Traffic Flow Optimization via Connected Cars

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ABSTRACT

Keywords

1. INTRODUCTION

Upcoming technology of connected vehicles hitting consumer market soon (TODO: Quelle finden). What are ITS. Overview of benefits of ITS especially as a measure against traffic congestion, reduced travel times and resulting reduction of emissions. In order to solve traffic related problems the Federal Highway Administration in the U.S. proposed and defined three general tactics[20]:

- Work on current capacity of roads and extend them
- Extension of alternative transportation that require less resources (e.g. non-automotive transport)
- More efficient using of current capacities of cities and roads

In this paper the

2. TRAFFIC FLOW OPTIMIZATION

The main parameters of traffic flow have to be quantified in order to evaluate and compare different traffic flows. Including others these parameters consist of speed, flow, density, mean speed, and headway. Flow describes the rate at which vehicles pass a fixed point in a time interval. Density is the concentration of vehicles over a fixed length of a roadway. Mean speed is divided into time mean speed, which is the arithmetic mean of vehicle speeds passing a point, and space mean speed, which is the harmonic mean of speeds passing a point during a period of time. The headway is the time that elapses between a vehicle and a following vehicle passing a certain point.
Traffic flow can be analyzed at three different levels of granularity. Microscopic traffic flow examines individual vehicles and their properties like speed and position. Macroscopic scale investigates traffic flow characteristics such as density, flow and mean speed on a traffic stream. Mesoscopic models allow the study of large areas with applications such as congestion relief through alternative routes.
As a result the types of traffic flow optimization can be applied to different types of granularity.
Microscopic optimizations focus on improving the mean travel time for single vehicles by finding optimal vehicle TODO actions actions such as finding the optimal lane or adjusting the speed to decrease the amount of brake/accelerations actions. These optimizations are discussed in chapter TODO
The goal of macroscopic optimizations is the increase of throughput and reduced travel times for a given traffic stream. They are discussed in section TODO
Mesoscopic optimizations are briefly mentioned in section TODO

2.1 Microscopic Traffic Flow Optimizations

2.1.1 Optimal Lane Selection

One driving behavior that can heavily interrupt the flow of traffic are lane changes. The need for lane changes derives from the inequality of desired driving speeds and mandatory lane changes like lane drops or exiting the current road. These lane changes may disrupt the traffic by aggressive maneuvers (i.e. cutting into small gaps). This papers TODO shows that lane changes disrupt the flow by creating a moving bottleneck under congested traffic conditions TODO cite quelle 3 des papers.
Jin et al.[8] propose a cooperative real-time lane selection algorithm in which connected vehicles share information to improve the system-wide operation of traffic. Well-coordinated lane changes can help maintain desired speeds and minimize shock wave impacts. [Zitat Seite 71 Absatz 3]
This is achieved by calculating the optimal lane target for each vehicle based on its location, speed, lane and desired driving speed. These parameters are transmitted from each car to a roadside communication unit (RSU) which can exchange these real-time information within a certain range. The RSU calculates the optimal lane for each vehicle and sends its optimal lane advice.
Jin et al.[8] tested the algorithm on a simulated 3-way highway of 2000 m length with one roadside communication unit with 300 meters communication range and connected vehicles with a speed of 50 mp/h using the microscopic simulation tool SUMO[10].In the simulation, the mean travel times of different road congestion levels (50%, 60%, ... 100%) with and without their proposed algorithm were compared. Besides the mean travel times, the reduction of energy con-

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sumption and the emission of pollutants was simulated (CO, HC, NOx, PM2.5) with MOVES[18] (Motor Vehicle Emission Simulator).
The simulated mean travel time was reduced by 0,57% at 50% road congestion, up to 3.79% improvement (118.4 s to 115.3 s) at 70% of the maximum density. At higher congestion levels the vehicles could not always find the needed space in their suggested lanes, which reduces the success rate of a lane change. At a level of 0.95% of the maximum capacity of the road, an improvement of 2.67% in mean travel times was still detected.
Similar to the travel times the reduction in pollutants peaked at 70% road congestion. Energy consumption and CO2 emissions are reduced by around 2.2% while CO and HC emissions are reduced by up to 17%. Jin et al. demonstrate how connected vehicles can improve the traffic flow through microscopic actions like well coordinated lane changes. However they do not take into account different penetration rates of interconnected vehicles, which could be useful for the transition years between current and next generation cars. They only simulate their algorithm on a 3-way highway with relatively low speed limit (50 mp/h) and equally treated vehicles. Different simulation runs with trucks, or 2-way highways and varying penetration rates of V2X technology could have given more insights into the usefulness of this approach.

2.1.2 Lane drop merging assistance

The second microscopic optimization next to optimal lane changes is the coordinated approach to a lane drop. Schuhmacher et al.[17] provide a Merging assistance algorithm which advices drivers on the individual speed limits and merging positions ahead of a lane drop. The current traffic control strategies in front of lane drop consist of

Gradual speed limit reduction Usually used at highway lane drops. The speed limit in front of a lane merge is decreased in several stages to achieve a harmonization of traffic with decreased frictions between vehicles and an increased traffic safety.

Late merge strategy Drivers are advised to stay in their lane up to the lane drop. This allows the usage of all available lanes until the lane drop. This strategy performs particularly well with heavily congested traffic and low speeds.

Early merge strategy Warning signs indicating the lane drop are placed far ahead encouraging the drivers to switch the lane early. This reduces forced merges in the vicinity of the drop. This strategy is preferred at low traffic demands with higher speeds.

Schuhmacher et al. present a method which reduces traffic jams and increases capacity in front of a lane drop by switching to a more effective strategy with the usage of car-to-x communication for controlled merging procedures.
The reference scenario is based on an empiric study[2] of a freeway lane drop between Heathrow and London, where the passing lane of a 3-way highway transitions to two lanes. The length of the sections and the placement of traffic detectors can be seen in Figure 1 which was taken from [17].

Their approach uses a Road-side Unit (RSU) 350 m in front of the lane drop (between detector 5 and 6 of Figure 1) and On-board units (OBUs) in the vehicles to allow the

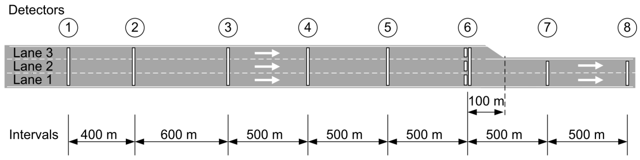


Figure 1: Reference scenario map with distance intervals

communication of traffic control messages. The communication parameters are chosen with respect to the IEEE 802.11 family of standards and the 802.11p amendment for Wireless Access in Vehicular Environments (WAVE). Specifically the RSU and OBUs communication range is set to 500 meters. The OBUs are aware of their position (e.g. through GPS) and can not only receive messages from the RSU but also forward messages to other OBUs to achieve a multi-hop communication.
The implementation of the merging assistance is a combination of dynamic merge strategies and dynamic gradual speed limits. The main part of the merging assistance algorithm is implemented in the RSU. It analyzes the current traffic conditions by monitoring the time mean speeds of vehicles at the detectors and transmitting traffic control messages to the OBUs accordingly. These messages consist of the gradual speed limit, the merging positions (e.g. at which point in front of the lane drop the lane switch should occur) and additional messages as "Stay in Lane" for upstream vehicles and special "Do Not Pass" messages for heavy vehicles after the merge point, which reduces frictions during the merge procedure as no heavy vehicles are permitted on the lane being merged to.
The algorithm works in different stages based on the time mean speed TMS of vehicles at detectors 5 and 6 (the two in front of the lane drop). The TMS are re-evaluated every 5 seconds. v_5 and v_6 describe the TMS of detector 5 and 6 respectively. DEM stands for Dynamic Early Merge, DLM for Dynamic Late Merge.

DEM Stage 1 $v_6 > 80km/h$
The traffic directly in front of the lane drop (at detector 6) is flowing freely with speeds over 80 km/h. The merge point is set to 400 m in front of the lane drop and a no passing zone for heavy vehicles 400 m ahead of the lane drop is established.

DEM Stage 2 $v_6 <= 80km/h$ and $v_5 > 80km/h$
The TMS reduction at detector 6 indicates increasing traffic density resulting in merging problems and braking vehicles. To counteract the merging point is shifted 400m upstream to a distance of 800 m to the lane drop. Ahead of it a "Stay in Lane" zone is established. After it the "Do not pass" rule for heavy vehicles apply. In addition the gradual speed limit reduction is applied to 110, 100, 90 km/h at distances of 2500, 2000, 1000 m ahead of the lane drop, respectively.

DEM Stage 3 $60km/h < v_6 <= 80km/h$
and $v_5 <= 80km/h$
The slightly congested area with decreased TMS between 60 and 80 km/h extended up to detector 5. The distance of the merging point and the "Stay in Lane" zone ahead of it is set to 1300 m. Heavy vehicles are

not allowed to pass after the merge point. Gradual speed limit is at 100/90/80 km/h at 2500, 2000, 1000 m.

DLM $v_6 <= 60km/h$
Under 60 km/h TMS the traffic condition is assumed to be heavily congested. At this stage it is more efficient to use all lanes as long as possible to maximize the capacity. The merge point is shifted to 100 m ahead of the lane drop, with the "Stay in Lane" and "Do not pass" zones adjusted accordingly. The speed limits are reduced to 90,70,60 km/h at 2500, 2000, 1000 m, respectively.

Schuhmacher et al. simulated their algorithm and the reference scenario with the AIMSUN [1] traffic simulator. The maximum capacity of a lane was set to 2000 vehicles per hour. The proportion of heavy vehicles was set to 15% and the maximum allowed speed is 112 km/h (70 mp/h). The traffic demand is increased in three stages every 30 minutes. Firstly 3000 veh/h, which is far under the capacity of 4000 veh/h of the reference scenario. Secondly the demand is increased to 3800 veh/h representing dense traffic close to the maximum capacity. And lastly 4600 veh/h which should result in heavy congestion.
In the first simulation run every vehicle is equipped with an OBU and every vehicle obeys the traffic control messages. Compared to a simulation run without the usage of the merging assistance significant traffic improvements were only observed at the highest density of 4600 veh/h. The mean travel time decreased from around 112 sec/km to around 70 sec/km at the end of the simulation run.
Figure 2 taken from [17], illustrates the travel time improvements under different penetration rates of equipped vehicles. Next to no improvements where noticeable in low traffic de-

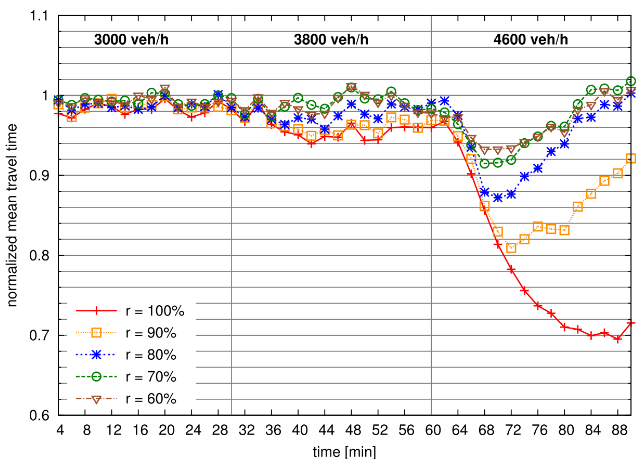


Figure 2: Mean flow rates for different penetration rates

mands (0-30 min.) for each penetration rate. Under higher traffic demands of 3800 veh/h a slight decrease in travel time can be observed. After the beginning of high traffic demand (4600 veh/h, 60-90 min.) the travel time for a ratio of 100% equipped vehicles decreased by up to 30%. With a lower ratio of equipped vehicles the mean travel time still decreases by up to 7% if only 60% of vehicles are equipped. It can be observed that except for 100% penetration rate, a traffic breakdown is encountered (e.g. at minute 68 for 80% penetration rate). The merging assistance application can however help to delay the traffic breakdown and thereby is able to absorb temporary traffic peaks.
Schuhmacher et al. present a valid approach to traffic flow optimization by implementing an abstract algorithm for microscopic driver recommendations such as the merging position and adaptive speed limits. Their multi-hop message forwarding communication model can also be extended to eliminate the need of a road side unit. This could be especially helpful for unpredictable lane drops (e.g. accident on lane).

[1] $http://www.aimsun.com/wp/?page\_id = 21$

2.2 Macroscopic Optimization

In contrast to the single vehicle, microscopic optimizations of section 2.1, this section focuses on traffic improvements on whole traffic streams. Applications can vary from intelligent traffic lights to intelligent speed limits and speed recommendations at uncontrolled intersections to harmonize the traffic flow.
Intersections belong to the most important components of urban road networks high accident rates and low efficiency in terms of vehicle throughput. Cooperative vehicle infrastructure systems (CVIS) focus on the improvement of safety and flow rates using Vehicle to Infrastructure (V2I) and Vehicle to Vehicle (V2V) communication. This section describes one approach for uncontrolled and one for traffic light controlled intersections.

2.2.1 *Cooperative optimization at an uncontrolled intersection*

Uncontrolled intersections are the most common types in urban road networks. CVIS are able to get the real-time individual vehicle states and allow the exchange of individual traffic control messages. This can be used to manipulate individual vehicles trajectories to guide them on a non colliding path through the crossing as proposed by Lee et al.[11]. While this approach can be used for fully autonomous vehicles, it induces problems for self-driven vehicles wihthout accurately driven paths.
Cai et al.[4] propose a method where drivers are guided by a cooperative negotiated "right of way" information on an installed On-Board Unit (OBU) coupled with speed guidance to preemptively solve conflicts.This reduces the intersections average vehicle delay, number of stops, length of the queue and increases the average speed of vehicles.
Vehicles approaching the intersection transmit in small intervals (0.5 s) their current position, speed and desired route to the intersection's traffic controller. For each vehicle the road-side unit calculates an optimal speed, under the assumption that a minimum and maximum speed and a certain acceleration/deceleration rate exists and a minimum headway needs to be retained. These speed guidances are then sent to the OBUs in the vehicles.
Cai et al. simulated their approach against a non cooperative intersection. Their results are shown in Figure 3. The queue length, amount of stops and average delay were decreased while increasing the average speeds of vehicles under all traffic conditions.
The results were however achieved under strong assump-

Traffic Flow (veh/h)	Unsignalized Cooperative Optimization Control Method				Actuated Control Method			
	Average delay (s)	*Average stops*	*Average queue length (m)*	*Average speed (km/h)*	*Average delay (s)*	*Average stops*	*Average queue length (m)*	*Average speed (km/h)*
1500	3.79	0.46	1.62	53.70	7.98	0.54	7.47	48.46
3000	6.11	0.47	4.79	63.70	9.31	0.59	11.22	57.42
4500	9.00	0.56	12.04	63.98	18.20	0.77	31.36	53.84
6000	8.68	0.61	18.80	61.86	23.72	0.94	35.37	30.01
7500	19.48	0.87	45.40	40.13	27.50	0.96	52.76	28.99

Figure 3: Unsignalized cooperative optimization simulation results

tions. First of all the interference of pedestrians and bicycles is not considered, which are a strong factor in urban areas. Secondly Cai et al. focus only on isolated intersections without left and right turns or the influence of adjacent intersections. And lastly a penetration rate of connected vehicles of 100% is assumed. This alleviates the results strongly.

2.2.2 Adaptive Traffic Lights

The message exchange with an infrastructure unit can also be extended to traffic light controlled intersections using the same technique as Cai et al. to convey the state of physical traffic lights directly to a display at the driver. This stands in contrast to computer vision traffic signal detection and recognition, which can be error prone under difficult lighting and weather conditions. Olaverri-Monreal et al.[14] present an in-vehicular traffic light implementation with the focus on the design aspects of an Human Machine Interface (HMI). In a driving simulator the design aspects are evaluated regarding the driving performance and acceptance of the novel virtual traffic lights.
The virtual traffic lights have to take care of the following characteristics:

Design The design components size, shape, color, composition, lighting and contrast have to provide a clear and easy to understand message. A Head Up Display (HUD) was chosen to display the few required elements (distance to traffic light, traffic light state).

Placement and operation To avoid a road vision obstruction in the central field of view, the images were projected 2.5 to 4 meter away from the drivers eyes in the lateral field of view.

Maintenance and uniformity The maintenance of the system is similar to other electronic devices in the vehicle. The installation of the sensors and the V2V communications allows similar functioning of all the traffic lights virtually displayed.

Color code Luminance requirements need to be followed to ensure that the projected images are visible in all weather conditions.

Signal timing Vehicles are detected at traffic lights, which is used to determine priority and traffic light phase duration. The virtual traffic light system uses a robust detection system based on beaconing and location tables through a geographic routing protocol. Additionally traffic light warnings alert the driver if a traffic violation occurs. Each vehicle maintains an internal database with information about intersections where a virtual traffic light can be created. If a vehicle approaches a intersections and does not detect a virtual traffic light, they consult their location table and the road map topology to infer crossing conflicts and then create a collaborative virtual traffic light. This requires lane-level accuracy on the location tables and digital road maps with lane-level information topology.

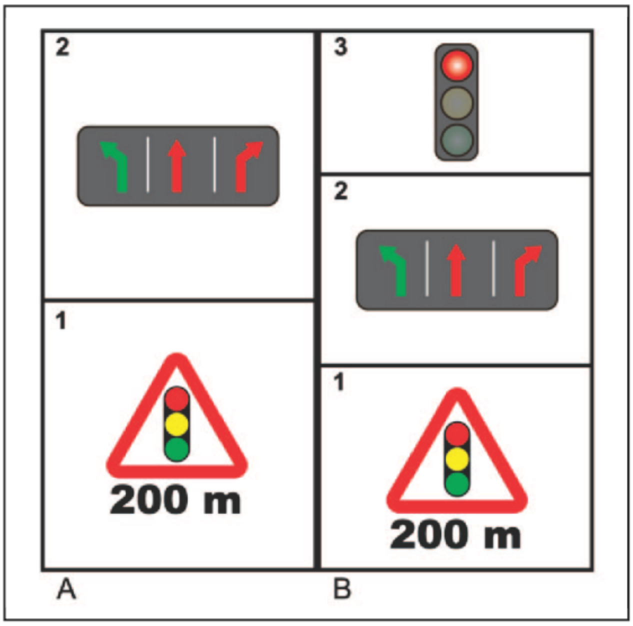


Figure 4: Different virtual traffic light designs

Two in vehicular traffic light designs can be seen in Figure 4. Design A1 and B1 show a traffic light ahead warning with a label indicating the remaining distance. Design A2 and B2 show the driving priority through green or red colored arrows. Design B3 shows the driving permissions through a traffic light image. This design was then tested in an urban driving simulator. To determine the driving performances Olaverri-Monreal et al. focused on speed metrics and brake activity, because the ability to adapt to new road circumstances such as traffic signs or intersections can be observed in the variation of speed.
From the 10 tested persons 9 declared the presented information as clear and intuitive and was not considered distracting or unsafe. The brake activity and deceleration rate differed

only slightly from the simulation run with the physical traffic lights. In general the test group adapted well to the shift from physical to virtual traffic lights

2.2.3 *Adaptive traffic light control for priority vehicles*

Intelligent traffic lights can further be extended to not only improve the traffic flow at intersections based on demand, but to also control the traffic flow based on different parameters such as the presence of emergency vehicles approaching this intersection. Top priority is given to emergency vehicles and their demanded lanes. This enables priority vehicles to drastically reduce their travel time to destination especially in heavily congested areas.
Ahmed et al.[1] compare two different scheduling schemes for intelligent traffic lights which receive the following information from the vehicles.

- Total number of vehicles within a lane.
- Vehicle type (i.e. priority or non priority)
- Total travel time of a vehicle
- Initial assigned deadline of each vehicle

The first scheme is a static Fixed Priority (FP) algorithm, where vehicles types are assigned to different priority levels.

- High Priority Vehicles (HV)
- Medium or Moderate Priority Vehicles (MV)
- Low Priority Vehicles (LV)
- Nil Priority Vehicles (NV)

The static algorithm firstly serves all edges with HV vehicles present, followed by MV, LV and lastly NV type vehicles.
The second algorithm proposed by Ahmed et al. also classifies vehicles into priority classes, but uses the deadlines of processes to prioritize vehicles. HV vehicles are assigned lower deadlines than MV vehicles. LV type vehicles get intermediate deadlines and NV type vehicles obtain the highest deadline. The algorithm then serves the intersection edge which has the vehicle with the lowest deadline first. This Earliest Deadline First (EDF) approach is a dynamic implementation as it makes its decision based on the dynamic deadlines of priority vehicles.
Ahmed et al. simulated the two scheduling schemes and the standard static traffic lights using the simulator SUMO[10]. They used a complex network as shown in Figure 5 taken from [1]. Different traffic intensities were simulated and the percentage of priority vehicles was set to 14% of the total traffic. In their results seen in Figure 6 it can be seen that both the adaptive traffic light implementation outperform the typical traffic lights in terms of mean waiting steps, mean trip time and mean speed for priority vehicles. It has to be noted that the gain for priority vehicles is achieved at the cost of no and low priority vehicles. The amount of mean waiting steps (Figure 6a)) are reduced by up to 50% compared to the static traffic lights. The mean trip time and mean speed parameters of priority vehicles are also greatly improved using EDF and FP schedulers. Also the EDF scheduler performs slightly better than the Fixed Priority implementation.

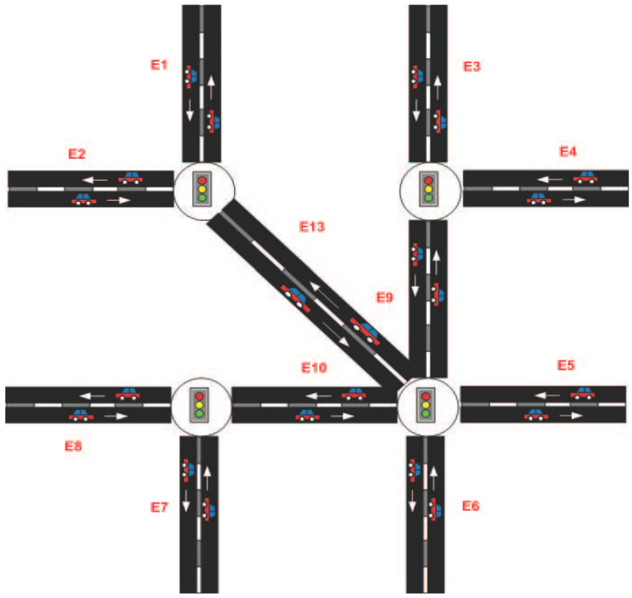
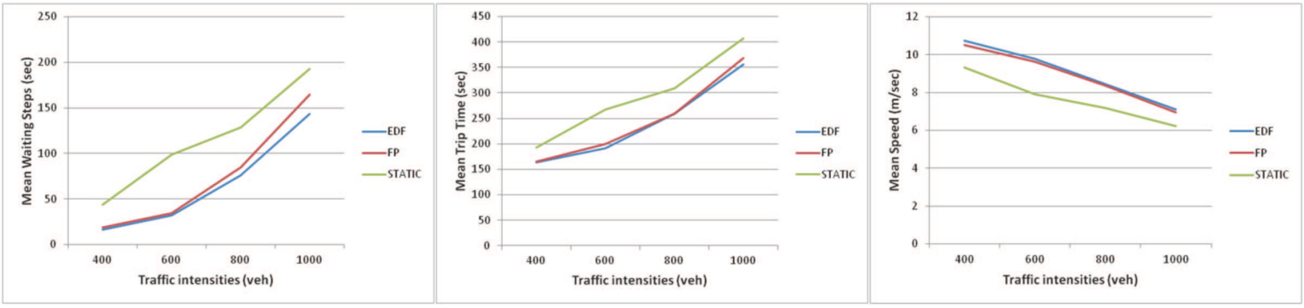


Figure 5: Network containing complex intersections

2.3 Mesoscopic Optimization

The previously mentioned optimizations had in common that the vehicles were directly in the communication range of a single infrastructure unit (e.g. one RSU at 2.1.1, the intersection control at 2.2.1 or the intelligent traffic lights at 2.2.3). For mesoscopic models, where the investigated area exceeds this communication range, a reliable and efficient method is required to exchange traffic information timely with as much vehicles as possible. As it is assumed that all V2X enabled vehicles have the ability to share their positional data (e.g. through GPS) current communication models favor Geocast over Cluster-Based or Broadcasting models. Kaiwartya et al.[9] provide an overview and classify the current Geocast routing protocols.
With reliable and timely traffic information over large areas it is possible to identify and avoid congested roadways. Finding the fastest vehicular route to a destination has several benefits, such as reducing traffic congestion, fuel consumption and traffic emissions.
Noori et al.[13] investigated a large scale V2X enabled urban area and developed an dynamic route planning algorithm using V2X communication and real-time traffic information.
To achieve this task their proposed methods consists of the following requirements:

- Every road segment has a Road-side-unit at the start and at the end of the segment.
- Every road segment has a Ideal Traveling Time (ITT). The ITT is the time required for a car to go from the beginning of the street to the end of the street under ideal circumstances (when the road is empty and with the maximum allowed speed). This can be calculated via the length of the road segment and the allowed maximum speed.
- Every road segment has a Current Traveling Time (CTT). The CTT is calculated by building the average over the traveling time for the 5 last recent cars



(a) Mean Waiting Steps of Priority Vehicles (b) Mean Trip Time of Priority Vehicles (c) Mean Speed of Priority Vehicles

Figure 6: Simulation results for a network of complex intersections using FP, EDF and static scheduler

in the street. When a vehicle enters a road segment, the RSU transmits the current time and date to the vehicle. The car holds this message and periodically broadcasts this message until it arrives at the end of the segment. The RSU at the end point calculates the traveling time by subtracting the real time and the starting time for this car.

- The CTT for every road segment is broadcasted and made available to all vehicles in the urban area.
- If a RSU did not receive any data or the time of the last transmission is greater than the ITT, the RSU assumes that there is no car in the street and assigns a CTT equal to the ITT of the segment.

With these requirements the road network forms a weighted graph, with the current traveling time labeling the weight for the edges. The search for the fastest route is then a classic shortest path problem. Noori et al. have chosen the A* algorithm to find the shortest path with the CTT as their cost function. To allow a dynamic route planning this shortest path is re-evaluated after every simulation step with the newest broadcasted CTTs. These changes to the car's route happen until the car arrives at the destination.
Noori et al. imported a realistic vehicle traffic and traffic related information model of the city of Cologne from the TAPAS-Cologne project from the German Aerospace Center, Institute of Transportation System and OpenStreeMap data covering approximately an area of 400 km^2 into the traffic simulator SUMO. This dataset contains car traffic from 24 hours consisting of 700.000 individual vehicle trips. Their simulation scenario investigates the impact of the route planning algorithm at the peak traffic demand between 6 a.m. till 8 a.m. The city map is divided into several zones based on the traffic status. After that 20 different zones are selected and one vehicle is added to each zone with a traveling distance of 5 km.
Three simulations are done to observe the vehicles traveling time:

- In the first run, only the mentioned 20 vehicles travel the city of Cologne without any traffic lights or other vehicles to measure the ideal traveling time.
- The real traffic of cologne is simulated with over 250.000 individual vehicles with the 20 vehicles included, in order to simulate the vehicles travel time without the route planning algorithm.

Figure 7: Travel time of vehicles based in different traffic densities

- Lastly the dynamic route planning is enabled for the 20 vehicles and their travel time is observed.

Figure 7 illustrates the simulated travel times for the 20 selected vehicles. A reduction of 41.12% in average travel time in low traffic areas (car number 1 - 7), 52,84% for medium traffic (car number 7 - 14) and 60,79% for high traffic areas (car number 14-20) compared to the real traffic of cologne was achieved in the simulation run. These results show that under perfect circumstances (traffic information is instantaneously broadcasted, all vehicles receive traffic information, every road segment is V2X equipped) the travel time in dense urban areas can be drastically reduced for a few selected cars. The impacts for large fleets of dynamically routed cars are not discussed.

3. DISCUSSION

4. CONCLUSION

5. ERSTER ENTWURF VERALTET

What is traffic flow optimiziation. What is needed for Traffic flow optimization (Traffic detection?) Traffic Prediction [16].
How to achieve optimization Self-organization?[19]

Overview of next subsections Traffic Control with its sub-subsections Traffic Lights and Traffic Management Systems.
Economic Driving: Improvements such as reduction of emissions via V2V communication.
Can V2V improve traffic? Yes example[15]

5.1 Traffic Control

Real-time lane selection[8]
Speed control at lane drop [17]
Noch ein zusätzliches Paper finden

5.1.1 Virtual and Adaptive Traffic Lights

In-vehicle virtual traffic lights[5] [6]
Dynamic lane grouping [21]
Dynamic traffic lights with emergency/high priority vehicles [1]

5.1.2 Route Guidance and Traffic Management Systems

Traffic Prediction Models [12]
Graphical Route Guidance [7]
Vanet based route guidance [13] Finding optimal routes through traffic with v2v find paper
Navigation System paper finden

5.2 Economic Driving

V2V communication helps reducing emissions. find more papers
Optimal trajectory and brake/acceleration [3]

5.3 Discussion and Comparison

Compare methods discuss benefits and disadvantages.

5.4 Conclusions

Improvement through usage of v2v communication.

5.5 Acknowledgments

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