# Simulating the Influence of IVC on Road Traffic using Bidirectionally Coupled Simulators

Christoph Sommer, Zheng Yao, Reinhard German and Falko Dressler
Computer Networks and Communication Systems
Dept. of Computer Sciences, University of Erlangen-Nuremberg, Germany
{christoph.sommer,german,dressler}@informatik.uni-erlangen.de

***Abstract*—We discuss the need for bidirectional coupling of network simulation and road traffic microsimulation for evaluating Vehicular Ad Hoc Networks (VANETs) in a simulation framework. As the selection of a mobility model influences the outcome of simulations to a great deal, the use of a representative model is necessary for producing meaningful evaluation results. Based on these observations, we present a hybrid simulation framework composed of the road traffic simulator SUMO and the network simulator OMNeT++. The coupled simulation environment is used for an evaluation of two protocols for incident warning in VANETs.**

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

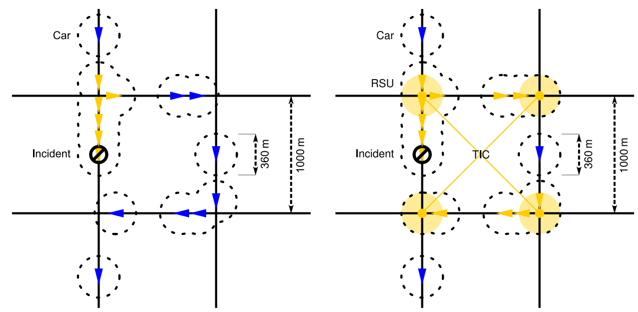
## I. Introduction

In this paper, we investigate the need for bidirectional coupling of network and road traffic simulation for more realistic Vehicular Ad Hoc Network (VANET) simulation experiments. Incident detection, e.g. traffic jam and accident detection, and the development of adequate Inter Vehicle Communication (IVC) protocols using VANETs are in the main focus of such simulations [1]. In the following, we motivate the demand for more sophisticated simulation techniques by investigating the state of the art in VANET simulation. As an example, we use the scenarios depicted in Figure 1 for evaluating the influence of IVC protocols on road traffic using bidirectionally coupled simulators. The setup is explained in detail in Section III.

### A. Simulating VANETs

It has long been established that the quality of results obtained from Mobile Ad Hoc Network (MANET) simulations is heavily influenced by the quality of the employed mobility model [2], [3]. The impact of mobility models on VANET simulation results, as well as the inadequacy of the mobility models usually adopted in MANET simulations, are well documented in the literature [4], [5]. For this reason, recent work in the field of VANET simulation commonly uses mobility traces which are more appropriate for VANETs. Such traces can be generated by real-world experiments, i.e. the observation of real road traffic behavior, or by a dedicated road traffic simulator before being fed as input to a network simulation environment.

Transportation and traffic science classifies road traffic models into Macroscopic, Mesoscopic, and Microscopic models, according to the granularity with which traffic flows are examined. Macroscopic models, like METACOR [6], model traffic at a large scale, treating traffic like a liquid and often apply hydrodynamic flow theory to vehicle behavior. Mesoscopic models like CONTRAM [7] are concerned with the movement of whole platoons, using e.g. aggregated speed-density functions to model their behavior. Simulations of VANET scenarios, however, are concerned with the accurate modeling of single radio wave transmissions between nodes and, therefore, require exact positions of simulated nodes. Both Macroscopic and Mesoscopic models cannot offer this level of detail, so only Microscopic simulations, which model the behavior of single vehicles and interactions between them, will be considered as mobility models for simulated VANET nodes.




(a) UDP communication scenario. IVC relies on VANET alone.

(b) TCP communication scenario. IVC supported by RSUs.

Fig. 1. The two types of IVC scenarios that have been examined.

Transportation and traffic science has developed a number of microsimulation models, each taking a different approach and thus each resulting in simulations of different complexity. Models that are in widespread use within the traffic science community include the Cellular Automaton (CA) model [8], the car-following model by Stefan Krauß (SK) [9], and the Intelligent-Driver/MOBIL Model (IDM/MOBIL) [10], [11].

When doing road traffic simulation, each approach has its particular advantages and particular drawbacks. However, the accuracy of many of these models was evaluated in [12], which concluded that, as far as network simulation is concerned, all common road traffic microsimulation approaches are of equal value as a mobility model.

Today, several simulation environments exist which can generate trace files of vehicles moving according to these microsimulation models. Common tools include FARSI by DaimlerChrysler or VISSIM by PTV AG. In the interest of

978-1-4244-2219-7/08/$25.00 (c)2008 IEEE

comparability of research results, however, it is evidently more beneficial to use readily available simulation environments like MOVE or VanetMobiSim, as using the same mobility model is the easiest and sometimes the only way of accurately reproducing results obtained in related work. MOVE uses the SUMO [13] environment for the simulation of roads, which in turn uses the aforementioned SK traffic model. VanetMobiSim extends the CANU Mobility Simulation Environment. It implements the adaptations IDM with Intersection Management (IDM_IM) and IDM with Lane Changing (IDM_LC), the latter of which also includes the MOBIL lane change model.

When these road traffic simulators are employed in VANET simulations, traces are commonly generated off-line to speed up network simulation performance, which can then re-use generated trace files. However, one major drawback of using off-line mobility traces, both pre-generated ones and those obtained from real-world measurements, is that they can only model the influence of road traffic on network traffic, but not vice versa. In order to achieve this goal, a bidirectional coupling between a network traffic simulator and a road traffic simulator is needed.

### B. Related Work

As we have seen, the mobility model is one of the most important factors in the evaluation of network protocols for VANETs. Mobility models currently used in many network simulation tools do not take into account driver behavior or specific characteristics of the urban environment (presence of stop lights, intersections, merge lanes, etc). As a result, the simulation of network protocols may be unrealistic.

One major advancement in this domain was the concept of trace-based mobility modeling to be used in network simulation environments. Here, realistic mobility patterns are generated (off-line) and used as representative models for the evaluation of network protocols. In fact, as a common practice in many simulation platforms, the mobility traces are normally inserted into network simulation modules as independently-generated off-line files. This way, the system complexity is reduced. Two methods for the generation of trace files can be distinguished. First, real-world observations can be used, i.e. the mobility of real vehicles is observed in a city or highway environment and the resulting trace information is processed for use in network simulations [14], [15]. Similarly, mobility patterns can be extracted from these real-world observations to analytically model traffic flows [16].

Another approach is to employ traffic microsimulation tools coupled with network simulators. An early example is based on the integration of VISSIM traces with the network simulator ns-2 [17], a frequently used simulation framework. Similarly, the SUMO traffic microsimulation tool has been integrated with ns-2 resulting in a hybrid simulation framework named TrANS [18]. Hybrid simulation and mathematical modeling have been combined in order to speed up the simulation process [19]. Also, our preliminary work facilitated coupled simulation using an IDM/MOBIL microsimulation and the OMNeT++ network simulation tool [20].

Nevertheless, such "de-coupling" design philosophy faces one dilemma: If results from the network simulation can affect the mobility trace, this off-line "isolated" methodology is unable to generate the real-time interaction between the mobility model simulation module and the network simulation module. For example, in vehicular safety applications, vehicles will generate alert messages to change the mobility patterns of other vehicles. In this case, the network simulation model and the mobility simulation model need to interact with each other in a real-time manner.

This problem has been addressed with the NCTUns simulation environment [21]. This tool is similar to TrANS, but allows integrated network and traffic simulation. The main problem of this tool, which has been developed from scratch, is that the models in both domains (network and road traffic microsimulation) are either unavailable or not properly tested.

### C. Contributions

This paper addresses the need for bidirectional coupling of realistic mobility models with network simulation tools in the evaluation of VANET protocols. We present such a means of bidirectional coupling, which allows the network simulation to directly control the road traffic simulation and thus to simulate the influence of VANET communications on road traffic. The contributions of this paper can be summarized as follows:

- Bidirectional coupling of network and road traffic microsimulation. Based on the SUMO road traffic microsimulation tool and the OMNeT++ network simulation framework, we developed an integrated VANET simulator that allows real interaction between both simulators (Section II).
- Proof of concept for incident warnings. We used the coupled simulation framework to evaluate two mechanisms for incident warnings and traffic jam prevention (Section III). The first solution is based on IVC relying only on a VANET using UDP messages. A second solution employs Roadside Units (RSUs) connecting the vehicles to a central traffic management system using the MANET routing protocol Dynamic MANET On Demand (DYMO) to maintain TCP connections to a server.

## II. Coupling Traffic Microsimulation and Network Simulation

### A. Traffic Simulation

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

SUMO performs simulations both running with and without a GUI and can import city maps from a variety of file formats. It thus allows high-performance simulations of huge networks with roads consisting of multiple lanes, as well as

978-1-4244-2219-7/08/$25.00 (c)2008 IEEE

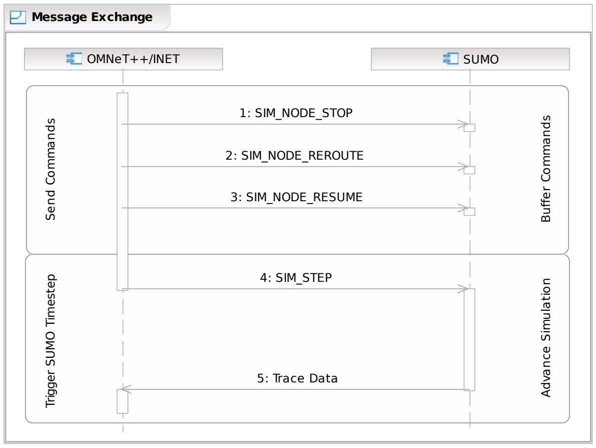



Fig. 2. Sequence diagram of messages exchanged between network and road traffic simulations. Command execution is delayed until the next road traffic simulation timestep is triggered.

of intra-junction traffic on these roads, either using simple right-of-way rules or traffic lights. Vehicle types are freely configurable with each vehicle following statically assigned routes, dynamically generated routes, or driving according to a configured timetable.

### B. Network Simulation

Realistic communication patterns of VANET nodes are modeled with the help of OMNeT++ 3.4b2 [22], a simulation environment free for academic use, and its *INET Framework* 20061020 extension [23], a set of simulation modules released under the GPL. OMNeT++ runs discrete, event-based simulations of communicating nodes on a wide variety of platforms and is getting increasingly popular in the field of network simulation. Scenarios in OMNeT++ are represented by a hierarchy of reusable modules written in C++. Modules' relationships and communication links are stored as *Network Description* (NED) files and can be modeled graphically. Simulations are either run interactively in a graphical environment or are executed as command-line applications.

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

### C. Bidirectional Coupling

In order to couple both simulators and create the simulation framework *Veins*[1] (Vehicles in Network Simulation), SUMO was extended by a module that allows the road traffic simulation to communicate with its counterpart via a TCP connection. As illustrated in Figure 2, using this interface, a connected network simulator is able to send a series of commands to individual vehicles, influencing their speed and routes. It is further able to trigger the execution of one simulation timestep, followed by the transmission of the resulting

[1] http://www7.informatik.uni-erlangen.de/veins/

```
tsp 20
add host[0005] Car;i=car1_vs
del host[0000]
mov host[0005] 998.35 219.10 0.00 0901
mov host[0004] 998.35 236.20 7.04 0901
mov host[0003] 998.35 268.40 10.09 0901
mov host[0002] 998.35 316.81 11.89 0901
mov host[0001] 998.35 367.12 12.88 0901
```

Fig. 3. Excerpt of the movement trace, as sent by the road traffic simulator

mobility trace from the road traffic simulator to the network simulator.

The network simulator has been extended by a module which allowed all participating nodes to send commands via the established TCP connection. Thus, it can also react to the received mobility trace by introducing new nodes, by deleting nodes that had reached their destination and by moving nodes according to their road traffic simulation counterpart.

During the simulation, at regular intervals, the manager module triggers the execution of one timestep of the road traffic simulation, receives the resulting mobility trace and triggers position updates for all modules it had instantiated. Special mobility modules contained in vehicles' modules process and act upon these updates. Figure 3 shows a small sample of the mobility trace, as received by the network simulator. This trace includes a command to advance the time (`tsp`), a command to add a node to the simulation environment (`add`) and to remove another one (`del`), respectively. Additionally, a number of movements are reported (`mov`). Further information on the coupling mechanism is presented in [24].

## III. Evaluating Protocols for Incident Warnings

### A. Scenario and Setup

The basic scenario we use for the evaluation is illustrated in Figure 4. Roads are laid out in a grid with the intersections of roads spaced $1\,\mathrm{km}$ apart. Simulations are performed for grid sizes ranging from $5{\times}5$ roads to $16{\times}16$ roads. In each simulation, all vehicles start, one by one, at a fixed source node in the top left corner of the grid. If no IVC takes place vehicles then travel along the shortest route to a fixed sink node located in the bottom right corner of the grid.

Traffic obstructions are introduced by stopping the lead vehicle for $60\,\mathrm{s}$ or $240\,\mathrm{s}$, depending on the scenario. As each road offers a single lane per driving direction, nodes cannot overtake each other and, hence, need to find a way around blocked roads by means of IVC, or get stuck in traffic.

TABLE I
Road Traffic Microsimulation Parameters

| Parameter | Value |
|---:|---|
| Maximum vehicle speed | $14\,\mathrm{m/s}$ |
| Maximum vehicle acceleration | $2.6\,\mathrm{m/s^2}$ |
| Maximum desired deceleration | $4.5\,\mathrm{m/s^2}$ |
| Assumed vehicle length | $5\,\mathrm{m}$ |
| Driver imperfection $\sigma$ ("dawdling") | 0.5 |

978-1-4244-2219-7/08/$25.00 (c)2008 IEEE

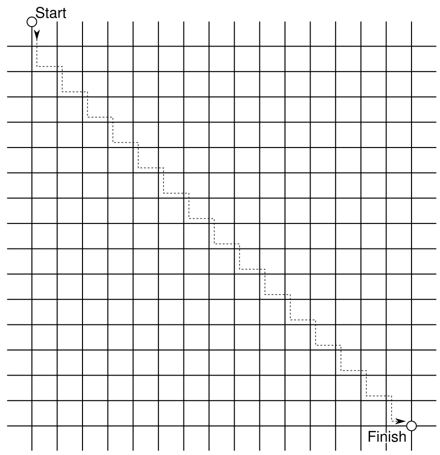



Fig. 4. Overview of the simulated VANET scenario: Single-lane roads are laid out in a grid with a cell size of 1 km. Start and finish node positions are fixed. With no IVC, cars always pick the shortest route between them.

Table I lists the values used to parameterize the vehicles of the road traffic microsimulation, modeling dense inner-city traffic with inattentive drivers.

For all communications, the complete network stack, including ARP, is simulated and wireless modules are configured to closely resemble IEEE 802.11b network cards transmitting at $11\,\mathrm{Mbit/s}$ with RTS/CTS disabled. For the simulation of radio wave propagation, a plain free-space model is employed, with the transmission ranges of all nodes adjusted to a fixed value of $180\,\mathrm{m}$, a trade-off between varying real-world measurements described in related work [25], [26].

To provide ad hoc routing among nodes, we use our implementation [27] of the DYMO routing protocol as an application-layer module of the *INET Framework* module set. As per the specification, it uses a node's UDP module to communicate with other instances of DYMO, to discover and maintain routes and thus to establish a VANET.

Two different types of IVC, illustrated in Figure 1, are examined. In both scenarios vehicles with a speed of zero, after some time, start to inform other vehicles of a potential incident on the current lane, causing them to avoid this lane. When the originating vehicle resumes its journey, it notifies other vehicles that the lane can be used again.

Figure 1(a) displays the UDP scenario, in which this notification was realized by flooding incident warnings through the VANET over $5\,\mathrm{hops}$ or $25\,\mathrm{hops}$, depending on the scenario. Upon receiving an incident warning, a vehicle would query the originating node if the warning was current and, if it received a positive reply, try and avoid the lane in question.

Figure 1(b) displays the TCP scenario, in which RSUs, each connected to a central traffic information service, were added to each intersection to support IVC. In this scenario, vehicles maintained a TCP connection to the central server, which was used to publish and revoke incident information. In intervals of $60\,\mathrm{s}$ or $180\,\mathrm{s}$, depending on the scenario, vehicles also used the TCP connection to retrieve a list of incident warnings from the central server.

### B. Simulation Results

In order to examine the impact of different IVC setups on communication performance, we measured the number of packet collisions on the wireless channel per packet sent. This measure is often used in the context of analyzing the efficiency of MANET routing protocols as it describes the effective utilization of the wireless channel. Figures 5(a) and 5(b) show the results of this evaluation for small-scale and large-scale simulations, respectively. As can be seen, collision ratios in the TCP scenarios always remained under a tolerable 10% packet loss, which could easily be compensated by TCP retry mechanisms. Collision ratios in UDP scenarios, however, exceeded 25% in large-scale simulations, which significantly hindered packet exchanges.

These results are also reflected in the impact different IVC setups had on road traffic performance. Plotted in Figures 6(a) and 6(b) is the effective average speed of vehicles, measured in small and large-scale simulations, respectively. It was obtained by dividing the length of the shortest route by each vehicle's total travel time.

As can be seen, in the case of free flowing traffic, the speed distribution among simulated vehicles in both scenarios is almost homogenous, as could be expected, but speeds average at well below the maximum speed of $14\,\mathrm{m/s}$. This is due to cars decelerating at every intersection, which, in combination with high traffic densities on the single, shortest route shared by all vehicles, leads to micro jams. In the second case, where the lead vehicle stopped for a short amount of time without IVC taking place, the average node speed is reduced by both this stop and by the traffic jam left behind.

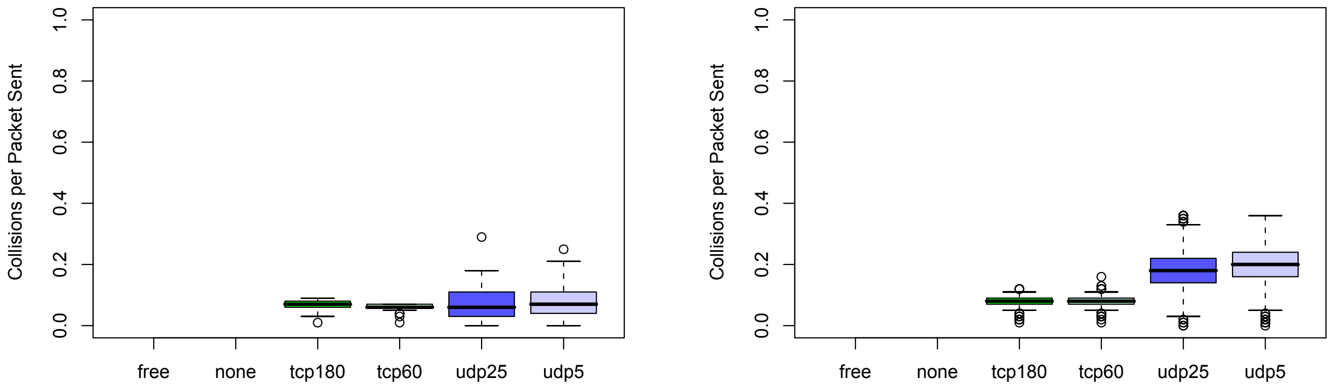
Depending on the scale of the simulation, different IVC scenarios performed differently at helping vehicles avoid this artificially-generated incident.

In the small-scale simulation of Figure 6(a), a polling interval of $180\,\mathrm{s}$ for TCP communications proved too long to significantly influence road traffic performance, but a polling interval of $60\,\mathrm{s}$ already led to a noticeable improvement. Performance was even better for UDP communication scenarios, where almost a quarter of vehicles did not suffer increased travel times due to the simulated incident if the TTL was reduced to $5\,\mathrm{hops}$.

In the large-scale simulations of Figure 6(b), results were almost reversed. Here, UDP communications could only insignificantly improve road traffic performance and TCP communication scenarios fared far better. When a small polling interval was used, almost all vehicles reached their goal even faster than they could in the case of unobstructed traffic without IVC, thanks to a large number of vehicles taking alternate routes, which reduced traffic densities and helped avoid micro jams.

In order to provide a more detailed look into traffic effects in this scenario, Figure 7 also shows the effective average speed of vehicles, but presents measurements separated by vehicles' departure times. Plotted is one single example run each, for both the case of free flowing traffic and the case of IVC with an artificially-triggered incident. As planned, this

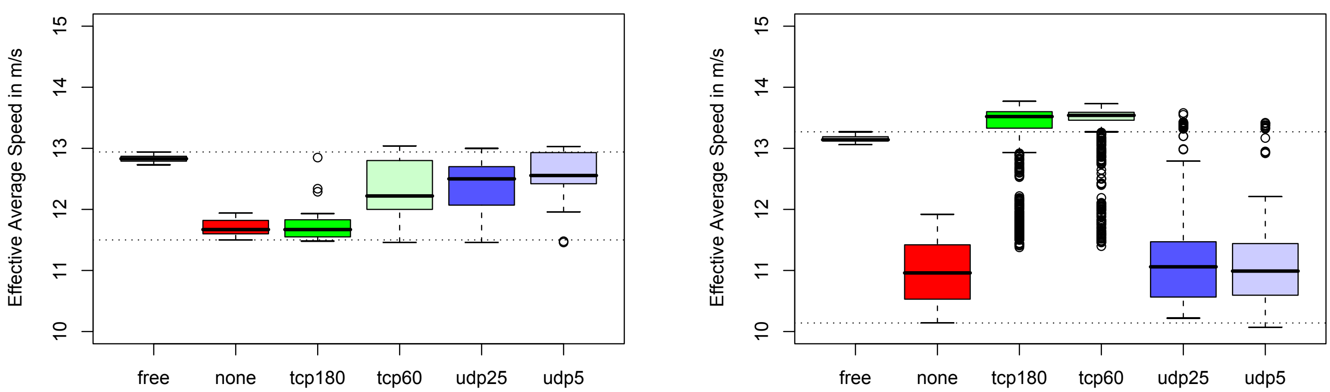
978-1-4244-2219-7/08/$25.00 (c)2008 IEEE




(a) 30 Vehicles on a 5x5 grid. Lead vehicle stops for 60 seconds.

(b) 1000 Vehicles on a 16x16 grid. Lead vehicle stops for 240 seconds.

Fig. 5. Packet collisions on wireless channel per packet sent. One scenario with free flowing traffic, one with no IVC, four scenarios with VANET communications.




(a) 30 Vehicles on a 5x5 grid. Lead vehicle stops for 60 seconds.

(b) 1000 Vehicles on a 16x16 grid. Lead vehicle stops for 240 seconds.

Fig. 6. Vehicle speed averaged over all vehicles and complete route. One scenario with free flowing traffic, one with no IVC, four scenarios with VANET communications.

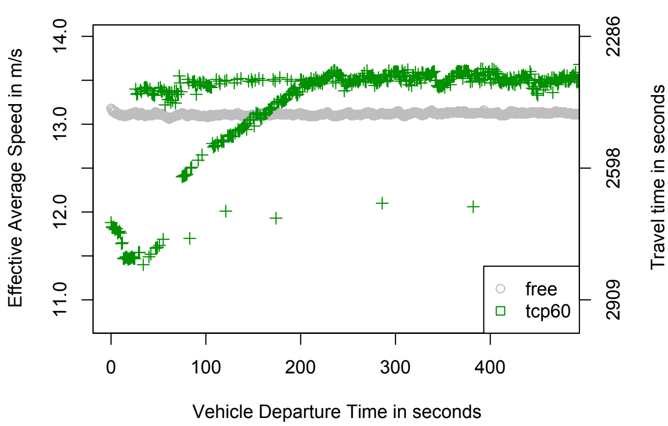



Fig. 7. Average speed of individual vehicles, ordered by time of departure. One scenario with free flowing traffic, one scenario with incident and IVC. 1000 Vehicles on a 16x16 grid. Lead vehicle stops for 240 seconds. Vehicles poll the Traffic Information Center every 60 seconds.

incident delayed the lead vehicle by 240 s, involving all cars following immediately behind it in a traffic jam and causing them to be delayed even further.

The first cluster of cars that were more than one road away from the incident, however, already had enough time to receive and process the incident warning early enough to be able to find alternative routes to the destination, allowing vehicles to reach it even faster than they could when they just followed the shortest route in the incident-free scenario. As can be seen, IVC managed to prevent permanent delays on the affected road segment, so even vehicles that were unaware of the incident were able to continue on their route shortly after the lead vehicle continued its journey: Up to a departure time of just over 240 s, their time spent in the jam linearly decreased towards zero.

Vehicles starting later than approx. 250 s were completely unaffected by the incident having taken place, the only noticeable delays being caused because of merging traffic streams as vehicles approached their destination.

## IV. Conclusion and Future Work

In conclusion, it can be said that the analysis of the different VANET protocols and scenarios provides reasonable proof that IVC might have a strong impact on the underlying mobility of the cars. Using the presented framework for bidirectional coupling of network simulation and road traffic microsimulation, we analyzed these effects based on a proof of concept. The two incident warning protocols for VANETs we discussed can be seen as two extremes of VANET protocols, relying either on infrastructure-based communication or on infrastructure-less broadcasting techniques. Simulation results show that the impact of IVC on the performance of road traffic can be directly evaluated in our framework.

Therefore, we see a direct applicability for a wide variety of VANET research activities that predominantly rely on accurate mobility modeling using road traffic microsimulation and that need to incorporate influences of the VANET on the vehicles' mobility into the simulation.

Our future work includes studies of further ad hoc routing techniques in VANETs and the analysis of mobile communication protocols in this domain.

## References


[1] J. J. Blum, A. Eskandarian, and L. J. Hoffman, "Challenges of Intervehicle Ad Hoc Networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 5, no. 4, pp. 347–351, December 2004.

[2] J. Yoon, M. Liu, and B. Noble, "Random waypoint considered harmful," *Twenty-Second Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM 2003)*, vol. 2, pp. 1312–1321, 30 March - 3 April 2003.

[3] T. Camp, J. Boleng, and V. Davies, "A Survey of Mobility Models for Ad Hoc Network Research," *Wireless Communications and Mobile Computing, Special Issue on Mobile Ad Hoc Networking: Research, Trends and Applications*, vol. 2, no. 5, pp. 483–502, 2002.

[4] A. Mahajan, N. Potnis, K. Gopalan, and A. Wang, "Urban Mobility Models for VANETs," in *Workshop on Next Generation Wireless Networks (WoNGen)*, December 2006.

[5] A. K. Saha and D. B. Johnson, "Modeling mobility for vehicular ad-hoc networks," in *1st ACM International Workshop on Vehicular Ad Hoc Networks (VANET 2004)*, Philadelphia, PA, USA, October 2004, pp. 91–92.

[6] N. Elloumi, H. Haj-Salem, and M. Papageorgiou, "METACOR: A macroscopic modeling tool for urban corridors," *Triennal Symposium on Transportation Analysis*, vol. 1, pp. 135–150, 1994.

[7] N. B. Taylor, "The CONTRAM Dynamic Traffic Assignment Model," *Networks and Spatial Economics*, vol. 3, pp. 297–322, 2003.

[8] K. Nagel and M. Schreckenberg, "A cellular automaton model for freeway traffic," *Journal de Physique I France*, vol. 2, pp. 2221–2229, 1992.

[9] S. Krauß, "Microscopic Modeling of Traffic Flow: Investigation of Collision Free Vehicle Dynamics," Ph.D. dissertation, 1998.

[10] M. Treiber, A. Hennecke, and D. Helbing, "Congested Traffic States in Empirical Observations and Microscopic Simulations," *Physical Review E*, vol. 62, p. 1805, 2000.

[11] M. Treiber and D. Helbing, "Realistische Mikrosimulation von Straßenverkehr mit einem einfachen Modell," in *16. Symposium Simulationstechnik (ASIM 2002)*, Rostock, Germany, September 2002.

[12] E. Brockfeld and P. Wagner, "Testing and Benchmarking of Microscopic Traffic Flow Simulation Models," in *10th World conference on transport research (WCTR)*, Istanbul, Turkey, July 2004.

[13] D. Krajzewicz, G. Hertkorn, C. Rössel, and P. Wagner, "SUMO (Simulation of Urban MObility); An open-source traffic simulation," in *4th Middle East Symposium on Simulation and Modelling (MESM2002)*, Sharjah, United Arab Emirates, September 2002, pp. 183–187.

[14] D. Li, H. Huang, X. Li, M. Li, and F. Tang, "A Distance-Based Directional Broadcast Protocol for Urban Vehicular Ad Hoc Network," *International Conference on Wireless Communications, Networking and Mobile Computing 2007 (WiCom 2007)*, pp. 1520–1523, 21-25 September 2007.

[15] H.-Y. Huang, P.-E. Luo, M. Li, D. Li, X. Li, W. Shu, and M.-Y. Wu, "Performance Evaluation of SUVnet With Real-Time Traffic Data," *IEEE Transactions on Vehicular Technology (ToVT)*, vol. 56, no. 6, pp. 3381–3396, November 2007.

[16] N. Wisitpongphan, F. Bai, P. Mudalige, V. Sadekar, and O. Tonguz, "Routing in Sparse Vehicular Ad Hoc Wireless Networks," *IEEE Journal on Selected Areas in Communications (JSAC)*, vol. 25, no. 8, pp. 1538–1556, October 2007.

[17] C. Lochert, A. Barthels, A. Cervantes, M. Mauve, and M. Caliskan, "Multiple simulator interlinking environment for IVC," in *2nd ACM International Workshop on Vehicular Ad hoc Networks (VANET 2005), Poster Session*. Cologne, Germany: ACM Press, September 2005, pp. 87–88.

[18] M. Piorkowski, M. Raya, A. L. Lugo, M. Grossglauser, and J.-P. Hubaux, "Joint Traffic and Network Simulator for VANETs," in *MICS 2006, Poster Session*, Zurich, Switzerland, October 2006.

[19] M. Killat, F. Schmidt-Eisenlohr, H. Hartenstein, C. Rössel, P. Vortisch, S. Assenmacher, and F. Busch, "Enabling Efficient and Accurate Large-Scale Simulations of VANETs for Vehicular Traffic Management," in *13th ACM International Conference on Mobile Computing and Networking (ACM MobiCom 2007): 4th ACM International Workshop on Vehicular Ad hoc Networks (VANET 2007)*, Montreal, Quebec, Canada, September 2007, pp. 29–38.

[20] C. Sommer and F. Dressler, "The DYMO Routing Protocol in VANET Scenarios," in *66th IEEE Vehicular Technology Conference (VTC2007-Fall)*. Baltimore, Maryland, USA: IEEE, September/October 2007, pp. 16–20.

[21] S. Y. Wang, C. L. Chou, Y. H. Chiu, Y. S. Tseng, M. S. Hsu, Y. W. Cheng, W. L. Liu, and T. W. Ho, "NCTUns 4.0: An Integrated Simulation Platform for Vehicular Traffic, Communication, and Network Researches," in *1st IEEE International Symposium on Wireless Vehicular Communications (WiVec 2007)*. Baltimore, MD, USA: IEEE, October 2007.

[22] A. Varga, "The OMNeT++ Discrete Event Simulation System," in *European Simulation Multiconference (ESM 2001)*, Prague, Czech Republic, 2001.

[23] ——, "INET Framework." [Online]. Available: http://www.omnetpp.org/staticpages/index.php?page=20041019113420757

[24] C. Sommer, Z. Yao, R. German, and F. Dressler, "On the Need for Bidirectional Coupling of Road Traffic Microsimulation and Network Simulation," in *9th ACM International Symposium on Mobile Ad Hoc Networking and Computing (ACM Mobihoc 2008): 1st ACM SIGMOBILE International Workshop on Mobility Models for Networking Research (MobilityModels'08)*. Hong Kong, China: ACM, May 2008, submitted.

[25] F. Hui and P. Mohapatra, "Experimental Characterization of Multi-hop Communications in Vehicular Ad Hoc Network," in *2nd ACM International Workshop on Vehicular Ad Hoc Networks (VANET 2005)*, Cologne, Germany, September 2005.

[26] H. Wu, M. Palekar, R. Fujimoto, J. Lee, J. Ko, R. Guensler, and M. Hunter, "Vehicular Networks in Urban Transportation Systems," in *National Conference on Digital Government Research (dg.o2005)*, Atlanta, GA, USA, May 2005.

[27] C. Sommer, I. Dietrich, and F. Dressler, "A Simulation Model of DYMO for Ad Hoc Routing in OMNeT++," in *1st ACM/ICST International Conference on Simulation Tools and Techniques for Communications, Networks and Systems (SIMUTools 2008): 1st ACM/ICST International Workshop on OMNeT++ (OMNeT++ 2008)*. Marseille, France: ACM, March 2008.


978-1-4244-2219-7/08/$25.00 (c)2008 IEEE