered are effectively disseminated and exploited. The corresponding activities have been organized within WP6. COLOMBO Deliverable 6.3 – Exploitation plan has been issued on this subject. The exploitation plan gives an overview on exploitable results, stakeholders and business-cases.

Project results have been disseminated during the project through various channels, including

- the COLOMBO website (http://www.colombo-fp7.eu/)
- the COLOMBO group on linked in (https://www.linkedin.com/grps/COLOMBO-Project-7478383)
- COLOMBO webinars in 2014 and 2015
- scientific publications at conferences
- a COLOMBO special session at the ITS world congress
- the presentation of the project results at workshops and invited presentations, like within the German Road and Transportation Research Association FGSV.

COLOMBO is in dialog with public authorities of the European cities Monza, Bologna and Amsterdam and the state of North-Holland. Scenarios of congestion hotspots within these cities have been studied within COLOMBO and were used to demonstrate the performance of the SWARM algorithm. COLOMBO has published the Guideline for emission optimised traffic light control intended to support traffic engineers in designing environmental friendly solutions with today's road traffic technology.

Dissemination and exploitation of the COLOMBO results will continue after the end of the project COLOMBO. The COLOMBO project partners seek opportunities for turning the concepts, ideas, prototypes and solutions into products and business-cases, as outlined in section 5 of the COLOMBO exploitation plan. Within COLOMBO, novel ideas were born inducing new project proposals in national and European (e.g. Eurostars and H2020) scope.

In the transition phase where the availability of V2X communication is still in its infancy, the use of class B vehicle information as proposed in Deliverable 1.2 section 4.4 and in Deliverable 1.3 section 2.2 can act as a bridge technology. The COLOMBO project partners have evidence that a traffic control solution like SWARM is feasible as a commercial product even in today's "pre-V2X"-world, if implemented on the basis of floating car traffic data available on the market.

Beside the perspective of turning results into a commercial product, COLOMBO provides many open source tools to the scientific community. Many of the results have already been integrated into the open source tools PHEMlight, SUMO, iCS and irace. All of the tools mentioned, except of iCS, are maintained and supported by the project partners making the COLOMBO achievements a sustainable contribution to the scientific community. The educational toolkit helps making small the initial hurdles for interested parties to start using the COLOMBO solutions.

Section A (public)

This section includes two Tables

- Table A1: List of all scientific (peer reviewed) publications relating to the foreground of the project.
- Table A2: List of all dissemination activities (publications, conferences, workshops, web sites/applications, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters).

These tables are cumulative, which means that they should always show all publications and activities from the beginning until after the end of the project. Updates are possible at any time.

TABLE A1: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES

NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[10] (if available)	Is/Will open access[11] provided to this publication?
1	*The Bologna ringway dataset: improving road network conversion in SUMO and validating urban mobility via navigation services*	*Härri, Jérôme (lead: Luca Bedogni)*	*IEEE Transactions on Vehicular Technology,*		*IEEE-Inst. Electronical Electronics Engineers Inc.*		*2015*		*ISSN: 0018-9545*	*Yes, personal websites. Dataset fully open*
2	*V2X data dissemination delay for vehicular traffic density estimations*	*Härri, Jérôme (Lead: Sosina Gashaw)*	*IEEE 16th International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM),*		*IEEE Computer Society press*		*2015*			*Yes, personal website*

[10] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).
[11] Open Access is defined as free of charge access for anyone via Internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

3	*Cloud PaaS Brokering in Action: The Cloud4SOA Management Infrastructure*	*Luca Foschini*	*the 82nd IEEE Vehicular Technology Conference 2015 (VTC2015-Fall)*	Sept 2015	*IEEE Computer Society Press*	*Piscataway, NJ*	2015			
4	*V2X Protocols for Low-Penetration-Rate and Cooperative Traffic Estimations*	*Paolo Bellavista*	*80th IEEE Vehicular Technology Conference 2014 (VTC2014-Fall)*	Sept. 2014	*IEEE Computer Society press*	*Piscataway, NJ*	2014	pp-1-6		
5	*Optimal driving of connected vehicles at traffic lights.*	*Marko Woelki*	*Proceedings of the TRB 94th Annual Meeting in Washington*	*2016*	*The National Academies of Sciences, Engineering, and Medicine*	*Washington*	*2016*	*n/a*		*Yes*
6	*Automatic (offline) Configuration of Algorithms*	*Thomas Stützle*	*Proceedings of the 15th annual conference companion on Genetic and evolutionary computation*	*2013*	*ACM Press*	*New York*	*2013*		http://dx.doi.org/10.1145/2464576.2482681	*Yes*
7	*Implementing and evaluating V2X protocols over iTETRIS: traffic estimation in the COLOMBO project*	*Federico Caselli*	*4th ACM Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications (DIVANet'14)*	*Sept. 2014*	*ACM Press*	*New York*	*2014*	*pp. 1-6*		
8	*Swarm-based traffic lights policy selection*	*Michela Milano*	*4th ACM Symposium on Design and Analysis of Intelligent Vehicular Networks and Applications (DIVANet'14)*	*Sept. 2014*	*ACM Press*	*New York*	*2014*			
9	*Swarm Based Controller for Traffic Light Management BEST PAPER AWARD*	*Michela Milano*	*Int. Conference of the Italian Association of Artificial Intelligence*	*Sept 2015*	*Springer Verlag*	*Heidelberg, Germany*	*2015*			
10	*COLOMBO: Exploiting Vehicular Communications at Low Equipment Rates for Traffic Management Purposes*	*Daniel Krajzewicz*	*Advanced Microsystems for Automotive Applications 2015*	*June 2015*	*Springer International Publishing*	*Berlin*	*2015*	*pp. 117-130*		

11	*An Analysis of Parameters of irace*	*Leslie Pérez Caceres*	*Evolutionary Computation in Combinatorial Optimisation - 14th European Conference, EvoCOP 2014*	*n/a*	*Springer Verlag*	*Heidelberg*	*2014*	*pp. 37-48*	*http://dx.doi.org/10.1007/978-3-662-44320-0_4_*	*Yes, personal and institutional website*
12	*Traffic management based on vehicular communication at low equipment rates*	*Daniel Krajzewicz*	*Proceedings of the 22nd ITS World Congress*	*Octobe r 2015*	*Omnipress*	*Bordeaux*	*2015*			
13	*Driving patterns reducing pollutant emission at traffic lights*	*Marko Wölki*	*Proceedings of the 22nd ITS World Congress*	*October 2015*	*Omnipress*	*Bordeaux*	*2015*			
27	*Emission optimized control for isolated intersections*	*Robbin Blokpoel*	*Proceedings of the 22nd ITS World Congress*	*October 2015*	*Omnipress*	*Bordeaux*	*2015*			
28	*Data fusion of cooperative data with adaptive traffic control*	*Robbin Blokpoel*	*Proceedings of the 22nd ITS World Congress*	*October 2015*	*Omnipress*	*Bordeaux*	*2015*			
	Unified Evaluation Method for Traffic Control Algorithms	*Robbin Blokpoel*	*Proceedings of the 21st ITS World Congress*	*Septem ber 2014*	*Omnipress*	*Detroit*	*2014*			
14	*Traffic simulation for all: a real world traffic scenario from the city of Bologna*	*Laura Bieker*	*Modeling Mobility with open Data 2nd SUMO Conference 2014*	*May 2014*	*Springer International Publishing AG*	*Berlin*	*2014*		*ISSN 2196-5544*	
15	*NETWORK CONVERSION FOR SUMO INTEGRATION*	*Robbin Blokpoel*	*Modeling Mobility with open Data*	*May 2014*	*Deutsches Zentrum für Luft und Raumfahrt e.V.*	*Berlin*	*2014*		*ISSN 1866-721X*	
16	*INTERFACE BETWEEN PROPRIETARY CONTROLLERS AND SUMO*	*Robbin Blokpoel*	*2nd SUMO Conference 2014*	*May 2014*	*Deutsches Zentrum für Luft und Raumfahrt e.V.*	*Berlin*	*2014*		*ISSN 1866-721X*	
17	*COLOMBO: Significant Differences concerning Traffic Light regulations and its Implication for Traffic Light Control across Europe*	*Cornelia Hebenstre it*	*Proceedings of ITS Europe 2014*	*June 2014*		*Helsinki*	*2014*			
18	*Traffic control using probe vehicle data*	*Robbin Blokpoel*	*Proceedings of ITS Europe 2014*	*June 2014*		*Helsinki*	*2014*			

19	*COLOMBO: Investigating the Potential of V2X for Traffic Management Purposes assuming low penetration Rates*	*Daniel Krajzewicz*	*Proceedings of ITS Europe 2013*	*June 20143*		*Dublin*	*2013*			
20	*Including pedestrian and bicycle traffic into the traffic simulation SUMO*	*Daniel Krajzewizc*	*Proceedings of ITS Europe 2014*	*June 2014*		*Helsinki*	*2014*			
21	*Großflächige Simulation von Verkehrsmanagementansätzen zur Reduktion von Schadstoffemissionen*	*Daniel Krajzewicz*	*Proceedings of VWT 2014*	*n/a*		*Dresden*	*2014*			
22	*Extending the iTETRIS platform for Smartphone sensing and communication simulation*	*Jérôme Härri*	*5th European Transport Research Arena (TRA)*	*n/a*		*Paris*	*2014*			
23	*Simulation of V2X applications with the iTETRIS system*	*Daniel Krajzewizc*	*4th European Transport Research Arena (TRA)*	*n/a*		*Athens*	*2012*			
24	*New traffic light control strategy based on probe vehicle data*	*Robbin Blokpoel*	*18th Euro Working Group on Transportation*	*July 2015*		*Delft*	*2015*			

TABLE A2: LIST OF DISSEMINATION ACTIVITIES

NO.	Type of activities[12]	Main leader	Title	Date/Period	Place	Type of audience[13]	Size of audience	Countries addressed
1	*Conference*	*Robbin Blokpoel*	*Special Session: SIS 2604 'Traffic management with cooperative detection'on 22nd ITS World Congress*	*October 2015*	*Bordeaux*	*Scientific Community, Industry, Policy Makers*	*70*	International
2	*Presentation*	*Michela Milano*	*City Contact COLOMBO traffic control system*	*2015*	*Monza*	*City community*	*2*	*Italy*
3	*Conference*	*Thomas Stützle*	*Invited Plenary Talk 2013 IEEE Congress on Evolutionary Computation*	*2013*	*Cancun, Mexico*	*Scientific Community*	*300*	*International*
4	*Workshop*	*Wolfgang Niebel*	*Constituting Meeting of FGSV working group 1.4.5*	*January 2015*	*Cologne*	*Scentific Community, Policy Makers, Industry*	*20*	*Germany*
5	*Workshop*	*Robbin Blokpoel*	*Meeting of the traffic engineering group of the state government of North-Holland*	*February 2015*	*Haarlem*	*Government, traffic engineering community*	*10*	*Netherlands*
6	*City contact*	*Jérôme Härri*	*COLOMBO Smart Traffic Light System*	*2015*	*Monaco/Nice*	*City community*	*5*	*France*
7	*Conference*	*Thomas Stützle*	*Tutorial Genetic and*	*2013 – 2015 (three times)*	*Madrid, Amsterdam,*	*Scientific Community*	*50*	*International*

[12] A drop down list allows choosing the dissemination activity: publications, conferences, workshops, web, press releases, flyers, articles published in the popular press, videos, media briefings, presentations, exhibitions, thesis, interviews, films, TV clips, posters, Other.

[13] A drop down list allows choosing the type of public: Scientific Community (higher education, Research), Industry, Civil Society, Policy makers, Medias, Other ('multiple choices' is possible).

			Evolutionary Computation Conference		*Vancouver*			
8	*Workshop*	*Jérôme Härri*	*Tutorial / Summer School A Vehicular Mobility Cookbook for Smart Mobility*	*2013*	*Munich*	*Scientific Community, Teaching*	*50*	*International*
9	*Workshop*	*Jérôme Härri*	*Tutorial / short Course Communication Technologies and the Internet of Things in ITS (Essentials of ITS)*	*2015*	*Munich*	*Scientific Community*	*20*	*International*
10	*Conference*	*Martin Dippold*	*Guideline for emission optimised traffic light control on Conference (21th International Transport and Air Pollution conference 2016)*	*2016*	*Lyon*	*Scientific Community*	*n/a*	*International*
11	*Presentation*	*Michela Milano*	*Lecture COLOMBO solution for low carbon mobility*	*2014*	*Bologna*	*Smart City Exhibition: audience of policy makers, local authorities*	*80*	*Italy*
12	*Other*	*Jérôme Härri*	*Lectures/Labs Traffic Efficiency and Environment*	*2012-2015 (three times)*	*Sophia-Antipolis*	*Master program*	*5-10*	*International*
13	*Conference*	*Thomas Stützle*	*Invited Plenary Talk 2nd Brazilian Conference on Intelligent Systems (BRACIS-13)*	*2013*	*Fortaleza, Brazil*	*Scientific Community*	*200*	*International*
14	*Exhibition*	*Michela Milano*	*Bologna smart city exhibition*	*November 2014*	*Bologna*	*Policy makers, Civil society, Industry*	*60*	*Italy*
15	*Posters*	*Laura Bieker*	*8th Car2Car Forum*	*November 2014*	*Brunswick*	*Industry*	*500*	*Germany*
16	*Conference*	*Thomas Stützle*	*Tutorial EURO 2015*	*2015*	*Glasgow*	*Scientific Community, Industry*	*200*	*International*

17	*Conference*	*Thomas Stützle*	*Invited Plenary Talk EVOLVE 2014*	*2014*	*Beijing, China*	*Scientific Community*	*70*	*International*
18	*Conference*	*Thomas Stützle*	*Invited Plenary Talk 8th International Symposium on Intelligent Distributed Computing (IDC'2014)*	*2014*	*Madrid, Spain*	*Scientific Community*	*80*	*International*
19	*Conference*	*Thomas Stützle*	*Invited Plenary Talk VIII ALIO/EURO Workshop on Applied Combinatorial Optimization*	*2014*	*Montevideo, Uruguay*	*Scientific Community*	*150*	*International*
20	*Conference*	*Thomas Stützle*	*Invited Plenary Talk Evolutionary Multi-objective Conference (EMO 2015)*	*2015*	*Guimaraes, Portugal*	*Scientific Community*	*120*	*International*
21	*Posters*	*Marek Junghans*	*9th Car2Car Forum*	*November 2015*	*Mainz*	*Industry*	*500*	*Germany*
22	*Workshop*	*Wolfgang Niebel*	*Workshop on socio-economic impacts of road vehicle automation organised by the FP7 project CityMobil 2*	*March 2015*	*La Rochelle*	*Scientific Community*	*100*	*International*

Section B
Part B1

No applications have been made for patents, trademarks, or registered designs.

Part B2

Please complete the table hereafter:

Type of Exploitable Foreground[14]	Description of exploitable foreground	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application[15]	Timetable, commercial or any other use	Patents or other IPR exploitation (licences)	Owner & Other Beneficiary(s) involved
Commercial exploitation of R&D results	*Traffic state estimation solution based on floating car probe vehicle data (FCD)*	*NO*	*31/12/2017*	*Hard-And-Software Solution*	*H49.3.1 - Urban and suburban passenger land transport*	*to be defined*	*none*	*IMTECH*
General advancement of knowledge	*Traffic state detector based on Bluetooth and V2I detection and data fusion*	*NO*	*31/12/2017*	*Software Solution*	*H49.3.1 - Urban and suburban passenger land transport*	*to be defined*	*patent is planned*	*DLR*

[19] A drop down list allows choosing the type of foreground: General advancement of knowledge, Commercial exploitation of R&D results, Exploitation of R&D results via standards, exploitation of results through EU policies, exploitation of results through (social) innovation.

[15] A drop down list allows choosing the type sector (NACE nomenclature) : http://ec.europa.eu/competition/mergers/cases/index/nace_all.html

Type of Exploitable Foreground[14]	**Description of exploitable foreground**	Confidential Click on YES/NO	Foreseen embargo date dd/mm/yyyy	**Exploitable product(s) or measure(s)**	**Sector(s) of application**[15]	**Timetable, commercial or any other use**	**Patents or other IPR exploitation (licences)**	**Owner & Other Beneficiary(s) involved**
General advancement of knowledge	*V2X based traffic controller based on SWARM*	*NO*	*31/12/2017*	*Software Solution*	*H49.3.1 - Urban and suburban passenger land transport*	*to be defined*	*none*	*IMTECH*
General advancement of knowledge	*SUMO with PHEMlight for simulating of emissions*	*NO*	*01/01/2016*	*Consulting Projects*	*H49.3.1 - Urban and suburban passenger land transport*	*To be defined*	*none*	*DLR*
General advancement of knowledge	*Impact analysis with COLOMBO tool chain*	*NO*	*01/01/2016*	*Consulting Projects*	*H49.3.1 - Urban and suburban passenger land transport*	*To be defined*	*none*	*IMTECH*

The different project results of COLOMBO yield different business cases which are:

1. Commercial launch of a cost efficient traffic state estimation solution based on floating car probe vehicle data (FCD)
2. Commercial launch of a cost efficient traffic state detector based on the hybrid approach comprising Bluetooth (Class B) and V2I detection and data fusion
3. Commercial launch of a cost efficient V2X based traffic controller based on low penetration cooperative traffic state estimation combined with the self-organising control (SWARM) algorithms.
4. Generation of commercial consulting project revenues for the use of SUMO with PHEMlight for simulating of emissions and the possible impact of traffic management measures on emissions.
5. Generation of commercial consulting project revenues for analyzing the possible improvement of traffic flow in bottleneck situations of traffic flow by advanced traffic light control algorithms using the COLOMBO evaluation tool.

The following sections highlight the business cases in more detail.

1.1 Target Market

For the business cases 1, 2, and 3 the main market for the short term horizon will be the improvement of existing fixed time controllers and as a competitor in so called “green fields”. Green fields are new intersections in which no detection or traffic lights are present yet and therefore the COLOMBO system has a major advantage in not requiring investment in detection. Similarly, existing fixed time control can be upgraded with less investment than upgrading to vehicle actuated control. To replace existing vehicle actuated control, the performance of the novel COLOMBO solutions need to

- either perform significantly better, which is not foreseen to happen with low penetration rates,
- or deliver a performance in the same order of magnitude for significantly lower acquisition or maintenance cost respectively.

Moreover, there needs to be considered that especially larger cities prefer more centralized solutions that allow to manage their entire traffic network in one environment. The amount of operator intervention varies, some cities prefer to have the possibility of full manual control over all parameters when needed, while others prefer to keep maintenance as low as possible and want a fully automated solution to which they don’t need to pay any attention. The COLOMBO SWARM algorithm is strong in the latter, but through software a manual override can always be integrated and integration in a city wide network management system should also be possible.

We think that business cases 1, 2, and 3 can be successful in developing countries and countries with large urban growth. These countries have either many new intersections without existing detection investments or static controllers that can be upgraded with little cost. From 2021 countries with existing SCOOT and SCATS systems can be targeted with the SWARM system for new intersections and gradually also for replacement of existing systems as V2X penetration raises. We suggest that after 2024 all countries worldwide can be targeted with the SWARM solution to improve actuated control both in new and existing intersections. Gradually also existing modern adaptive systems can be enhanced with COLOMBO data and finally, when close to 100% penetration has been achieved, all controllers can be replaced. It should be noted that by now less than 5% of all controllers are modern adaptive controllers. So despite the long required time to reach such a high penetration, the low penetration requirements for other COLOMBO solutions can still cover at least 95% of the market by 2024.

Based on these considerations we assume market potential of 200 installations per year in the Netherlands and 1000 installations per year worldwide. We estimate maximum sales numbers of 1,000 units per year with a 10 year ramp up phase.

1.2 Traffic State Estimation based on Probe Vehicle Data

This business case comprehends the estimation of the traffic state for traffic control based on floating car data as described in COLOMBO deliverable 1.2, section 4.4 and more comprehensively in [[i]]. The idea here is to deduce the traffic state and especially queue lengths from probe vehicle trajectories that are being collected online by a navigation system provider. The floating car data is collected and distributed to the traffic light controllers by software. The software is running on a central server. The quality of the traffic state data would allow delivering traffic control performance higher than fixed time control but lower than with inductive loop data at significantly lower cost. The benefit for the user is visible when comparing running and installation cost:

- an equipped 4 arm intersection would require an installation cost of 12,000 € and running cost of 1,700€ per year (See COLOMBO D1.2)
- the probe vehicle data solution could be marketed for an initial cost of 1,000€ and a running cost of 100€ per year

Since the probe vehicle data solution is much highly efficient in terms of installation and maintenance cost, a higher (compared with ~40% sector average) gross margin of 66% can be assumed in this business case. We further assume an operating margin of 33% for the same reason.

Table 7: Estimated profit from probe vehicle data traffic state estimation

Year	Sales number (worldwide)	Cumulated sales number	Revenue from installations	Revenue from maintenance	Profit
1	10	10	10.000 €	1.000 €	3.630 €
2	100	110	100.000 €	11.000 €	36.630 €
3	200	310	200.000 €	31.000 €	76.230 €
4	300	610	300.000 €	61.000 €	119.130 €
5	400	1010	400.000 €	101.000 €	165.330 €
6	500	1510	500.000 €	151.000 €	214.830 €
7	600	2110	600.000 €	211.000 €	267.630 €
8	700	2810	700.000 €	281.000 €	323.730 €
9	800	3610	800.000 €	361.000 €	383.130 €
10	900	4510	900.000 €	451.000 €	445.830 €
11	1000	5510	1.000.000 €	551.000 €	511.830 €
12	1000	6510	1.000.000 €	651.000 €	544.830 €
13	1000	7510	1.000.000 €	751.000 €	577.830 €
14	1000	8510	1.000.000 €	851.000 €	610.830 €
15	1000	9510	1.000.000 €	951.000 €	643.830 €

The development of a market ready solution would require a fixed cost development budget of estimated 200.000€ to bring the solution to TRL 9. Table 7 illustrates that the business case is attractive, reaching break even after 4 years if the expected sales numbers hold. However, we see the risk that the market does not accept the solution. The outlook to secure a financing for a related product development project is not yet clear.

1.3 Traffic State Estimation based on Fusion of Bluetooth and V2I Data

The estimation of traffic state using Class B vehicle information could deliver traffic state information needed by traffic light controllers for lower acquisition and maintenance cost than state of the art inductive loop detectors. A cost estimation made within COLOMBO gives a potential for cost reduction by 75% in a Green Field or induction loop replacement scenario.

Class B Vehicle based traffic state estimation comprehends introducing a new type of road side unit to the transport systems technology market. The new RSU is detecting the unique network IDs of mobile devices that are equipped with Bluetooth and/or Wi-Fi, processing the data and delivering estimated vehicle counts and/or vehicle speeds to the traffic controller. The benefit for the user is explained at hand of comparing running and installation cost:

- an equipped 4 arm intersection would require an installation cost of 12,000€ running cost of 1,700€ per year (See COLOMBO D1.2)
- the probe vehicle data solution could be marketed for an initial cost of 6,000€ and a running cost of 400€ per year

The estimated cost for bringing the solution to TRL 9 is 300.000 €. The development comprehends extending an existing V2X RSU with a Bluetooth detection device and integrating the software into that existing solution. An established company providing RSUs on the transportation systems market would be contracted as a manufacturer of the hardware with a special firmware. The gross margin for this type of business is assumed to be 40%. We further assume here an operating margin of 10% because of expenses for mounting hardware in the field.

Table 8: Estimated profit from Bluetooth and V2X sensor fusion traffic state estimation

Year	Sales number (worldwide)	Cumulated sales number	Revenue from installations	Revenue from maintenance	Profit
1	10	10	60.000 €	4.000 €	6.400 €
2	100	110	600.000 €	44.000 €	64.400 €
3	200	310	1.200.000 €	124.000 €	132.400 €
4	300	610	1.800.000 €	244.000 €	204.400 €
5	400	1010	2.400.000 €	404.000 €	280.400 €
6	500	1510	3.000.000 €	604.000 €	360.400 €
7	600	2110	3.600.000 €	844.000 €	444.400 €
8	700	2810	4.200.000 €	1.124.000 €	532.400 €
9	800	3610	4.800.000 €	1.444.000 €	624.400 €
10	900	4510	5.400.000 €	1.804.000 €	720.400 €
11	1000	5510	6.000.000 €	2.204.000 €	820.400 €
12	1000	6510	6.000.000 €	2.604.000 €	860.400 €
13	1000	7510	6.000.000 €	3.004.000 €	900.400 €
14	1000	8510	6.000.000 €	3.404.000 €	940.400 €
15	1000	9510	6.000.000 €	3.804.000 €	980.400 €

Table 8 illustrates that the business case is attractive, reaching break even after 3 years if the expected sales numbers hold. Again, we see the risk that the market does not accept the solution. An additional risk is that the market penetration with V2X is less than expected. The outlook to secure a financing for a related product development project is not yet clear.

1.4 SWARM Traffic Light Controller

This business case is an overall system containing low penetration cooperative traffic state assessment combined with the self-organising traffic control. The main advantage of the solution is less installation costs: no sensors are required, only an RSU will be sufficient. Additionally, the system should be self-organising and therefore require little effort to configure. Parameters like safety timing and intersection layout still need to be configured. Contemporary traffic controllers, on the other hand, need many extra parameters like detector location and function, stage planning, signal group timing and possibly network coordination parameters.

The SWARM traffic light controller is a new electronic control unit which works solely on the basis of Car2I data collected by a RSU. The benefit for the user is running and installation cost for detection (we assume the traffic light controller hardware for SWARM is the same as for conventional control, only new SWARM control software needs to be installed):

- an equipped 4 arm intersection would require an installation cost of €12,000 and running costs of €1,700 per year (See COLOMBO D1.2)
- The standard road side unit can be marketed for an initial cost of 5,500€ and a running cost of €350 per year (See COLOMBO D1.2)

The estimated cost for bringing the solution to TRL 9 is 500.000 €. The development comprehends porting of the software to an embedded platform and software qualification. The gross margin for the business of selling the turnkey solution inclusive controller and RSU is assumed to be 40%. We again assume an operating margin of 10% because of the expenses for mounting hardware in the field.

Table 9: Estimated profit from SWARM traffic control

Year	Sales number (worldwide)	Cumulated sales number	Revenue from installations	Revenue from maintenance	Profit
1	10	10	260.000 €	4.000 €	26.400 €
2	100	110	2.600.000 €	44.000 €	264.400 €
3	200	310	5.200.000 €	124.000 €	532.400 €
4	300	610	7.800.000 €	244.000 €	804.400 €
5	400	1010	10.400.000 €	404.000 €	1.080.400 €
6	500	1510	13.000.000 €	604.000 €	1.360.400 €
7	600	2110	15.600.000 €	844.000 €	1.644.400 €
8	700	2810	18.200.000 €	1.124.000 €	1.932.400 €
9	800	3610	20.800.000 €	1.444.000 €	2.224.400 €
10	900	4510	23.400.000 €	1.804.000 €	2.520.400 €
11	1000	5510	26.000.000 €	2.204.000 €	2.820.400 €
12	1000	6510	26.000.000 €	2.604.000 €	2.860.400 €
13	1000	7510	26.000.000 €	3.004.000 €	2.900.400 €
14	1000	8510	26.000.000 €	3.404.000 €	2.940.400 €
15	1000	9510	26.000.000 €	3.804.000 €	2.980.400 €

Table 9 illustrates that the business case is profitable and break even can be reached within 3 years if the expected sales numbers hold. However, the highest risk is that the market penetration with V2X is less than expected. The outlook to secure a financing for a related product development project is weak, because V2X penetration is less than expected in 2015.

1.5 Emission and Flow Assessment Consulting

In the course of the project, the COLOMBO partners have gained expertise in testing new traffic light control algorithms in a given real world environment. This expertise can be used for providing consulting services to public authorities willing to assess the impact of more efficient ways of traffic control in terms of level of service and emissions. Reference studies were conducted within COLOMBO for the cities of Bologna, Monza and Helmond. It is difficult to see the market volume at this moment, therefore more detailed information on this business case cannot yet be given.

The project partners discussed a commercial perspective for the evaluation tool. In their point of view, the willingness-to-pay for a generic add-on tool license would be about €500. Transforming the current tool into such a generic one would be a major development effort of over 500 hours. Assuming the cost per development hour at €50 and the optimistic estimation of 25 licenses sold per year, the investment cost of €25.000 require two years of revenue at €12.500 p.a..

An option for the evaluation tool is to release it open source as part of the educational toolkit. This way, parts of the code can be reused for specific applications and as it increases the ease of use of the total SUMO solution it should help growing the SUMO community. For now technology readiness level is at 3, the tool has been used for a few specific COLOMBO publications only and will be used further in WP5. Release with the educational toolkit requires some adjustments to the code to increase user friendliness, but would increase TRL to 9. Any of the partners could provide consulting services for deployment or case specific adaptation of the evaluation tool to different customers.