Mitigating Flash Crowd Effect Using Connected Vehicle Technology

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Abstract

A Flash Crowd Effect (FCE) occurs when in the case of non-recurring congestion a large portion of drivers follows similar re-routing advice. Consequently, congestion is transferred from one road to another. Coping with the FCE is challenging, especially if the congestion results from a temporary loss of capacity (e.g. due to a traffic incident). The existing route guidance systems do not address FCE, as they either do not consider the effects of guidance on the rest of the road network, or predict link travel times based on the number of vehicles traveling on the link, which in the case of the loss of capacity is unreliable. We demonstrate that the FCE can be addressed in a distributed way with Vehicle-to-Vehicle (V2V) communication provided by Connected Vehicle (CV) technology. The proposed in-vehicle TrafficEQ system provides vehicles with mixed route guidance strategy—i.e. a route is autonomously chosen by the vehicle with a probability that is inversely proportional to the latest reported travel time on the route. Real-time travel time information is crowd-sourced by TrafficEQ users. Using realistic simulations of incident-related capacity drops on a classic two-route highway example and a realistic urban road network, we demonstrate that TrafficEQ can address the FCE by reducing travel time oscillations among the alternative routes. The system's drawbacks—in particular the occasional necessity of providing incentives to follow the guidance—are discussed.

Keywords: Intelligent Transportation Systems (ITS), traffic information, route guidance, connected vehicle technology, flash crowd effect.

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1. Introduction

Traffic Informations Systems (TISs) enable better utilisation of road networks by providing drivers with real-time information about traffic conditions and allowing them to make better routing decisions [1]. The future TISs will be enhanced with Connected Vehicle (CV) technology, allowing vehicles to create a wireless vehicular *ad hoc* network (VANET)—a cost-effective alternative to the existing traffic sensing technologies such as inductive-loop detectors. The technology provides various *ad hoc* communication patterns such as between vehicles (V2V) and between vehicles and road infrastructure (V2I) [2]. However, provision of traffic information is only the first step in dealing with congestion. The second step consists of route selection. This is a challenging task, especially in cases of unpredictable *non-recurring* congestion when traffic incidents result in temporary loss of capacity and when a strong link between routing decisions of drivers and the travel time exists (e.g. when several vehicles share the same origin-destination pairs and the number of alternative routes is limited). In the literature this is often illustrated by a two-route example, in which the main route is a two-lane highway with one lane blocked by a stalled vehicle and the second route is a bypass with a lower speed limit [3]. If everyone uses the same *pure routing strategy* (e.g. based on the shortest-time principle) combined with similar traffic information, the congestion is shifted from one road to another. In the literature this is referred to as the *Flash Crowd Effect* (FCE) [4], *similar advice problem* [5], or *overreaction* [6]. In this case real-time information about prevailing conditions can be misleading, as it does not include the delayed effect of vehicles entering the route in its associated travel time. Moreover, it is difficult to predict travel times based on the number of traveling vehicles when the road capacity unpredictably changes [6]. Research literature gives very little attention to how to cope with the FCE problem in practice. While it is noticed in [4, 5, 6]—only general indications, such that a mixed route guidance strategy should be used instead of the pure shortest-time route guidance [7]—are given. The exception—work reported by Davies in [3]—explicitly studies the problem. By using the two-route example, the authors demonstrate that the FCE can be mitigated by means of anticipation of delay which is learned over time. However, the approach of Davies is centralised. It also relies on information about the exact number of vehicles and their travel times on the route obtained from fixed sensors. Moreover, practical aspects of system deployment are not addressed.

CV technology offers new tools to approach the FCE problem. Whereas most of the V2V-based TISs focus on efficient traffic information dissemination (e.g. [8, 9, 10, 11]), route guidance is included in several V2I-based systems (e.g. [12, 13, 14, 15]). Although these systems were not evaluated in situations where the FCE is likely to develop, they may have potential to cope with the problem via route choice coordination. However, this requires an entity dedicated to coordination (e.g. agents [12, 13] or an online environment [14]). Moreover, relying on link travel time prediction (e.g. in [13]) in cases of unpredicted road capacity drops—typically found in FCE—is not trivial.

In this paper we tackle the FCE problem explicitly by proposing an alternative CV technology-based approach (in V2V mode). The proposed method, hereafter referred to as *TrafficEQ* is fully distributed and infrastructure-less. It uses autonomous in-vehicle route guidance relying on traffic information crowd-sourced by vehicles using V2V communication. Moreover, it does not use travel time prediction or route selection coordination. Guidance provided by TrafficEQ is based on a mixed routing strategy where the probability of selecting a route is inversely proportional to its latest reported travel time. It is compared to conventional guidance based on the shortest-time principle. System evaluation is carried out using the classic two-route example and a realistic urban road network, both simulated with traffic (SUMO [16]) and network (NS-3 [17]) simulators. The main finding is that the FCE can be mitigated by combining latest travel time information crowd-sourced via V2V communication with autonomous probabilistic routing. Moreover, FCE-related time oscillations among the alternative routes are significantly reduced even if only a small portion of vehicles uses the system, while the rest applies shortest-time routing. The main drawback of TrafficEQ is that users are periodically requested to select a sub-optimal route. In the case of drivers with self-regarding preferences, our approach needs to be extended with incentives, e.g. based on the road pricing concept.

The remainder of this paper is organised into five sections. We start with a review of the literature. Section 3 introduces the TrafficEQ system. Section 4 contains the description of the simulation setup and the results of our experiments. Section 5 points out system weaknesses and future research directions. Finally, Section 6 summarises the article.

2. Related work

First we start with an overview of route guidance in the context of the FCE. Then, we discuss different traffic information architectures. Finally, guidance solutions based on CV technology are analysed.

2.1. Route guidance and FCE

Route guidance can be either (i) *centralised*—i.e. route selection is performed at some central site (as in the approach proposed by Davies [3]), (ii) *decentralised*—i.e. route selection is performed at an autonomous sub-system (as in the BeeJamA system [12]), (iii) *distributed*—i.e. route selection is performed in-vehicle (as in the proposed TrafficEQ). The advantage of centralised and decentralised guidance systems is that they allow coordinated routing decisions. However, this requires an additional traffic management component.

In general, recent work demonstrates that route guidance can improve the overall road network performance [18, 19]. Several commercial TISs (e.g. TomTom [20] or Waze [21]) provide guidance relying on prediction of traffic conditions. The prediction is based on a combination of prevailing conditions and historical values [22]. However, due to low market penetration these systems do not consider the effects of guidance on the rest of the road network and future

Table 1: Comparison of TISs.

	Information collection	Route guidance	FCE measures	Traffic simulation	Network simulation	Evaluation scenario
SOTIS [8]	V2V (distributed)	no	NA	microscopic based on cellular automata	NS-2	highway
Davis [3]	NA	centralised	yes: travel time anticipation based on number of vehicles	microscopic using Kerner and Klenov traffic model	no	two-route
Claes et al. [13]	V2I (decentralised)	distributed	no: always shortest travel time anticipated based on route intentions	microscopic using intelligent driver model (IDM)	no	urban (Louven, Belgium)
BeeJamA [12] and extension ([15])	V2I (decentralised)	decentralised	yes: route guidance by sub-systems (navigators), path reservation and pricing	queuing-based MATSim	middleware	urban (Shanghai, China; German Ruhr District)
Du et al. [14]	V2V, V2I details not given	distributed	yes: iterative negotiation of routes	MATLAB	no	urban (city of Sioux Falls, USA)
TrafficEQ	V2V (distributed)	distributed	yes: probabilistic route choice according to current travel times	microscopic SUMO	NS-3	two-route and urban (Kirchberg, Luxembourg)

road conditions [22]. Consequently, they cannot react to the FCE. The question of how to best use traffic information in cases of non-recurring congestion, where the number of alternative paths is low and a capacity drops are observed, is much more difficult to address. While there is a consensus that route guidance based on the shortest-time principle leads to the FCE [4, 5, 6, 7], very little attention has been devoted to how to practically solve the problem. The exception—work reported by Davies [3]—focuses on the FCE in a two-route scenario. A hypothetical system in which the route guidance is based on anticipation (the system learns the maximum number of vehicles that can travel on each route) is proposed. The authors demonstrate that characteristic oscillations in travel time among the alternative routes resulting from the FCE can be significantly reduced. The solution is implicitly based on a centralised architecture. Moreover, information about the practical implementation of the proposed approach is not given.

2.2. Centralised vs. decentralised vs. distributed traffic data management

In general, systems with centralised traffic-related data processing such as Waze or TomTom have a greater capability to predict the traffic situation. This is mainly due to the network-wide traffic awareness and collection of traffic data based on the floating cellular data method. In such systems updates are far from real-time—lag time is typically in the range of 2 to 30 minutes [12] (although this is system designers' choice rather than technical restriction). However, bandwidth limitation, dissemination delays, and communication costs are the main drawbacks of such systems [23, 24]. These drawbacks can be addressed by systems with decentralised (e.g. Claes et al. [13] and BeeJamA [12]) or distributed (e.g. TrafficEQ) traffic data management. In the former traffic awareness is provided by dedicated entities via V2I communication with vehicles, while in the latter traffic information is exchanged directly between vehicles using V2V communication. Decentralised and distributed systems can easy be extended (via V2I communications with signal controllers) with real-time Signal Phase and Timing (SPaT) information. Access to SPaT has great potential to further improve traffic efficiency [25, 26] via additional speed advisory systems extending route guidance.

2.3. CV technology-based TIS approaches

Most of the CV technology-based TISs proposed in the literature focus on message dissemination (e.g. [9]) and estimation of traffic conditions (e.g [27]). In general, infrastructure-less TISs (i.e. based on V2V communication only) allow for efficient traffic information crowd-sourcing even with low penetration rates of the system [8] (for details please refer to [24]). A comparison of selected systems is given in Table 1. Some infrastructure-based TISs (i.e. relying on V2I communication) also include route guidance. For instance, the multi-agent V2I system introduced by Claes et al. ([13]) uses decentralised traffic data collection combined with distributed route selection. In the system vehicles send their route intentions to the infrastructure agents, which predict travel times based on the received intentions. Next, vehicles—based on the predicted travel times—select the fastest route, which might lead to the FCE. Sharing of route intentions allows partial coordination of route selection among vehicles, thus can reduce the consequences of the FCE. The BeeJamA system [12] is also based on a multi-agent V2I approach with decentralised traffic data collection, although it uses smaller sub-systems. In addition, it relies on decentralised guidance provided by the agents which allows efficient coordination of route selection. In [15] the system is extended with guidance based on path reservation combined with marginal pricing. The approach of Du et al. ([14]) uses guidance with coordination achieved thanks to the iterative negotiation provided by online communication environment. Similar to the system of Claes et al. ([13]) it uses distributed guidance. However, the coordination is carried out via iterative negotiation. This gives better potential to deal with the FCE. The implementation details, as well as how traffic information is collected are not presented, as the work focuses on the guidance.

In this article we introduce an alternative approach explicitly designed to cope with the FCE (the above-mentioned systems were not evaluated in the

FCE scenario). Unlike other systems, TrafficEQ has a fully distributed architecture (for information collection and route selection) with infrastructure-less communication. That is, routing decisions are made autonomously by vehicles, while information about traffic conditions is exchanged between vehicles using V2V communication without agent-based support. Instead of coordination TrafficEQ uses a simple probabilistic routing which in case of congestion distributes vehicles among alternative routes. The system is explicitly evaluated in two scenarios where the FCE typically appears—the reference two-route highway and a realistic urban road network.

3. The TrafficEQ system

Our system consists of independent TrafficEQ units installed in vehicles. We assume that a vehicle is additionally equipped with a digital map, a Satellite Navigation System (SNS), and a radio interface enabling V2V communication. The in-vehicle TrafficEQ unit, as illustrated in Fig. 1, has three functional modules: (i) V2V-based traffic information collection and dissemination, (ii) estimation of current travel times, and (iii) route guidance. They are described in detail in the next sections.

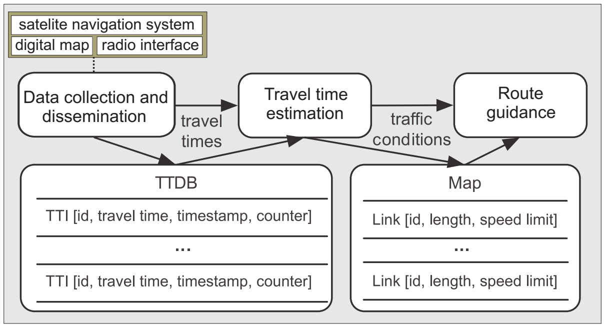


Figure 1: Modules of TrafficEQ.

3.1. Module 1: V2V-based information collection and dissemination

This module enables a vehicle to collect and share traffic information with other TrafficEQ-equipped vehicles. Individual information collection is possible because of a SNS combined with a digital map. Vehicles exchange traffic information-related messages over a wireless communication channel. The dissemination is based on a one-hop broadcasting technique, similar to the ones used in [8, 28, 29]. Details of the dissemination method are given below.

3.1.1. Data abstraction

The TrafficEQ system of each vehicle has a local *travel time database* (TTDB) in which it stores *travel time information* (TTI) for each road segment: its identifier, value of travel time, and a timestamp of the stored travel time. In addition, a TTI contains the information about the number of reports received about the road segment during the last p seconds (the system stores the number of reports for each of the last p seconds in order to maintain the total count). The number of reports is referred to as *segment popularity counter*. Each vehicle has access to a digital map. The digital map represents a road network as a graph of road segments. Each road segment has the following attributes: identifier, length, and speed limit. A vehicle is interested in estimating the travel times between two locations: origin (O) and destination (D). We assume that there exists at least one route for the pair O-D represented as a sequence of n road segments s_i, $R = [s_1, s_2, \ldots, s_n]$. In particular we allow for m alternative routes $R = \{R_1, R_2, \ldots, R_m\}$, where $m \geq 1$. The TrafficEQ system can estimate travel times between O-D by querying the map for available alternative routes for the given O-D and the TTDB for current travel times on the respective road segments.

3.1.2. Dissemination protocol

The pseudo-code of the dissemination and collection algorithm is presented in Algorithm 1.

```
Initialise TTDB
{Disseminate}
for each broadcasting step do
    create packet from TTDB
    broadcast packet
end for
while traveling do
    {Collect first-hand TTI}
    if event of traversing a road segment then
        create TTI
        update TTDB with TTI
    end if
    {Collect second-hand TTIs}
    if event of receiving a packet then
        for TTI $\in$ packet do
            if TTI newer than TTDB.TTI then
                update TTDB with TTI
            end if
        end for
    end if
end while
```

Algorithm 1: Dissemination algorithm.

It is a one-hop dissemination protocol combining *local broadcast* and *store-and-forward* mechanisms. Each TrafficEQ module periodically broadcasts packets with TTIs from its TTDB. Due to bandwidth limitations only selected TTIs from TTDB are broadcasted. The selection is based on a *utility function*, which is a linear sum of the following two ranks: *up-to-dateness*—TTIs with the most recent timestamp are preferred—and *scarcity*—segments with the lowest segment popularity counter are preferred. Only k TTIs with the highest value of the utility function are encoded to a packet (line 4) and broadcasted at every broadcasting step (line 5). Vehicles travelling in the opposite directions also participate in the dissemination of TTIs. This helps in propagating the information in low density scenarios.

To address a scenario of low density traffic, a vehicle carries the packet until it discovers a neighbour in its transmission range (i.e. when it receives a packet from another vehicle). TTIs can be classified as either first- or second-hand. The former come from vehicle's own experience, i.e. after traversing a road segment the vehicle creates a TTI about the segment (lines 8–12). Specifically, for each segment a vehicle records two timestamps—the first one when entering a segment and the second one when leaving it. This allows for calculating travel time on each segment. In this work, the distinction between road segments is provided by the simulator. In reality, every car would be required to run a map-matching algorithm in order to identify a road segment it is currently travelling on [30]. Finally, created TTIs are then shared with the neighbouring vehicles. The second-hand TTIs are received from other vehicles (lines 13–20). A vehicle continuously listens for second-hand TTIs. Information about a given segment stored in the TTDB is updated either if first-hand TTI is created or if the timestamp of the received TTI is newer than the one stored in the TTDB. In both cases the new TTI replaces the old one.

3.2. Module 2: Estimation of the current travel time

Travel time T on route R_i is calculated as a sum of travel times on the route's segments s_j:

$$T(R_i) = \sum_{j \in 1,\ldots,n} T(s_j), s_j \in R_i. \quad (1)$$

Initially the $T(s_j)$ is set to a default value called *static travel time* ($STT(s_j)$), which is calculated as the time needed to complete segment s_j at the maximum speed allowed on this segment:

$$STT(s_j) = \frac{length(s_j)}{max\ speed(s_j)}. \quad (2)$$

On a straight highway segment, the STT value is close to the *free-flow travel time* (FFTT) (i.e. the time needed to travel a segment when the vehicle speed is not affected by dense traffic conditions). However, for urban roads which often include turns, intersections and traffic signals, the FFTT value is often lower that STT. As we cannot assume that the FFTT value is known to TrafficEQ users, a default TTI value is initially set to STT. Travel time on a road segment depends on the traffic demand (flow) and the supply (capacity) which can change dynamically [31]. Whereas fluctuations in demand are rather easy to predict (increase of flow during rush hour), the fluctuations in supply (e.g. due to traffic accidents) are often unpredictable. Therefore it is challenging to estimate travel times on a road segment knowing only the number of vehicles (demand). In the case of a traffic accident the estimate would be too optimistic (as in [13]). For these reasons, the TrafficEQ system describes traffic conditions by means of the latest travel times of the segments reported by the system users. Therefore, the newest information about a given segment replaces the older one. This approach has the fastest reaction to changes in traffic conditions [18]. Additionally, we developed a method to discard outdated information in cases where no information about a segment is available for a specific period of time. We use a *time-to-live* (TTL) threshold which determines the maximum age of the information used in the system. If a timestamp of a TTI in TTDB is older than the predefined TTL, the TrafficEQ system resets the value to the default value (i.e. to STT).

3.3. Module 3: Route guidance

The route guidance problem is modelled as the shortest path problem for an O-D pair on a weighted graph, where weights represent the cost of travel on road segments (expressed as travel times). TrafficEQ finds several alternative routes for the O-D by using Yen's algorithm [32], which produces K-shortest and single-sourced paths. The routes are calculated at the origin (hereafter referred to as a *decision area*) until the destination, whereby loops are avoided. Two routing strategies are defined. The first one, called *probabilistic*, is the main strategy of TrafficEQ designed to mitigate the FCE. According to this strategy the probability of choosing a route is inversely proportional to its estimated travel time. This strategy in addition to travel times, takes into consideration a correlation factor (related to the fact that some segments can be shared) between the alternative routes. The cost of a route route i ($c(R_i)$) is the travel time on this route $T(R_i)$ penalised by a *correlation factor* (cf):

$$c(R_i) = T(R_i) \cdot cf_i, \tag{3}$$

where cf is a correlation factor expressed as:

$$cf_i = \beta \cdot N_i, \tag{4}$$

where N_i is number of common route segments of route i and all alternative routes. The probability of choosing route R_i is calculated as follows:

$$p(R_i) = \frac{\sum_{j \in 1,\ldots,m} c(R_j) - c(R_i)}{(m-1) \cdot \sum_{j \in 1,\ldots,m} c(R_j)}, \tag{5}$$

which causes the route with the smallest cost to be chosen most frequently.

In selected experiments we extended the probabilistic strategy with an additional probability of not following a guidance when it does not suggest the route with the shortest-time. In this case the probability of not following the route with a longer time ($p(st)$) is now correlated with time difference between the proposed route and the route with the shortest-time:

$$p(st) = \frac{c(R_p) - c(R_{st})}{c(R_p)}, \tag{6}$$

where $c(R_p)$ is a cost (travel time) of the route given by the probabilistic strategy, and $c(R_{st})$ is a cost (travel time) of the shortest-time route.

The second strategy, *shortest-time*, represents the conventional approach used in current route guidance systems and is defined for comparison purposes. Drivers choose the route (among m alternatives) with the shortest current travel time:

$$R_{st} = \arg\min_{R_i \in R} \{T(R_1), T(R_2), \ldots, T(R_m)\}. \tag{7}$$

4. Simulation experiments

In this section the probabilistic strategy is compared with the conventional shortest-time strategy in terms of how well it mitigates the FCE. First, in Sec. 4.1 we describe the types of drivers and the performance measures. Next, in Sec. 4.2 details about the simulation model are given. In particular, the two scenarios—highway and urban—are explained and preliminary experiments analysing general route properties are given. Finally, simulation results are given in Sec. 4.3.

4.1. Driver types and performance measures

We define three classes of drivers. The first one, called *Uninformed*, refers to drivers who do not use a route guidance system, i.e. they do not modify their routes. In the second one, called *TrafficEQ-P*, drivers use the TrafficEQ system with the probabilistic route guidance. The third class of drivers—*TrafficEQ-ST*—assumes that drivers use the TrafficEQ system with the shortest-time route guidance. In order to evaluate the performance of the road network under different distributions of driver classes, we measure the *throughput* (N), i.e. the number of completed trips within the simulation time. The trips are characterised by the following performance measures: T_{sum}—total travel time (i.e. summed travel time of all trips), T_{avg}—average trip travel time; T_{min}—minimum trip travel time, T_{max}—maximum trip travel time, and T_{stddev}—standard deviation of travel times. These metrics are compared at two levels: *global-level*—describing the average performance of all vehicles—and *route-level*—describing the performance related to individual routes.

4.1.1. Quality of V2V-based traffic information

The proposed system uses a purely distributed V2V-based data dissemination protocol. As described in Sec. 3.1.2 the proposed dissemination protocol is designed to handle both types of networks—sparse by using store-and-forward technique, and dense by controlling the number of forwarded packets. In order to test the quality of the information crowd-sourced by vehicles we define a Mean Absolute Percent Error (MAPE). It measures the error between the estimated travel time from the local database and the ground truth, known directly from the simulator:

$$MAPE = \sum_{s \in S} |\frac{\hat{T}(s) - T(s)}{T(s)}|, \tag{8}$$

where $T(s)$ is the actual travel time on the segment (given by the micro-simulator) and $\hat{T}(s)$ is the estimated travel time on the segment provided by the TrafficEQ system.

4.1.2. Comparison with alternative sources of traffic information

Additionally, we evaluate the impact of the VANET-based information on the route guidance performance. That is, we compare the performance of both route guidance strategies in two cases where the TrafficEQ system uses only local travel time estimates crowd-sourced from a VANET to two cases in which the system uses other sources of information:

- TMC-based—equivalent to information provided via the Traffic Message Channel (TMC) technology [33]. In our implementation, as in [13], the average travel time on a segment is calculated during five minutes intervals and with a five minute delay.

- Perfect—the most recent travel time information is available to drivers without any delays (a hypothetical perfect real-time information).

4.2. Simulation setup

We developed an open source simulation platform especially for testing VANET-based applications [34]. Its overview is shown in Fig. 2. The platform is composed of (a) a microscopic traffic simulator SUMO (version 0.18), (b) a network simulator NS-3 (version 3.16), (c) a bi-directional coupling between the simulators, and (d) an application layer.

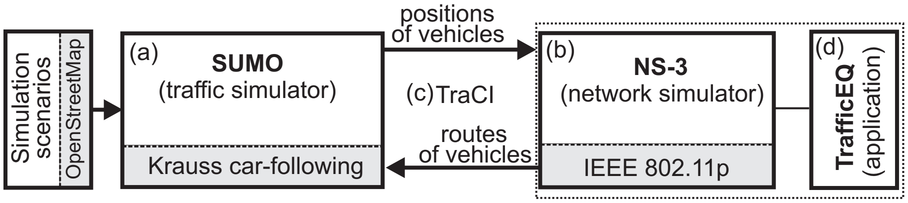


Figure 2: Overview of our simulation platform.

SUMO's microscopic traffic flow model is based on the Krauss car-following model [35]. NS-3 models the wireless communications according to the IEEE 802.11p standard [36]. We also programmed a Traffic Control Interface (TraCI) to create a bidirectional connection between NS-3 and SUMO. This allowed us to obtain parameters of simulated vehicles as well as to influence their behaviour given the information exchanged over the wireless network. The specification of the 802.11p protocol in NS-3 is given in Table 2.

The simulation settings are given in Table 3. Each experiment lasted one hour and was repeated ten times. TrafficEQ broadcasts packets (with a frequency of one per second) containing traffic information from the last two minutes. We run simulations in two scenarios (urban and highway, described below), each of them having a flow of 1000 vehicles/hour/lane traveling in the same direction. The parameter values of the dissemination method (broadcasting step,

Table 2: Parameter values for IEEE 802.11p.

Parameter	Value
Transmission Power	21.0206 / 16.02 dBm
Transmission/Reception Gain	0/0
Energy Detection Threshold	-96.0dBm
CAC Model Threshold	-99.0dBm
OFDM Rate	6Mbps
Bandwidth	10MHz
Propagation Loss Model	m-Nakagami Model
m for m-Nakagami	1.5 $ifdistance < 80m$, 0.75 otherwise
Propagation Delay Model	Constant Speed Model

history of TTDB, number of TTIs in the packet and TTL) were obtained in preliminary experiments.

Table 3: TrafficEQ simulation settings.

Simulation time	3600 seconds (1 hour)
Number of independent runs	10 for each experiment
Communications standard	IEEE 802.11p
Maximum wireless communication range	500 meters
Broadcasting step	1 second
Penetration rate	0-100%, every 5%
History of TTDB (p)	120 seconds
Number of TTI in a packet (k)	10
Time-to-live (TTL)	120 seconds
Input flow	1000 vehicles/hour/lane (one direction only)

4.2.1. Highway scenario

We use the highway scenario from [3] consisting of a two-lane highway—also referred to as the main route—and a one-lane bypass as illustrated in Fig. 3. The accident (marked with the dot) happens at a distance of 1.5 kilometres from the decision area. During the accident, one lane of the main route is closed so vehicles need to merge onto the second lane. In the decision area (marked with the rectangle) drivers can choose whether or not to exit the highway and take the bypass. Table 4 specifies the length and speed limits of the routes, as well as STT and FFTT values (FFTT were obtained using simulations). As there are no turns or intersections in this scenario, the FFTT is close to the STT for both routes.

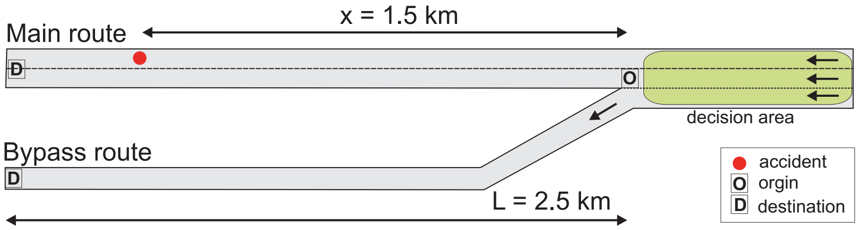


Figure 3: The highway scenario.

Table 4: Highway road network settings.

Route	Length [m]	Speed [m/s (km/h)]	STT [s]	FFTT [s]
Main	3492	31.94 (115)	93.72	97.10
Bypass	3497.57	25 (90)	115.52	119

To empirically define the critical flow, we run preliminary simulations with flows ranging from 500 to 1200 vehicles/lane/hour. A rapid increase in travel times was observed for the flow equal to 900 vehicles per lane per hour (transition of the traffic state from free-flow to congested [3]). Above this *critical flow* vehicles start queuing up before the area of the accident and the congestion propagates. In the experiments the flow is set to 1000 vehicles/hour/lane (which is above the critical flow).

4.2.2. Urban scenario

The urban scenario represents a part of a real road network from Kirchberg (neighbourhood in north-eastern Luxembourg City) exported from OpenStreetMap [37]. The scenario consists of three routes: a main route Kennedy (K), and two alternative routes: Adenauer (A) and Thuengen (T) as presented in Fig. 4. This scenario is an example of a typical urban road network which includes signalised intersections and overlapping routes (route Kennedy and Thuengen have common segments). Based on real observations, the default split was set to 0.9, 0.05, and 0.05 for Kennedy, Adenauer and Thuengen respectively. The accident (marked with the dot) happens on the Kennedy route and causes a decrease of the maximum speed at which vehicles can pass the accident point from 19.44 m/s (70 km/h) to 2 m/s (7.2 km/h). In the decision area (marked with the rectangle) drivers can choose which of the three alternative routes to take.

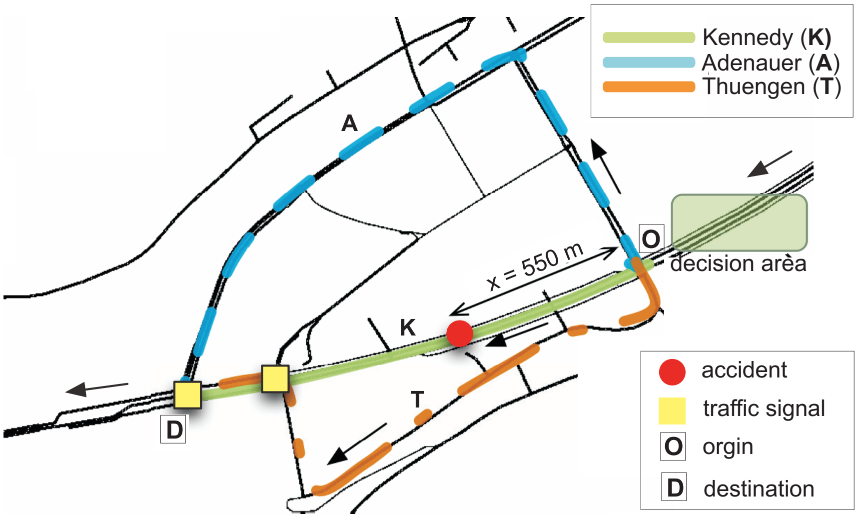


Figure 4: The urban scenario (Kirchberg, Luxembourg).

Table 5 specifies the length, speed limits, and SST. Table 6 shows the route performance (without accident) with default split (90% for Kennedy and 5% for Adenauer and Thuengen). The value of T_{avg} approximates FFTT. Table 6 shows that FFTT on the Adenauer route is shorter than on Thuengen route despite the fact that SST on the Adenauer route is longer. This difference between STT and FFTT shows the importance of considering the actual travel times even if the road capacity is not reduced.

Table 5: Static urban road network settings.

Route	Length [m]	Speed [m/s (km/h)]	STT [s]
K (Kennedy)	2069.63	19.44 (70)	97.96
A (Adenauer)	2598.22	13.89 (50)	156.02
T (Thuengen)	2460.76	13.89 (50)	142.34

Table 6: FFTT performance for the 0.9, 0.05, and 0.05 split.

Route	N	$T_{avg}[s]$	$Std_T[s]$	$T_{min}[s]$	$T_{max}[s]$
K	1735	127.43	10.40	104.29	150.87
A	93	196.90	13.57	178.58	223.00
T	96	200.81	18.99	167.87	232.88
Global	1924	134.45	24.01	104.29	232.88

In all figures presenting time series, the value of travel time is calculated including the decision area, whereas the number of vehicles on segments does not include the decision area. This enables distinguishing between causes of the increased travel times. In our preliminary experiments we discovered that the critical flows for the Kennedy route are 500 (with an accident) and 1000 (without the accident) vehicles per lane/hour. In the rest of simulations reported in this work we used the flow equal to 1000 vehicles per lane/hour.

4.3. Simulation results

First the TrafficEQ guidance is evaluated in the highway scenario (Sec. 4.3.1), and the urban scenario (Sec. 4.3.2). In each experiment all drivers belong to one of the three groups (*uninformed*, *TrafficEQ-ST*, or *TrafficEQ-P*). Results of the study with different groups coexisting within the same experiment are reported in Sec. 4.3.3. In Sec. 4.3.4, we analyse the quality of V2V-based traffic information dissemination. Finally, in Sec. 4.3.5 we study how different sources of traffic information influence performance of TrafficEQ.

4.3.1. Highway scenario

Table 7 compares performance of the road network for the three groups of drivers. The values in parentheses represent the standard deviation of ten different runs of the experiment. The use of traffic information with the shortest-time strategy (represented by TrafficEQ-ST) significantly improves network performance compared to the case where drivers did not modify their original routes (i.e. the uninformed group). The average travel time drops by around 52% (from 284.3 to 135.22 seconds). This means that approximately 65 hours of total driving hours are saved if the uninformed group switches to the shortest-time strategy. In addition, throughput of the network (number of traveling vehicles) is increased by approximately 10% (from around 1744 to 1924 vehicles). The use of the probabilistic strategy (TrafficEQ-P) further improves the average travel time (decreases by 6% compared to TrafficEQ-ST drivers).

Table 7: Global-level performance (highway scenario), std. dev. in parenthesis.

	Uninformed	TrafficEQ-ST	TrafficEQ-P
N	1744.6 (34.2)	1924.3 (0.90)	1928 (1.00)
$T_{sum}[h]$	137.77 (4.10)	72.28 (0.07)	70.10 (0.01)
$T_{avg}[s]$	284.30 (3.04)	135.22 (0.08)	130.89 (0.07)
T_{avg} [s] with confidence interval 99%	284.11–284.49	135.22–135.23	130.89–130.89
$T_{min}[s]$	124.47 (0.14)	123.5 (0.40)	123.21 (0.09)
$T_{max}[s]$	441.98 (5.77)	147.05 (0.31)	138.38 (0.31)
T_{stddev}	90.64 (1.70)	4.81 (0.05)	5.10 (0.01)

Table 8 presents travel times on each of the routes individually. In case of TrafficEQ-ST only 31.4% of drivers chose the bypass route. The average travel time is slightly lower on the main route (134.47 vs. 136.87 seconds). In the case of TrafficEQ-P the share of the bypass route increases to 45.9%. TrafficEQ-P users have a lower standard deviation of travel times (especially on the main route—1.23 vs. 5.6).

The decrease in travel time variability can be seen when comparing Fig. 5a with Fig. 5b. With the shortest-time routing all vehicles initially take the main

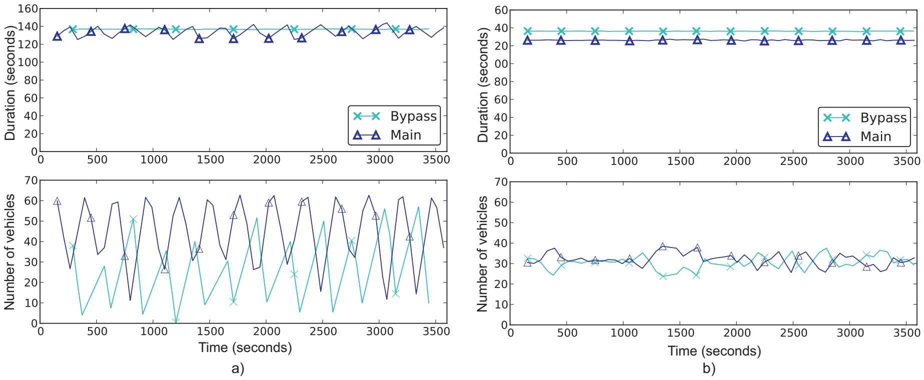
Table 8: Route-level performance (highway scenario), std. dev. in parenthesis.

	Uninformed	TrafficEQ-ST	TrafficEQ-P
Main			
N	1744.60 (34.20)	1320.90 (68.60)	1044.00 (54.10)
$T_{sum}[h]$	137.80 (4.10)	49.34 (0.63)	36.63 (0.46)
$T_{avg}[s]$	284.30 (3.04)	134.47 (0.08)	126.30 (0.00)
$T_{min}[s]$	124.47 (0.14)	123.5 (0.40)	123.21 (0.09)
$T_{max}[s]$	441.98 (5.77)	147.04 (0.30)	131.55 (0.31)
T_{stddev}	90.64 (1.70)	5.60 (0.03)	1.23 (0.01)
Bypass			
N	NA	603.40 (31.4)	884 (45.9)
$T_{sum}[h]$	NA	22.94 (0.70)	33.47 (0.46)
$T_{avg}[s]$	NA	136.87 (0.01)	136.31 (0.01)
$T_{min}[s]$	NA	135.09 (0.02)	135.03 (0.00)
$T_{max}[s]$	NA	138.98 (0.01)	138.38 (0.32)
T_{stddev}	NA	0.98 (0.01)	0.86 (0.01)

route (having the shortest STT). Because of the accident, vehicles start reporting longer travel times which at some point become longer than that of the bypass route making all vehicles in the decision area choose the bypass route. Since no vehicles select the main route anymore, after the TTL period the travel time on that route is set to the default STT value and vehicles start selecting the main route again. This situation—traffic switch from the main route to the bypass and vice versa—repeats several times until the full capacity of the main route is restored (i.e. the accident is removed). The visible reductions of oscillations in travel times and numbers of traveling vehicles on both routes indicates that the probabilistic strategy copes with the FCE more effectively than the shortest-time strategy.

4.3.2. Urban scenario

Analogously to the highway scenario, drivers using the TrafficEQ-ST or TrafficEQ-P routing strategy improve the overall network performance—throughput



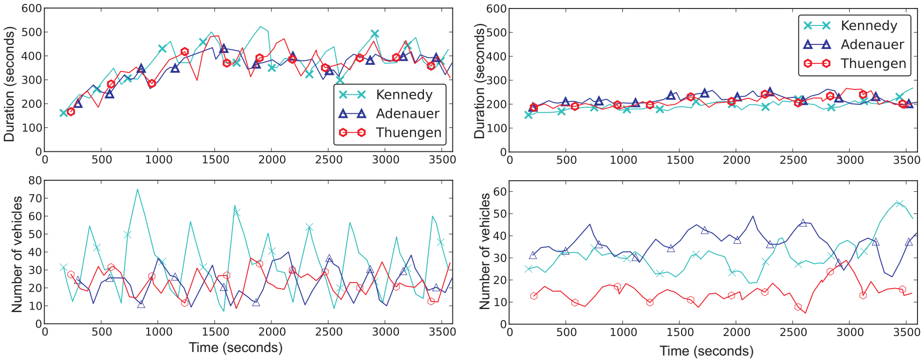
a) b)

Figure 5: Trip durations reported by individual vehicles and the number of vehicles on each route (highway scenario): TrafficEQ-ST (a), TrafficEQ-P (b).

Table 9: Global-level performance (urban scenario), std. dev. in parenthesis.

Measure	Uninformed	TrafficEQ-ST	TrafficEQ-P
N	885.2 (119.4)	1560.45 (24.06)	1722.09 (9.74)
$T_{sum}[h]$	176.10 (29.33)	162.01 (1.41)	107.10 (29.44)
$T_{avg}[s]$	711.27 (36.47)	373.83 (5.18)	221.22 (14.16)
T_{avg} [s] with conf. interval 99%	708.11–714.43	373.49–374.17	220.34–222.1
$T_{min}[s]$	155.68 (0.09)	156.68 (0.17)	136.47 (2.88)
$T_{max}[s]$	968.46 (1.19)	588.91 (27.93)	336.73 (43.58)
T_{stddev}	246.77 (3.14)	77.82 (3.76)	36.13 (9.66)

is almost doubled (see Table 9). The average travel time decreases from 717.27 seconds for uninformed drivers to 373.83 for TrafficEQ-ST drivers and 221.22 for TrafficEQ-P drivers. Contrary to the highway scenario, the improvement in the average travel time observed for TrafficEQ-P strategy is much greater—it is about 40% shorter that of TrafficEQ-ST. Similar observations can be made when looking at the performance of the individual routes presented in Table 10. With TrafficEQ-ST the distribution of trips was as follows: 42.3% of traffic to Kennedy, 29.8% to Adenauer, and 27.9% to Thuengen. For TrafficEQ-P the values were 42.6, 39.7, and 17.7 respectively. This change of the ratio for Adenauer and Thuengen routes resulted in a significant improvement of road network per-



a)

b)

Figure 6: Trip durations reported by individual vehicles and the number of vehicles on each route (urban scenario): TrafficEQ-ST (a), TrafficEQ-P (b).

formance. TrafficEQ-P drivers saved 54.91 hours over TrafficEQ-ST drivers. In terms of individual routes, the performance also improved as the average travel times drop by 40.1% for Kennedy, 39.9% for Adenauer, and 43.7% for Thuengen in comparison with the TrafficEQ-ST strategy. Reductions in oscillations in the experienced travel times due to the TrafficEQ-P strategy are shown in Fig. 6—see TrafficEQ-ST (a) vs. TrafficEQ-P(b).

4.3.3. Analysis of different penetration rates of the probabilistic strategy

In the experiments reported so far, all informed vehicles within a single experiment used the same strategy—either the probabilistic (TrafficEQ-P) or the shortest-time (TrafficEQ-ST). However, in reality some users would deviate from systems' guidance, especially if a route with longer travel time is advised. In this section we analyse this case by mixing the two strategies within a single experiment. TrafficEQ-ST represent users with route advice based on the shortest-time principle, while TrafficEQ-P corresponds to drivers who follow the probabilistic guidance. Fig. 7 and Table 11 show the average travel times for different penetration rates of TrafficEQ-ST users.

In the highway scenario the average travel time of all vehicles first decreases, reaches a minimum for approximately 50% of TrafficEQ-P penetration rate and

Table 10: Route-level performance (urban scenario), std. dev. in parenthesis.

Route	Routing strategy		
Kennedy (K)	Uninformed	TrafficEQ-ST	TrafficEQ-P
N	776.40 (106.84)	665.91 (42.30)	733.73 (42.60)
$T_{sum}[h]$	160.70 (27.11)	71.51 (1.82)	48.24 (14.36)
$T_{avg}[s]$	739.95 (37.79)	386.61 (3.77)	231.63 (30.63)
$T_{min}[s]$	155.68 (0.09)	156.68 (0.17)	136.47 (2.88)
$T_{max}[s]$	968.46 (1.19)	587.15 (29.89)	328.72 (54.62)
T_{stddev}	739.95 (37.79)	88.44 (2.43)	40.74 (13.94)
Adenauer (A)			
N	50.00 (6.00)	465.64 (29.80)	683.82 (39.70)
$T_{sum}[h]$	7.17 (1.07)	46.43 (0.82)	41.16 (11.03)
$T_{avg}[s]$	513.41 (23.15)	359.17 (8.96)	215.87 (4.82)
$T_{min}[s]$	189.56 (0.22)	187.85 (3.47)	178.59 (0.68)
$T_{max}[s]$	696.25 (4.19)	507.34 (18.71)	286.85 (16.53)
T_{stddev}	176.90 (2.98)	58.89 (6.73)	21.73 (2.71)
Thuengen (T)			
N	58.80 (6.60)	428.91 (27.90)	304.55 (82.37)
$T_{sum}[h]$	8.23 (1.15)	44.08 (0.81)	17.70 (4.83)
$T_{avg}[s]$	501.64 (19.78)	369.99 (5.23)	208.16 (6.06)
$T_{min}[s]$	163.66 (0.30)	162.80 (0.32)	161.00 (2.08)
$T_{max}[s]$	682.60 (0.17)	553.83 (19.17)	280.79 (21.45)
T_{stddev}	184.68 (5.32)	74.83 (3.53)	25.36 (3.14)

then increases slightly. The grey area in Fig. 7 illustrates where the system may be considered inefficient, because the mean travel time for all drivers is not at its minimum. In fact, by looking at the users of TrafficEQ-ST (blue line) and TrafficEQ-P (red line) separately, we observe that their average travel time decreases monotonically for the increasing number of TrafficEQ-P users. This is because maximum travel times experienced by both groups of drivers decrease (due to the reduction of the oscillations). Fig. 9a also demonstrates that the more TrafficEQ-P drivers are present in the network, the lower the standard deviation is in the experienced travel time, which increases the reliability of the

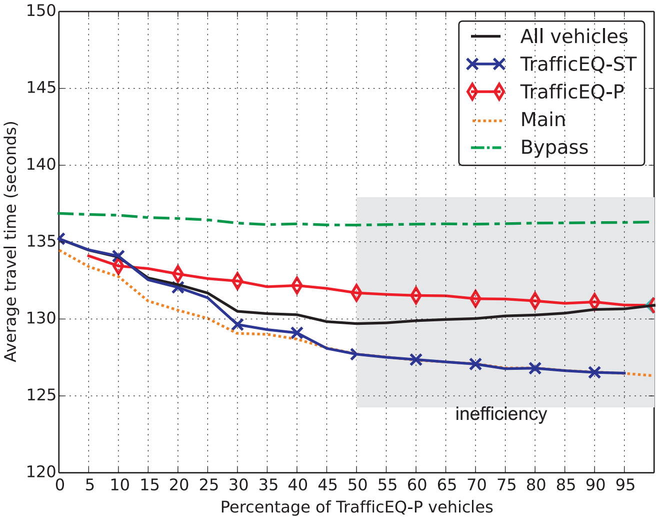
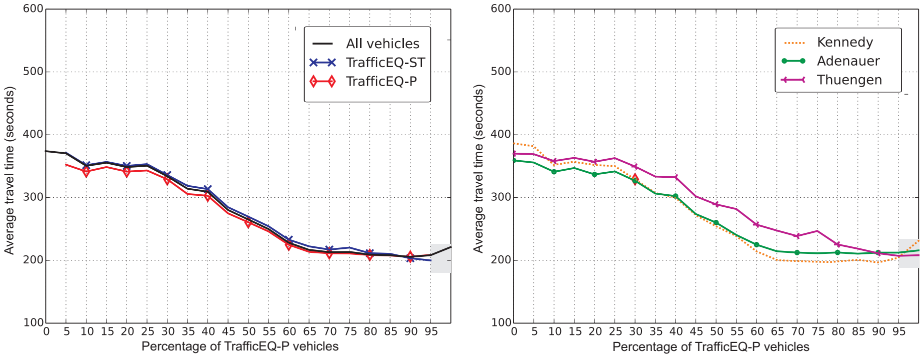


Figure 7: Average travel time vs. penetration rate of TrafficEQ-P drivers (highway scenario).

estimated travel times.

Fig. 8 and Table 12 present the results for the urban scenario. Unlike in the highway scenario, the average travel time of all vehicles decreases almost until the maximum penetration rate of TrafficEQ-P vehicles (95%). The grey area where the average travel time is not at its minimum is observed only for the remaining 5% of the penetration. However, as in the highway scenario, the more TrafficEQ-P users are present in the network, the lower the average travel time of TrafficEQ-ST and TrafficEQ-P users is, and in most cases lower standard deviation of travel times is observed (see Table 12 and Fig. 9). In contrast to the highway scenario, TrafficEQ-P users are always better off than TrafficEQ-ST drivers and the minimum total time travelled is observed for the rate of 100% (107.10 hours, see Table 12). Worth noticing also, is the fact that travel times on the alternative routes are close to each other for any composition of drivers which indicates that the system reaches a type of a user equilibrium state (only the travel time on Thuengen route is usually longer than on the two



a) b)

Figure 8: Average travel time vs. penetration rate of TrafficEQ-P drivers (urban scenario).

other routes).

The results of an alternative evaluation, where there is a certain probability that a vehicle will not follow the alternative in case if it is not the one with shortest travel time (according to Equation 6) are shown in Table 13. Among all 1876 vehicles, 65% were provided with a route with longer travel time, hence, they were tempted to select the route with a shorter travel time. Among those drivers, 21% decided to deviate, which resulted in shorter average travel time (198.91 seconds). The average travel time is 210.88 seconds. Therefore, this corresponds to a situation, were the percentage of TrafficEQ-P is between 70–90%.

4.3.4. Quality of V2V-based traffic information

Table 14 shows the MAPE values in the highway and urban scenarios. Two cases are analysed. In the first one, the population is composed entirely of TrafficEQ-ST, while in the second case only TrafficEQ-P users are present in the network. One can notice that errors are greater in the urban scenario. For instance, in the highway scenario the error on all segments is lower than 20%. In the urban scenario this is true only for the 75% and 84% cases, for TrafficEQ-ST and TrafficEQ-P respectively. The reason is that in the highway scenario the two routes are close to each other and vehicles traveling on both routes take part

Table 11: Performance for different penetration rates of TrafficEQ-P (highway scenario). T_{avg} ST and T_{avg} P denote the average travel times for TrafficEQ-ST and TrafficEQ-P users, respectively.

PR	$T_{sum}[h]$	$T_{avg}[s]$	$T_{stddev}[s]$	T_{avg} ST [s]	T_{avg} P [s]
0	72.28	135.22	4.81	135.22	NA
10	71.71	134.03	4.21	134.09	133.45
20	70.83	132.24	4.08	132.06	132.93
30	69.89	130.50	3.58	129.64	132.47
40	69.81	130.28	3.69	129.10	132.18
50	69.50	129.70	3.91	127.71	131.70
60	69.62	129.89	4.27	127.36	131.53
70	69.70	130.03	4.47	127.07	131.32
80	69.82	130.26	4.72	126.80	131.18
90	69.96	130.62	4.95	126.53	131.11
100	70.10	130.89	5.10	NA	130.89

in data dissemination, whereas in the urban scenario distances between the alternative routes are larger than the communication range. Another observation is that in both scenarios TrafficEQ-P results in lower traffic information error than TrafficEQ-ST. This is because the probabilistic strategy distributes drivers more evenly over the road network. TrafficEQ-ST causes vehicles to travel in more compact groups and thus creates larger gaps in V2V communication.

In the results reported so far we used the m-Nakagami propagation loss model. Now, we briefly compare these results with more realistic propagation models: the Two-Ray Ground Propagation (TRGP) model and the TRGP model extended with the Obstacle Shadowing Propagation model according to [38] (TRGP-OSP). In both cases antennas had heights set to 1.5 meters with radio propagation via two paths—one ray received directly, the other one reflected on the ground. The TRGP-OSP model adds the shadowing effect of buildings (i.e. propagation loss is higher when a transmission ray goes through a building). The average transmission distance using m-Nakagami model was the longest (97 meters), followed by TRGP (92 meters) and TRGP-OSP (88

Table 12: Performance for different penetration rates (PR) of TrafficEQ-P (urban scenario). T_{avg} SP and T_{avg} P denote the average travel times of TrafficEQ-ST and TrafficEQ-P users, respectively.

PR	$T_{sum}[h]$	$T_{avg}[s]$	$T_{stddev}[s]$	T_{avg} ST [s]	T_{avg} P [s]
0	162.01	373.83	77.82	373.83	NA
10	144.75	350.51	72.41	351.52	341.39
20	157.16	348.54	76.29	350.36	341.32
30	155.93	333.90	66.74	335.92	329.04
40	149.93	309.27	64.86	313.45	302.83
50	128.39	265.12	55.66	269.59	260.68
60	118.21	228.11	38.70	232.91	224.86
70	111.49	213.06	31.12	217.17	211.31
80	109.33	209.12	27.28	211.42	208.56
90	107.49	205.62	24.22	203.40	205.88
100	107.10	221.22	36.13	NA	221.22

meters). In addition, the TRGP-based models had higher number of dropped packets than the m-Nakagami due to modelling of ray reflection. Nevertheless, this did not impact the performance of TrafficEQ. The results of the system performance were comparable for each of the three propagation loss models, with the average travel times around 222 seconds.

4.3.5. Alternative sources of traffic information

So far we have studied the TrafficEQ system with traffic information crowdsourced using V2V communication. In this section we analyse what happens if TrafficEQ relies on traffic information from two alternative non-V2V sources—TMC and perfect (see Sec. 4.1.2 for details). The comparative results are given in Tables 15 and 16 (highway and urban scenarios respectively). Each scenario has two cases. In the first one, the network is composed of TrafficEQ-ST users only and in the second one everyone uses TrafficEQ-P strategy.

In the highway scenario performance of TrafficEQ-ST users is sensitive to traffic information type. While very similar performance is observed when per-

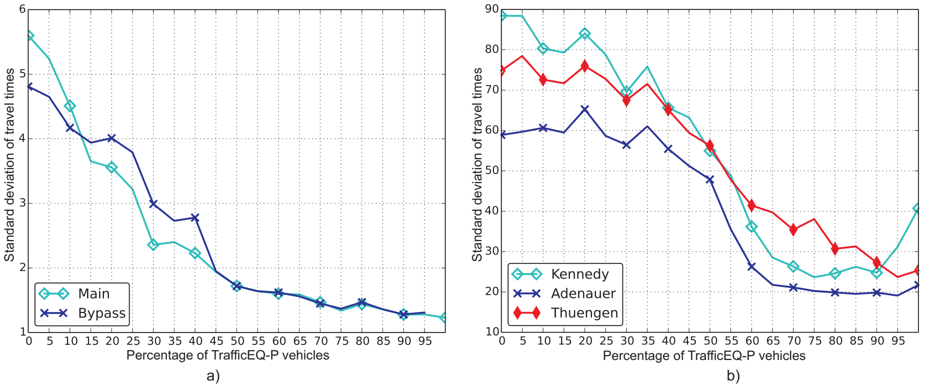


Figure 9: Standard deviation of travel times with various distributions of TrafficEQ-ST and TrafficEQ-P users: highway scenario (a), urban scenario (b).

Table 13: Performance when drivers selectively do not follow the probabilistic guidance, urban scenario. D_{avg} is an average difference between the suggested travel time by the probabilistic strategy and the shortest route time.

Group	N	$T_{avg}[s]$	$T_{stddev}[s]$	$D_{avg}[s]$
All vehicles	1876	210.88	35.65	-
Vehicles tempted to deviate (TD)	1218 (65%)	216.93	36.74	38.39
Vehicles that did not deviate	959 (79% of TD)	221.79	36.38	34.59
Vehicles that did deviate	259 (21% of TD)	198.91	32.26	52.60

Table 14: Mean absolute percent error (MAPE).

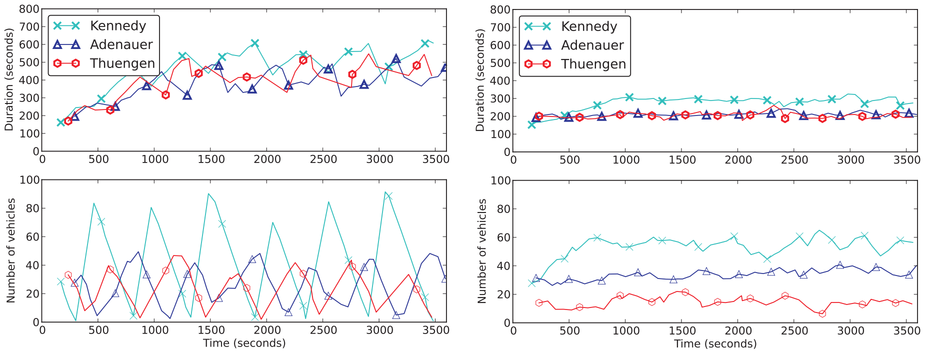
		Percentage of segments with	
Routing	MAPE	MAPE < 10%	MAPE < 20%
Highway			
TrafficEQ-ST	0.04	83.33%	100%
TrafficEQ-P	0.02	91.67%	100%
Urban			
TrafficEQ-ST	0.29	61.36%	75.00%
TrafficEQ-P	0.12	68.18%	84.09%

fect and V2V are used, the use of TMC increases the average travel time from approximately 135 (for V2V) to 147 seconds (for TMC). In the case of the TrafficEQ-P strategy similar results are observed for all information sources. The five minute delay related to TMC does not influence network performance, because we assume that TMC is aware of the accident from the beginning of the simulation.

In the urban scenario, similarly to the highway case, TMC significantly degrades the overall network performance when the TrafficEQ-ST strategy is used. Surprisingly, the V2V information results in better guidance performance than when perfect information is used (regardless of the routing strategy). The reason is that when perfect information is used, more vehicles are routed to the Kennedy route, which decreases the overall performance (see Figs. 6 and 10). The use of V2V information results in higher variation of traffic information among vehicles (when perfect information is used all vehicles have the same information). Hence, the use of such information further contributes to route choice diversification.

Table 15: Comparison of information sources (highway scenario).

	TMC	Perfect	V2V
Shortest-time (only TrafficEQ-ST used)			
N	1921 (0)	1925.5 (2.06)	1928 (1.67)
$T_{sum}[h]$	78.57 (0.01)	72.77 (0.15)	72.28 (0.07)
$T_{avg}[s]$	147.25 (0)	136.06 (0.16)	135.22 (0.08)
$T_{max}[s]$	189.85 (0.10)	147.73 (1.2)	147.05 (0.31)
T_{stddev}	15.71 (0)	4.28 (0.11)	4.81 (0.05)
Probabilistic (only TrafficEQ-P used)			
N	1928 (1.67)	1929.5 (0.5)	1928 (1)
$T_{sum}[h]$	70.15 (0.08)	70.21 (0.04)	70.10 (0.01)
$T_{avg}[s]$	130.98 (0.07)	130.99 (0.05)	130.89 (0.07)
$T_{max}[s]$	138.73 (0.2)	138 (0)	138.38 (0.31)
T_{stddev}	5.12 (0.03)	5.12 (0.01)	5.1 (0.01)



a) b)

Figure 10: Trip durations for the drivers provided with perfect knowledge (urban scenario): TrafficEQ-ST (a), TrafficEQ-P (b).

Table 16: Comparison of information sources (urban scenario).

	TMC	Perfect	V2V
Shortest-time (only TrafficEQ-ST used)			
N	1193 (0)	1386 (12.63)	1560 (24.06)
$T_{sum}[h]$	179.65 (0)	168.29 (1.20)	162.01 (1.41)
$T_{avg}[s]$	542.12 (0)	437.07 (3.50)	373.83 (5.18)
$T_{max}[s]$	1148.6 (0.26)	755.76 (16.52)	588.91 (27.93)
T_{stddev}	162.12 (0)	118.39 (3.2)	77.82 (3.76)
Probabilistic (only TrafficEQ-P used)			
N	1193 (0)	1865 (9.46)	1722 (9.74)
$T_{sum}[h]$	115.94 (7.72)	119.17 (3.59)	107.10 (29.44)
$T_{avg}[s]$	226.72 (17.93)	230.01 (7.58)	221.22 (14.16)
$T_{max}[s]$	391.26 (86.37)	335.06 (24.01)	336.73 (43.58)
T_{stddev}	46.75 (20)	38.73 (6.69)	36.13 (9.66)

5. Weaknesses of TrafficEQ and future research directions

In this paper we demonstrate that a distributed V2V-based approach can address the FCE. However, reported results indicate that there are several aspects that need further research. Below, we discuss weaknesses of our system and point out potential research directions that could address them.

5.1. Traffic information

The use of the latest reported travel time information may lead to stability and reliability issues. Hence, it requires further attention. For simplicity, we rely on a simple V2V model which could be improved. For instance, instead of using a fixed TTL, a dynamic value proportional to the distance from a vehicle to the related segment could be used. This would allow keeping information about more distant segments for longer. The proposed TrafficEQ system can also use other sources of information, including advanced V2V-based techniques proposed in the literature (e.g. [8, 9, 10, 11]).

5.2. User behaviour

The work presented in this article demonstrates how probabilistic route guidance can address the FCE. Like other CV technology-based TISs mentioned in this article we do not model behavioural processes involved in route choice, but rather focus on the control aspect of routing. In preliminary experiments (not reported in this article) we analysed guidance under the C-logit model [39]. It resulted in only slight improvement over our base TrafficEQ-ST routing, i.e. the percentage of drivers following the non-fastest route was much lower than in the probabilistic guidance. This suggests that in order to be realistic, the probabilistic route selection needs to be extended with incentives (e.g. based on road pricing as in [15]). Using gamification approaches [40] as an alternative to pricing is also worth investigating. Another way to influence collective behaviour of vehicles is to use artificial information perturbation [41]. Nevertheless, for the future work we believe that behavioural processes should be included in the route choice modelling in the FCE case (see e.g. [42] for potential directions).

Even if we assume that drivers comply with the guidance provided by our system, the probabilistic approach could be improved to provide more efficient distribution of vehicles among the alternative routes. The network with TrafficEQ-P users (regardless of their number) was more efficient than the network with only TrafficEQ-ST users. However, in the highway scenario presence of more than 50% of TrafficEQ-P vehicles had a negative influence on the average travel time (see the grey area in Fig. 7).

Currently, guidance provided by TrafficEQ is autonomous, which makes the system simple and easy to implement in practice. There are two obvious extensions are: i) V2V-based negotiations (similar to [14]), and ii) V2V-based dissemination of information indicating whether or not a vehicle selected the route advised by the system.

5.3. FCE problem quantification

The metrics used in our study are highly related to our two scenarios. Designing additional scenario-independent metrics that can quantify the FCE problem from the system and an individual user perspectives should be developed. Moreover, an analytical model giving theoretical insights on the impacts of various parameters would be desirable.

6. Conclusion

This work tackles the problem of routing guidance in non-recurring congestion caused by temporary loss of capacity. The problem is challenging when there is a strong link between link travel time and routing decisions of drivers. Typical route guidance based on the shortest-time principle will simply transfer congestion from one road to another. We argue that in such a situation travel time prediction is difficult, especially due to capacity loss and the uncertainty related to routing decisions of vehicles. The existing route guidance systems do not cope with the FCE as they either do not consider the effects of guidance on the rest of the road network, or they predict link travel times based on the number of vehicles traveling on the link, which in case of the loss of capacity is unreliable. As demonstrated in the paper, the use of guidance based on the shortest-time principle leads to the FCE, expressed in strong oscillations in travel times on available routes.

The main goal of this article is to demonstrate how a distributed approach based on V2V communications provided by CV technology can be used to mitigate the FCE. Our distributed TrafficEQ system combines traffic information crowd-sourcing via V2V communication with autonomous route guidance, in which a route choice is made with a particular probability. The probabilistic approach distributes traffic among alternative routes using only information about prevailing conditions. Performance of such guidance was compared with conventional routing based on the shortest-time principle. Realistic simulations of vehicular traffic and wireless communication were carried out in highway and urban scenarios. We demonstrated that the probabilistic strategy significantly reduces oscillations in travel times and the numbers of traveling vehicles on alternative routes compared to when the shortest-time strategy is used. Overall road network performance was improved by reducing the average travel times as well as their standard deviation. However, some shortcomings of our approach—constituting our future work—were observed. For instance, the network performed better when some users applied the probabilistic strategy, compared to the case of all vehicles using conventional shortest-time guidance. However, the system's optimal performance was achieved when only a fraction of vehicles use probabilistic guidance—approximately 50% for highway and 90% for urban. Moreover, in some cases, nodes with self-regarding preferences had no reason to use the probabilistic approach. Consequently, a social dilemma leading to a situation where everyone was worse-off was created. Therefore, extension of our system with incentives (e.g. based on road pricing) should be provided. Also, designing larger-scale scenarios with the FCE effect, and using them to test guidance strategies is desirable. Experimental work reported in this article provides a support for the development of theoretical work in the future.

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7. References

[1] D. Levinson, "The value of advanced traveler information systems for route choice," *Transportation Research part C*, vol. 11, no. 1, pp. 75–87, 2003.

[2] C. Campolo, A. Molinaro, and R. Scopigno, "From today's VANETs to tomorrow's planning and the bets for the day after," *Vehicular Communications*, vol. 2, no. 3, pp. 158—171, 2015.

[3] L. C. Davis, "Realizing Wardrop Equilbria with Real-Time Traffic Information," *Physica A*, vol. 388, pp. 4459–4474, 2009.

[4] A. Casteigts, A. Nayak, and I. Stojmenovic, "Communication protocols for vehicular ad hoc networks," *Wireless Communications and Mobile Computing*, vol. 11, no. 5, pp. 567–582, 2011.

[5] N. Hounsell, B. Shrestha, J. Piao, and M. McDonald, "Review of urban traffic management and the impacts of new vehicle technologies," *Intelligent Transport Systems, IET*, vol. 3, no. 4, pp. 419–428, 2009.

[6] M. Ben-Akiva, A. D. Palma, and K. Isam, "Dynamic network models and driver information systems," *Transportation Research Part A: General*, vol. 25, no. 5, pp. 251–266, 1991.

[7] D. E. Boyce, "Contributions of transportation network modeling to the development of a real-time route guidance system," in *Transportation for the Future*. Springer, 1989, ch. 10, pp. 161–177.

[8] L. Wischhof, L. Ebner, and H. Rohling, "Information dissemination in self-organizing intervehicle networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 6, no. 1, pp. 90–101, 2005.

[9] T. Nadeem, S. Dashtinezhad, C. Liao, and L. Iftode, "TrafficView: Traffic data dissemination using car-to-car communication," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 8, no. 3, pp. 6–9, 2004.

[10] S. Dornbush and A. Joshi, "StreetSmart Traffic: Discovering and disseminating automobile congestion using VANETs," in *Proc. IEEE 65th Vehicular Technology Conference (VTC-Spring)*, 2007, pp. 11–15.

[11] M. Jerbi, S.-M. Senouci, T. Rasheed, and Y. Ghamri-Doudane, "An infrastructure-free traffic information system for vehicular networks," in *Proc. IEEE 66th Vehicular Technology Conference (VTC-Fall)*, 2007, pp. 2086–2090.

[12] H. Wedde and S. Senge, "BeeJamA: A distributed, self-adaptive vehicle routing guidance approach," *IEEE Transactions on Intelligent Transportation Systems*, vol. 14, no. 4, pp. 1882–1895, 2013.

[13] R. Claes, T. Holvoet, and D. Weyns, "A decentralized approach for anticipatory vehicle routing using delegate multiagent systems," *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 2, pp. 364–373, 2011.

[14] L. Du, L. Han, and X.-Y. Li, "Distributed coordinated in-vehicle online routing using mixed-strategy congestion game," *Transportation Research Part B: Methodological*, vol. 67, pp. 1—17, 2014.

[15] S. Senge and H. Wedde, "Marginal cost pricing and multi-criteria routing in a distributed swarm-intelligence approach for online vehicle guidance," in *Proc. 16th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, 2013, pp. 1396–1401.

[16] M. Behrisch, L. Bieker, J. Erdmann, and D. Krajzewicz, "SUMO - Simulation of Urban MObility: An Overview," in *Proc. 3rd International Conference on Advances in System Simulation (SIMUL)*, 2011, pp. 63–68.

[17] NS-3 Netwtwork Simulator, [online] http://www.nsnam.org/.

[18] I. Leontiadis, G. Marfia, D. Mack, G. Pau, C. Mascolo, and M. Gerla, "On the effectiveness of an opportunistic traffic management system for vehicular networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 12, no. 4, pp. 1537–1548, 2011.

[19] S. Gao, "Modeling strategic route choice and real-time information impacts in stochastic and time-dependent networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 13, no. 3, pp. 1298–1311, 2012.

[20] TomTom International BV. [Online]. Available: http://www.tomtom.com/

[21] S. Hind and A. Gekker, "'outsmarting traffic, together': Driving as social navigation." *Exchanges: the Warwick Research Journal*, vol. 1, no. 2, 2014.

[22] R. Balakrishna, M. B.-Akiva, J. Bottom, and S. Gao, "Information impacts on traveler behavior and network performance: State of knowledge and future directions," in *Advances in Dynamic Network Modeling in Complex Transportation Systems*. Springer, 2013, vol. 2, pp. 193–224.

[23] Y. E. Hawas and H. El-Sayed, "Autonomous real time route guidance in inter-vehicular communication urban networks," *Vehicular Communications*, vol. 2, no. 1, pp. 36—46, 2015.

[24] M. Seredynski and P. Bouvry, "A survey of vehicular-based cooperative traffic information systems," in *Proc. 14th International IEEE Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2011, pp. 163–168.

[25] M. Seredynski, G. Arnould, and D. Khadraoui, "The emerging applications of intelligent vehicular networks for traffic efficiency," in *Proc. 3rd ACM international symposium on Design and analysis of intelligent vehicular networks and applications*, 2013, pp. 101–108.

[26] "Investigating the potential benefits of broadcasted signal phase and timing (SPaT) data under IntelliDrive," California PATH Program, University of California, Berkeley, Tech. Rep., 2011.

[27] H. R. Arkian, R. E. Atani, and S. Kamali, “Cluster-based traffic information generalization in vehicular ad-hoc networks,” *Vehicular Communications*, vol. 1, no. 4, pp. 197—207, 2014.

[28] S. Panichpapiboon and W. Pattara-Atikom, “A review of information dissemination protocols for vehicular ad hoc networks,” *Communications Surveys & Tutorials, IEEE*, vol. 14, no. 3, pp. 784–798, 2012.

[29] S. Dashtinezhad, T. Nadeem, B. Dorohonceanu, C. Borcea, P. Kang, and L. Iftode, “TrafficView: a driver assistant device for traffic monitoring based on car-to-car communication,” in *Proc. IEEE 59th Vehicular Technology Conference (VTC-Spring)*, vol. 5, 2004, pp. 2946–2950.

[30] M. A. Quddus, W. Y. Ochieng, L. Zhao, and R. B. Noland, “A general map matching algorithm for transport telematics applications,” *GPS solutions*, vol. 7, no. 3, pp. 157–167, 2003.

[31] D. Branston, “Link capacity functions: A review,” *Transportation Research*, vol. 10, no. 4, pp. 223–236, 1976.

[32] J. Y. Yen, “An algorithm for finding shortest routes from all source nodes to a given destination in general networks,” *Quarterly of Applied Mathematics*, vol. 27, no. 4, pp. 526–530, 1970.

[33] P. Davies, “The radio system-traffic channel,” in *Proc. Vehicle Navigation and Information Systems Conference.* IEEE, 1989, pp. A44–A48.

[34] Github open source project. (2013) OVNIS - an online simulation platform for VANETs. [Online]. Available: http://github.com/agacia/ovnis

[35] S. Krauss, P. Wagner, and C. Gawron, “Metastable states in a microscopic model of traffic flow,” *Phys. Rev. E*, vol. 55, pp. 5597–5602, 1997.

[36] “IEEE standard for wireless LAN medium access control and physical layer specyfication 802.11,” 1997. [Online]. Available: http://standards.ieee.org/getieee802/802.11.html

[37] OpenStreetMap project, [online] http://www.openstreetmap.org/.

[38] C. Sommer, D. Eckhoff, R. German, and F. Dressler, “A computationally inexpensive empirical model of IEEE 802.11p radio shadowing in urban environments,” in *Proc. 2011 Eighth International Conference on Wireless On-Demand Network Systems and Services (WONS)*, 2011, pp. 84–90.

[39] X. Xu, A. Chen, Z. Zhou, and S. Bekho, “Path-based algorithms to solve c-logit stochastic user equilibrium assignment problem,” *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2279, 2012.

[40] V. Magana and M. Munoz-Organero, “GAFU: Using a gamification tool to save fuel,” *Intelligent Transportation Systems Magazine*, vol. 7, no. 2, pp. 58–70, 2015.

[41] L. Du and L. H. and, “Coordinated online in-vehicle routing balancing user optimality and system optimality through information perturbation,” *Transportation Research Part B*, vol. 79, pp. 121–133, 2015.

[42] S. Bekhor, M. E. Ben-Akiva, and M. S. Ramming, “Evaluation of choice set generation algorithms for route choice models,” *Annals of Operations Research*, vol. 144, no. 1, pp. 235–247, 2006.