Next Road Rerouting: A Multiagent System for Mitigating Unexpected Urban Traffic Congestion

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Abstract—During peak hours in urban areas, unpredictable traffic congestion caused by en route events (e.g., vehicle crashes) increases drivers' travel time and, more seriously, decreases their travel time reliability. In this paper, an original and highly practical vehicle rerouting system, which is called Next Road Rerouting (NRR), is proposed to aid drivers in making the most appropriate next road choice to avoid unexpected congestions. In particular, this heuristic rerouting decision is made upon a cost function that takes into account the driver's destination and local traffic conditions. In addition, the newly designed multiagent system architecture of NRR allows the positive rerouting impacts on local traffic to be disseminated to a larger area through the natural traffic flow propagation within connected local areas. The simulation results based on both synthetic and realistic urban scenarios demonstrate that, compared with the existing solutions, NRR can achieve a lower average travel time while guaranteeing a higher travel time reliability in the face of unexpected congestion. The impacts of NRR on the travel time of both rerouted and nonrerouted vehicles are also assessed, and the corresponding results reveal its higher practicability.

Index Terms—Road traffic congestion, unexpected en route events, multiagent system, vehicle rerouting.

I. INTRODUCTION

DUE to recent rapid urbanization, many large cities in the world are experiencing an unprecedented increase in road traffic congestion. According to a recent urban transportation report [1], in the U.S., the incurred economic loss in terms of both travel time delay and fuel consumption was estimated as $121 billion in 2011 and is expected to reach $199 billion in 2020. In addition to monetary costs, en-route events such as special events, unplanned road works, vehicle crashes etc. have a significant impact on drivers requiring them to triple their planned peak hour travel time in order to reach their destination on time, as stated in [1]. Naturally, this unpredictability is of significant inconvenience and concern to drivers.

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Unfortunately, the two most commonly used congestion handling solutions: *traffic light control systems* and *vehicle navigation systems*, are not able to efficiently handle en-route events. In particular, adaptive traffic light control systems based on locally collected real-time traffic information such as the Sydney Coordinated Adaptive Traffic System (SCATS) [2] and the Split Cycle Offset Optimization Technique (SCOOT) [3], can improve the throughput of urban traffic at each main intersection under normal conditions. However, they have neither a mechanism for detection and notification of en-route events, nor the functionality to guide the event-influenced vehicles to their most appropriate next roads. Vehicle navigation systems (VNS), such as Google Map and TomTom, frequently have access to city-wide traffic information and are designed to give every single driver the fastest route to finish a specific trip. However, VNS calculate a route once, and do not consider sudden changes of the traffic along the suggested route. Even though some solutions [6], [7] can provide a route with a guaranteed minimum travel time using massive historical traffic data and prediction models, their low execution efficiency [19] makes them impractical in large-scale urban scenarios. Additionally, the update of traffic information used in VNS has low frequency (2 mins or more) and limited coverage (only the major roads in a city). Therefore, the routing decisions of VNS can potentially create secondary congestion, especially when most of vehicles in congested roads share similar destinations.

In addition to the practical implemented systems, some theoretical models have been developed to find the optimal route for a vehicle in real time when an en-route event occurs [8], [30], [31], [35]. However, there is still a long way to apply these solutions in practice, e.g., lacking analysis on the practicability of the constructed models, there are few deployment recommendations.

To reduce the average travel time, and more importantly, enhance travel time reliability, in the presence of en-route events this paper proposes a novel vehicle re-routing system called Next Road Rerouting (NRR), which fills the gap between the aforementioned widely used practical solutions and state-of-the-art theoretical approaches. As an extension of our previous work [21], the contributions and substantial improvements of this paper are outlined as follows:

- **Realistic implementation**

  Reduced computation cost. Relative to solutions which immediately calculate complete route at once, as in, NRR can significantly reduce the computation cost, thanks to two-step rerouting. NRR works by: (1) calculating the optimal next roads for the set of concerned vehicles to bypass the blocked road, and (2) using a VNS to update

the new route to complete the rest of the journey. As the optimal next-road computation is much faster than recalculating the entire route, this two-step re-routing approach fits perfectly in this time-critical scenario in which the vehicle needs to be rerouted before reaching the location of the en-route event.

Reasonable deployment cost. We propose that NRR could be deployed in as a software plug-in regional computers of SCATS, a system already in use in 27 countries and over 37,000 intersections. Additionally, Vehicle-to-Infrastructure (V2I) communication module needs to be added in NRR. This update solution is feasible and practical due to high similarity between the protocol of V2I (IEEE 802.11p) and existing Wi-Fi [26].

Efficient MAS architecture. In our novel Multi-agent System (MAS) design, for each intersection, traffic lights and outgoing roads represent an intelligent agent. Compared to other vehicle based MAS solutions [9]–[12] which heavily rely on Vehicle-to-Vehicle (V2V) communication, and region-based MAS solutions [13] which need an impractical time to converge iteratively, our MAS architecture is not only much easier to deploy on the existing infrastructure, but can also coordinate agents by making use of the natural traffic propagation without incurring excessive computation and storage cost.

- **Validated effectiveness**

    The ability to realistically implement this system is not achieved via huge sacrifices in the performance. In our simulation experiments, results show that in grid map NRR can reduce average trip time by 19.25% and increase travel time reliability by 43.98%. When compared with the competing solutions, in city center of Cologne, the advantages NRR brings in terms of average trip time and travel time reliability can be up to 38.02% and 65.42%, respectively.

- **Improvements over the previous work**

    Practical objective. Rather than achieving higher system stability (i.e., the degree of traffic load balance), this work is focused on increasing travel time reliability which is more meaningful for the drivers in the face of unplanned events.

    Improved applicability. Comprehensive suggestions on the upgrade and deployment of NRR are given in this work, including its computation, storage and communication modules. In particular, due to the fact that the average speed of vehicles on one road is not measurable by a single induction loop [29] in SCATS, Greenshield's model [25] is used in our enhanced routing cost function for estimating the speed.

    Enriched evaluation. We demonstrate NRR's effectiveness relative to two commonly used solutions in terms of travel time and travel time reliability. Moreover, we show that NRR can be beneficial to both rerouted (almost all) and non-rerouted (more than 50%) vehicles. A discussion of the influence of penetration rate on the rerouting solutions is provided.

In the remainder of this paper, the basic concepts used in NRR along with its main motivation are presented in next Section. Then, Section III illustrates the architecture and detailed operations of NRR. The evaluation methodology and the analysis of simulation results are presented in Section IV. Finally, we draw the conclusion and discuss the future work in Section V.

II. BASIC CONCEPTS AND MOTIVATION

This section firstly clarifies some basic concepts that are used throughout this paper, then introduces our original and highly-applicable idea of next road rerouting and explains why it is suitable for alleviating unexpected urban traffic congestions.

A. Fundamental Concepts

This sub-section explains the key concepts used for the description of NRR system and its performance evaluation.

Road Segment & Road: In this paper, a *road segment* connects two neighboring intersections. In each road segment, a *road* represents a unidirectional part of it. Roads may be further subdivided into one or more lanes of traffic.

Trip & Route: Each vehicle has an associated trip to finish, bringing the vehicle from a source to destination road along a certain route. The *trip* of a vehicle is determined by origin and destination (O/D) locations and starts in a specific time interval. The *route* of this vehicle is a set of consecutive roads that it will follow from origin to destination.

Travel Time: Also called trip time in this paper, is the amount of time a specific vehicle needs to finish its trip. It is calculated as the sum of the travel time this vehicle spends on each individual road along its route.

Free-Flow Travel Time: Free-flow travel time for a specific road is the amount of time a vehicle needs to traverse it at the maximum-allowed speed on this road.

Average Travel Time (ATT): Average travel time is a mean value of the travel time of all vehicles' trips. It indicates the overall status of traffic for the whole observed road network.

Travel Time Index (TTI): Also called congestion index, is a commonly used metric for measuring urban traffic congestion level [1]. It is calculated as the ratio of the sum of the travel time to the sum of the free-flow travel time for all vehicles. This metric is more meaningful than the average travel time because it gives a measure of the proportional increase over the ideal.

Travel Time Reliability: This concept refers to the unpredictability of travel time. For drivers it can give some measure of likely worst case delay [24]. The focus of this paper is on the travel time reliability for the whole set of trips instead of a single trip only.

Planning Time Index (PTI): In practice, travel time reliability is measured by the planning time index [23]. In order to keep consistency with TTI, for all trips as a whole, PTI is calculated as the ratio of the 95th percentile travel time (i.e., which is shorter than 5% of all trips) to the average free-flow travel time.

System Instability (SI): System instability is a metric that we introduce to describe the variation of traffic load distribution over the whole simulation duration and road network. Given the set of discrete time intervals of a simulation duration $T = \{t_1, t_2, \ldots, t_n\}$ and the set of all roads in the simulated road network $E = \{e_1, e_2, \ldots, e_n\}$

$$SI = \sigma\left(\sigma(e.OC_t, e \in E), t \in T\right) \qquad (1)$$

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where σ means the computation of standard deviation, $e.OC_t$ means the occupancy of road e at the time interval t. When the value of SI is low, the *system* is described as *stable* which represents that the traffic load is more or less evenly distributed on all roads. Note that both non-congested and fully congested road networks will result in low SI. In these cases, further rerouting is not necessary or helpful, as the existing road capacity is already well used. A high value for SI indicates that further rerouting may be of benefit, as the traffic is unevenly distributed.

B. Motivation

Generally, traffic rerouting decisions may be classified as altruistic, where vehicle routing decisions are made to benefit the overall system, or selfish, where individual vehicles make decisions to try to optimize their own performance. While in theory global rerouting would offer the best system wide benefits, the lack of practical implementations and fairness issues make it unlikely to be adopted by users. Selfish solutions are already in use in the form of VNS, but these solutions suffer in terms of performance as penetration rates rise. Our solution heuristically tries to balance the benefits of selfish and altruistic solutions while mitigating the drawbacks of these solutions. That is, it is implementable, has benefits for individual users, but also seeks to balance traffic to obtain global benefits.

Altruistic routing works under the assumption that urban traffic congestion is a result of unevenly assigned traffic with respect to the capacity of existing road infrastructure [32] and hence seeks to balance the traffic load throughout the road network. Working cooperatively [34] by exchanging route choices (i.e., altruistic routing) among vehicles can lead to system optimum, in which the minimum ATT is obtained, as stated in Wardrop's second principle [23]. Although the fairness issue of system optimum solutions is addressed in [33], there are two limitations which hinder their application in the real world. Firstly, the route choice information is not always available for exchange due to privacy issues and drivers unawareness of their full routes. Secondly, the dynamic traffic assignment for system optimum is practically intractable due to its huge complexity [20] which cannot provide real-time response to en-route events.

By contrast to altruistic routing, selfish routing is relatively easily implemented via the use of VNS. However, according to Wardrop's first principle [22], if every vehicle chooses the fastest route for itself, then a user equilibrium will eventually be reached wherein no one can unilaterally choose a faster route. This represents a local rather than global optimum, even if the user equilibrium can now be achieved in both travel time and travel time reliability [36]. Additionally, in the context of en-route events, the VNS response time might not be sufficiently responsive to allow the vehicle to avoid the impacted area.

To address the aforementioned issues with selfish and altruistic rerouting, NRR proposes a heuristically inspired two step rerouting process.

At an NRR enabled junction NRR seeks as a first step to divert vehicles around en-route events. Depending on the area of junctions enabled near the event, this will have the effect of routing the vehicle over a small number of road segments around the event. These immediate rerouting decisions are
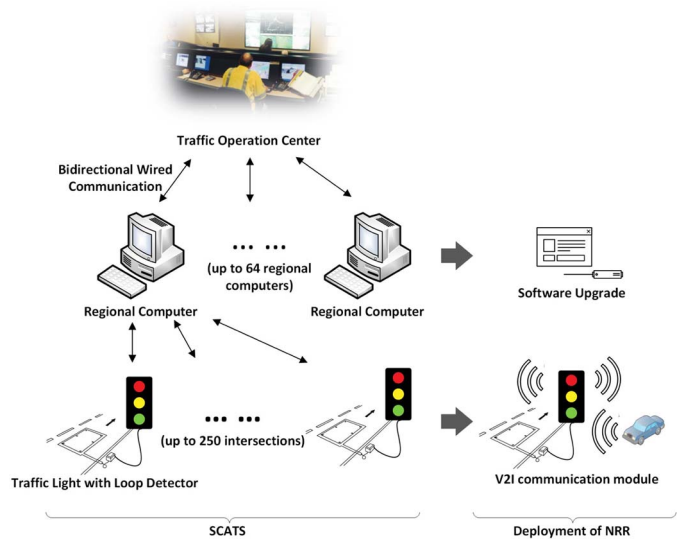

Fig. 1. Architecture and deployment of NRR based on the existing SCATS.

based on both global and vehicle-centric considerations, taking into account both the balancing of traffic exiting the junction (altruistic rerouting) and the impact of the diversion on the individual vehicle's optimal route (selfish rerouting). These decisions are based on quickly calculable factors, and can be made in time to avoid the en-route event.

As a second step, while being diverted to an area beyond the influence of the en-route event, a VNS is used to propose a route from the end of the diversion to the destination. The static optimal route suggested by VNS is usually very close to the exact fastest route computed by dynamic A∗ [6] with considerable computational and storage cost [19], but still easily achieved within the time frame of traversing one or more road segment.

III. System Description

This section presents the deployment and architecture of NRR, as well as the employed rerouting process based on the existing widely used adaptive traffic control system—SCATS. Specifically, the routing cost function used in NRR is described in terms of road occupancy, travel time estimation, geographic distance to destination and geographic closeness of congestion.

A. Deployment and Architecture of NRR

NRR may be deployed as an add-on to the typical 3-tier architecture of SCATS which is depicted on the left side of Fig. 1. In the top of this architecture is the SCATS Central Manager located at the Traffic Operation Center (TOC). It can manage up to 64 regional computers residing in the middle tier. At the bottom tier, up to 250 intersections, where traffic lights and in-ground loop detectors are deployed, can be controlled by each regional computer. The regional computer is responsible for adjusting the scheduling and synchronization of various traffic lights' phase it controls, based on the real-time traffic information gathered from loop detectors it connects.

As shown on the right of Fig. 1, firstly, NRR needs only one hardware upgrade to the existing SCATS architecture (i.e., V2I communication module) at the bottom tier to enable the exchange of the information required for the rerouting process
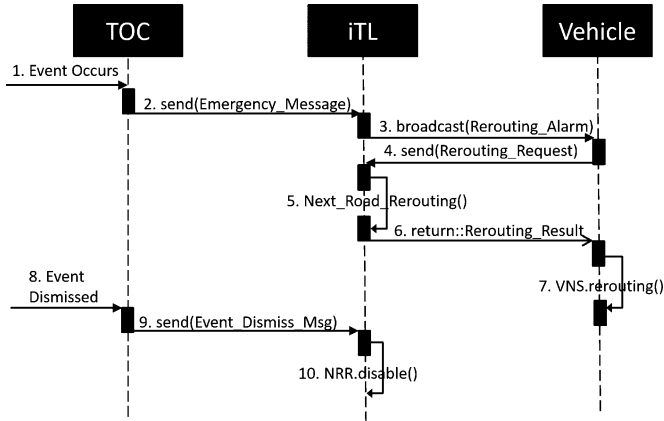
Fig. 2. Sequence diagram of a typical re-routing process using NRR.

between traffic light and vehicle. As opposed to V2V communication, V2I is much less likely suffer from non-line-of-sight (NLOS) communication problem, meaning that almost full communication coverage can be achieved around each intersection by avoiding signal blockage due to buildings and other obstacles. Moreover, in unexpected congestion scenarios, V2I can ensure high rate of timely and successful transmissions in the range of all the roads that each traffic light controls. Secondly, instead of deploying high-cost hardware such as a powerful road side unit, an additional feature of NRR is the low-cost software upgrade for all regional computers in order to enable the re-routing calculation and its corresponding local data management.

In practice, at each intersection the traffic lights, loop detectors combined with the regional computer controlling them are all connected with cable. This bidirectional wired communication has prompt transmission rate and fairly low loss rate. As a result, in the rest of this paper, we consider regional computers, traffic lights and loop detectors together as one entity called *intelligent Traffic Light (iTL)*.

B. Overview of Rerouting Using NRR

The proposed vehicle rerouting process using NRR is presented in this sub-section along with the corresponding UML sequence diagram. As shown in Fig. 2, when an en-route event occurs, (1) the Traffic Operation Center (TOC) verifies it and (2) notifies the iTL located at the upstream of the road where the event occurred to activate NRR by sending *emergency message*. (3) This iTL broadcasts the *rerouting alarm* to all the vehicles in the incoming roads that it controls. (4) Those vehicles which, first, confirm that the blocked road is included in their ongoing route, then send *re-routing request* which contains their destination locations, rather than the full route information which are usually unaccessible, to respond to the iTL. (5) For each rerouting request, the iTL uses the latest local traffic information gathered from induction loops, along with the local map (all outgoing roads that it controls) to compute the routing cost for each of its possible next road choices. (6) Subsequently, it suggests the one with the least cost value by sending back *rerouting result*. (7) The vehicle then enters the NRR suggested optimal next road and recomputes the route for the rest of its journey with the help of its on line VNS. Finally,
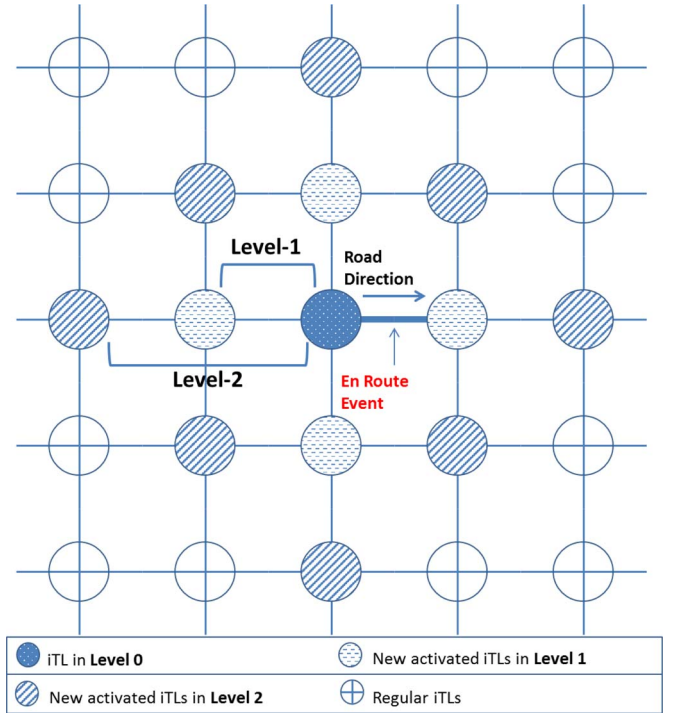

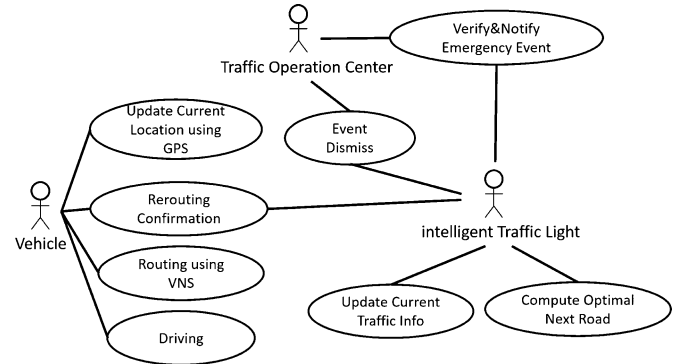Fig. 3. Activated iTLs in different NRR levels.

Fig. 4. Use case diagram of all key actors in NRR.

when the event is cleared the TOC sends *event dismiss* to the iTL to disable NRR as described in steps 8, 9, and 10 shown in Fig. 2.

In general, adapting the route of vehicles which are only one junction away from the blocked road is not enough to avoid congestion. In addition to the general seven steps mentioned above, our scalable NRR can also work in different *operating levels* involving more iTLs to alleviate the congestion in a wider area around the blocked road segment. As shown in Fig. 3, we define $Level_0$ NRR as the NRR system with the closest iTL enabled only. Without loss of generality, $Level_{i+1}$ NRR means we enable all of $Level_i$ NRR's neighboring iTLs additionally with the iTLs that already enabled in $Level_i$. By enabling $Level_i$, we have access to additional road segments for the rerouting process, allowing traffic to be more evenly spread around the en-route event. To enhance the description of NRR rerouting process, all use cases of the key actors are visualized in Fig. 4 and the messages exchanged among them are presented in Table I.

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TABLE I
SUMMARY OF ALL MESSAGES USED IN NRR

Message name	Message content	Transmission mode	Transmission direction
Emergency Event	Blocked Road ID, Level of NRR	Wired	TOC $\longrightarrow$ iTL
Rerouting Alarm	Blocked Road ID, iTL ID	Wireless Broadcasting/IEEE 802.11p	iTL $\longrightarrow$ Vehicles
Rerouting Request	Destination Location, Current Location, Vehicle ID	Wireless Unicasting/IEEE 802.11p	Vehicle $\longrightarrow$ iTL
Rerouting Result	Suggested Road ID, Vehicle ID	Wireless Unicasting/IEEE 802.11p	iTL $\longrightarrow$ Vehicle
Event Dismiss	Released Road ID, Level of NRR	Wired	TOC $\longrightarrow$ iTL

TABLE II
KEY ABBREVIATIONS

ve	Vehicle which sends rerouting request to iTL
$ve.curLoc$	The current location of ve
$ve.destLoc$	The destination location of ve
$ve.nrs$	The set of all available next roads for ve
$ve.nr$	The NRR suggested next road for ve
e	A certain road in $ve.nrs$
e_{blk}	The blocked road
OC	Road occupancy
TT	Estimated travel time
GD	Geographic distance to destination
GC	Geographic closeness of congestion
x	A certain factor in $\{OC, TT, GD, GC\}$
$e.x$	A certain factor of e. E.g. $e.OC$ represents the road occupancy of e
CV_x	The coefficient of variation for x of $ve.nrs$
CV_{sum}	The summation of all CV_x
w_x	The weight value of x. E.g. w_{OC}, i.e., the weight value of road occupancy
$\boldsymbol{w}$	The weight value of all factors. $\boldsymbol{w} = (w_{OC}, w_{TT}, w_{GD}, w_{GC})^T$
$\boldsymbol{c_e}$	The cost of all factors for e. $\boldsymbol{c_e} = (e.OC, e.TT, e.GD, e.GC)$

TABLE III
SIMULATION SCENARIOS STATISTICS

	Cologne Center	8×7
#Junctions	389	86
#Roads	737	254
#Roads / #Junctions	1.89	2.95
Average Road Length (m)	93.20	115.80
Covered Area (km^2)	3.69	1.22
Total Lane Length (km)	95.15	58.83
Traffic (#vehicles)	7665	2942
Traffic Density (#vehicles/km/lane/hour)	96.86	100

C. Routing Cost Function in NRR

In step 5 of NRR rerouting process, the iTL will suggest the next road with the least cost for each rerouting request. Particularly, after receiving a rerouting request from a specific vehicle ve, iTL retrieves the current location of this vehicle ($ve.curLoc$) as well as its intended destination location ($ve.destLoc$) (see Table II for key abbreviations).

Firstly, iTL uses ve.curLoc and its map data to retrieve all available next roads ve.nrs $= \{e_1, e_2, \ldots, e_{N_e}\}$ (N_e: the total number of available next roads). If $N_e > 1$, then iTL should select **the most suitable next road** (ve.nr) for ve to follow.

Then, iTL measures the routing cost of each road e in ve.nrs considering the weighted linear combination of the following four factors: a measure of occupancy the new road, estimated travel time for the new road, distance to destination using the new road, and geographic closeness to the congestion using the new road. These are:

Road Occupancy ($e.OC$): This factor is measured as the percentage of time when a loop detector is occupied by a vehicle during a fixed time interval, which is commonly known as degree of saturation in SCATS [2]. It is a significant indicator showing the real time traffic load of a certain road, thus it can be used for balancing the local traffic. In this study, $e.OC$ can be directly retrieved by the loop detector.

Travel Time ($e.TT$): This factor is the estimated mean travel time over the road e. It is the ratio of the road length ($e.len$) to the mean travel speed on this road ($e.u$). Greenshield's

Model [25] is used to estimate $e.u$ because the induction loop in SCATS can only provide $e.OC$. Let us denote by $e.k$ the current traffic density (i.e., number of vehicles per km) of e and by $e.k_j$ the traffic density when traffic jam occurs on e, then basically, $(e.k/e.k_j) = $ (current number of vehicles on e/maximum number of vehicles on e) [28]. In this particular problem, we only need to suggest e with the minimum cost, rather than getting its accurate cost value, as $e.OC$ is proportional to the number of vehicles on e, thus $\frac{e.k}{e.k_j} \approx e.OC$, then:

$$e.TT = \frac{e.len}{e.u} = \frac{e.len}{e.u_f \left(1 - \frac{e.k}{e.k_j}\right)} \approx \frac{e.len}{e.u_f(1 - e.OC)} \quad (2)$$

where $e.u_f$ is the free flow speed or maximum permitted speed of e. It is worth noting that $e.u_f$ and $e.len$ are static values that can be retrieved from the digital map data stored in iTL.

Geographic Distance to Destination ($e.GD$): This factor shows how close a road e can lead ve to ve.destLoc. Considering the facts that the size of map that NRR needs to mitigate an unexpected congestion is not large (i.e., less than 1000 nodes, refer to Table III) and its topology is almost static (i.e., rarely changes), NRR precomputes the shortest distance in km for all possible origin and destination pairs using one-to-all Dijkstra's Algorithm, and loads this data to the server's memory. Thus, $e.GD$ can be accurately retrieved in much faster way (i.e., memory access time only without any on-line computation) than applying on-line estimation using Euclidean distance.

Geographic Closeness of Congestion ($e.GC$): This factor shows how far e can deviate ve from the blocked road e_{blk}. In general, when a road is blocked, the congestion level of other roads around it is increased, and the closer a road is to the blocked road, the higher its congestion level will be. This factor is expressed by the similarity of the vector $\boldsymbol{v_e} = (e.\text{sLoc}, e.\text{eLoc})$ from the start junction location to the end junction location of e, and the vector $\boldsymbol{v_{e_{blk}}} = (e_{blk}.\text{sLoc}, e_{blk}.\text{eLoc})$

from the start junction location to the end junction location of e_{blk}, as shown in Eq. (3). Notice that v_e can be obtained when iTL receives the rerouting request while $v_{e_{blk}}$ can be retrieved when iTL verifies the reported event in the rerouting step 2. The law of cosine is used for calculating the similarity of the two vectors, more details can be found in our previous paper [21].

$$e.GC = \text{similarity}\left(\boldsymbol{v_e}, \boldsymbol{v_{e_{blk}}}\right). \qquad (3)$$

So far, NRR can construct the cost vector $\boldsymbol{c_e} = (e.OC, e.TT, e.GD, e.GC)$ for each possible next road e. It is worth to mention that lower values of the above four factors lead to a better rerouting for ve. Given a specific weight assignment vector for the aforementioned four factors $\boldsymbol{w} = (w_{OC}, w_{TT}, w_{GD}, w_{GC})^T$, the NRR suggested next road for ve is the one with the least value of cost function $\hat{\boldsymbol{c}}_{\boldsymbol{e}} \cdot \boldsymbol{w}$ as shown in Eq. (4)

$$ve.nr = \arg\min_{e} \hat{\boldsymbol{c}}_{\boldsymbol{e}} \cdot \boldsymbol{w} \qquad (4)$$

where $\hat{\boldsymbol{c}}_{\boldsymbol{e}}$ is the normalized $\boldsymbol{c_e}$ with each of its element $e.x$ scaled in the range [0,1] using Eq. (5)

$$e.\hat{x} = \frac{e.x - \min\left(\{e.x, e \in ve.nrs\}\right)}{\max\left(\{e.x, e \in ve.nrs\}\right) - \min\left(\{e.x, e \in ve.nrs\}\right)}. \qquad (5)$$

Through identifying the importance of each of these four factors, we will be able to assign the most suitable weight value to each of them to compute the final routing decision. In NRR, the values of the factors used in the next road cost function vary depending on the different time stamp (i.e., $e.OC, e.TT$) and different current/destination location of the vehicle to be rerouted (i.e., $e.GD, e.GC$). Therefore, a suitable weight value allocation $\boldsymbol{w}$ should be variable for different rerouting requests [14]. In the next road selection, for a particular factor of e, the greater the variation of its value is, the more importance should be given to this factor in the computation of the rerouting decision. Since all factors represent different measurements, we use the coefficient of variation (CV) instead of standard deviation to compute the variability for each factor. Specifically, iTL calculates CV for each factor $x \in \{OC, TT, GD, GC\}$ over all available next roads in Eq. (6), then, it gets summation of all factors in Eq. (7). Finally, the weight value of x is its corresponding proportion to CV_{sum}, shown in Eq. (8).

$$CV_x = CV\left(e_1.x, e_2.x, \ldots, e_{N_e}.x\right) \qquad (6)$$

$$CV_{\text{sum}} = \sum CV_x \qquad (7)$$

$$w_x = \frac{CV_x}{CV_{\text{sum}}}. \qquad (8)$$

D. MAS in NRR: From Local to Global

In addition to improving the trip performance of individual vehicles in the presence of en route events, the MAS design makes it possible for NRR to improve the global road traffic. In our MAS architecture of NRR, we define an *agent* as a iTL and all outgoing roads that it controls. As depicted in Fig. 5,
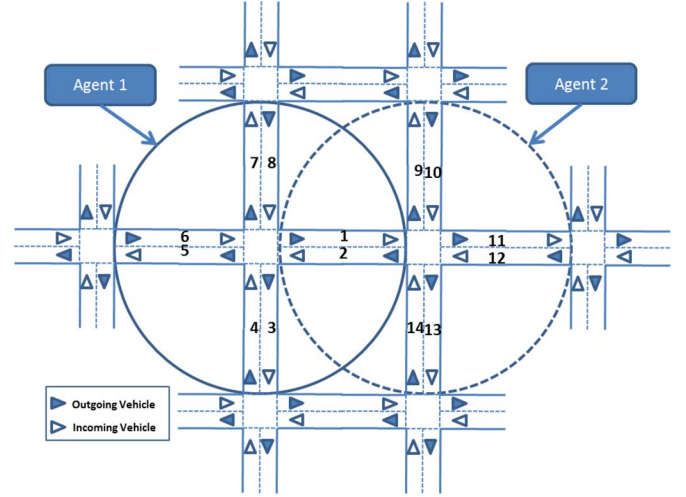

Fig. 5. MAS design in NRR.

the outgoing roads of agent 1 are the lanes 1, 3, 5, and 7 which are the available options of a vehicle to be rerouted (i.e., agent's *actions*). This decision should be taken by collecting the current traffic information of these outgoing roads with the vehicles' re-routing requests (i.e., agent's *status*: sum of $\hat{\boldsymbol{c}}_{\boldsymbol{e}} \cdot \boldsymbol{w}$) that are received by the iTL from the incoming roads (e.g., roads 2, 4, 6, and 8 in the case of agent 1). The purpose of balancing the traffic load is to maximize the utility of the existing road infrastructure. In general, balancing the local traffic load only does not guarantee that the global traffic load will be balanced as well. NRR starts to balance the local traffic load from the area where the stability of traffic load decreases most (i.e., where an en-route event occurred), then takes the advantage of the agents connectivity in urban road networks to propagate this mitigation effect. For instance, in Fig. 5, when the road 3 is blocked the traffic load of all other three outgoing roads will be suddenly increased due to 1/4 loss of output under the same traffic input. NRR starts to guide the vehicles requesting re-routing to different road directions to stabilize the local traffic distribution. The key point here is that each outgoing road in this agent is also an incoming road for another agent. In this case, lane 1 is an outgoing road in agent 1 but also incoming road in agent 2, thus the en-route event will soon affect the status of agent 1 and the other agents follow because the heavy traffic in lane 1 will quickly increase the traffic on lanes 9, 11 and 13 as well. If NRR is enabled for a suitable amount of surrounding agents, the traffic load will be more widely balanced, leading to the reduction of average travel time of all vehicles running in this area.

IV. PERFORMANCE EVALUATION

A. Simulation Environment & Settings

1) Simulation Platform: The version (0.24.0) of Simulation of Urban Mobility (SUMO) [15] combined with the Traffic Control Interface (TraCI) [17] is the simulation platform used to carry out the performance evaluation of NRR.

2) Testing Map and Traffic: The evaluation of NRR is carried out in both realistic and synthetic scenarios.

A sub-set of TAPASCologne 0.17.0 [16] is chosen as a realistic evaluation scenario for NRR. TAPASCologne is an open source project providing a large-scale dataset with the highest realism for urban vehicular simulation based on SUMO. It uses a realistic map of Cologne extracted from OpenStreetMap [18] and generates traffic demand from 6:00 am to 8:00 am using Travel and Activity PAtterns Simulation (TAPAS) methodology [27] and Gawron's traffic assignment algorithm [20]. A subset only of this map is used in our evaluation because the original size of TAPASCologne is too large (1129.71 km^2) to investigate the impact of a single closed road. The chosen sub map is a 3.69 km^2 large area located on the west of the river in the Cologne city center. The first 30 min of original traffic of this sub-map, ranging from 6:00 am to 6:30 am is used for NRR evaluation.

Even though a realistic map can provide trustworthy evaluation results, the great diversity of urban road network topologies may lead to a significant difference in the corresponding NRR evaluation results. In order to mitigate this impact, in our evaluation, we generated grid maps. Due to the limited rerouting choices of small grid maps and the large observation area for studying the impact of closing one road in a big grid map, the 8 × 7 map (i.e., 8 intersections in the horizontal axis and 7 intersections in the vertical axis) is chosen as a representative grid map for the following evaluations. Apart from the number of junctions, they share all the rest of settings, e.g., all road segments in this grid map set have equal length of about 120 meters. Each road segment comprises of two roads each of which has two lanes (i.e., mimic main urban roads) in the same direction.

For the 8 × 7 grid map testbed, 30 minutes traffic demand is generated evenly according to the road length and the number of lanes for each road. Three key parameters in this random generation process are chosen to ensure that the synthetic scenario can still simulate the city center scenario in peak hours traffic. First, the repetition rate is the amount of time in seconds between vehicles insertion over the whole network. Its value varies across all grid map scales to maintain the consistency of the traffic density with that of the city center of Cologne, which is about 100 vehicles per km per lane per hour (see Table III). Second, the minimum trip distance is set to twice the average road length because a meaningful route in this study should have at least two consecutive roads. Last but not least, the fringe factor is set to 10, which means edges that have no successor or predecessor will be 10 times more likely to be chosen as start or endpoint of a trip. This allows us to model through-traffic which starts and ends outside of the simulated area. The setting of traffic lights is also set to static, meaning that every traffic light has a fixed phase duration regardless of the changes in traffic conditions.

It is worth emphasizing that to make these synthesis maps capable of simulating a realistic urban road network, the three configuration parameters (i.e., the ratio between number of roads to junctions (#R/#J), the average road length, as well as the traffic density outlined in Table III) should be in line with their corresponding values in the city center of Cologne.

For both scenarios, grid map and city center of Cologne, the whole simulation keeps running until all the vehicles finish
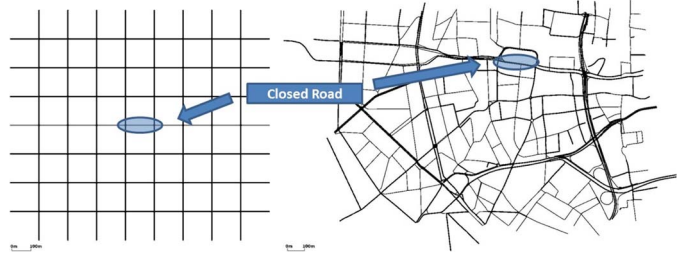

Fig. 6. Location of the closed road in grid map (left, 8 × 7) and realistic map (right, city center of Cologne).

their trips. Therefore, the full simulation time is longer than the predefined 30 mins trip generation time.

B. Evaluation Results and Analysis

In the following we first explore the impact of purely altruistic and selfish routing strategies on traffic performance in the presence of en-route events. The benefits and disadvantages of these strategies are illustrated through simulations using a grid map. It should be noted, however, that implementations of altruistic strategies do not exist in practice. Thus when evaluating the performance of our NRR routing policy we compare it to two commonly used selfish rerouting strategies. These comparisons are made both for a grid map and a subset of the city centre of Cologne.

1) Impact of Selfish and Altruistic Rerouting on Traffic Conditions: We have evaluated 4 scenarios, as described below, and compared their results against each other:

Original (**ORG**): The original scenario with the initial 30 minutes traffic demand, as described previously in Section IV-A2, without any closed road or any particular dynamic routing strategies applied. The routes for all vehicles are generated before the simulation using Gawron's traffic assignment algorithm [20].

En Route Event (**ERE**): The ORG scenario with two roads of one road segment in the center of the map (as shown in Fig. 6) closed for 20 minutes (from the 5th min to the 25th min).

Constant Rerouting (**ConRe**): This scenario represents selfish rerouting. Here, upon encountering an en-route event, vehicles update their fastest route according to up to date traffic information.

Load Balance Rerouting (**LoaRe**): We choose this scenario to represent altruistic rerouting which focuses on balancing local traffic without considering the destinations of individual vehicles. In this scenario, when encountering an en-route event, vehicles update their next road choice according to current local traffic, choosing the road with the lowest occupancy level.

Table IV summarizes the performance metrics (Average Travel Time, Travel Time Index, 95th Percentile Travel Time, Planning Time Index, and System Instability) for each of the four above scenarios. We observe that in ERE scenario, compared to ORG, 2 closed roads only, representing 0.79% of

TABLE IV
PERFORMANCE COMPARISON OF CONRE AND LOARE AGAINST ORG AND ERE IN 8 × 7 GRID MAP

	Average Travel Time (sec)	Travel Time Index (TTI)	95th Percentile Travel Time (sec)	Planning Time Index (PTI)	System Instability
ORG	207.55	2.79	375.95	5.05	0.56
ERE	267.61	3.40	719.75	9.14	1.25
ConRe	246.42	2.96	446.95	5.37	0.61
LoaRe	212.99	2.82	573.0	7.59	0.45

the total number of roads in the map, can bring a significant negative impact even on those vehicles running through the other 252 open roads. This table reveals as well that the Average Travel Time (ATT) has increased by 28.94%, in addition to an 80.99% rise in Planning Time Index (PTI), which means that the trip time becomes extremely unreliable. Moreover, the considerable growth of system instability up to 123.21% is also in line with the degradation of travel time reliability.

Compared to ERE scenario, both ConRe and LoaRe can mitigate the unexpected traffic congestion in terms of the achieved ATT and trip time reliability. However, the 7.92% reduction of ATT that ConRe brings is much less than 20.41% that LoaRe does. This is due to the exceptionally good system stability achieved by the latter, which is even 19.64% better than the original scenario, whereas the former is 8.93% worse than the ORG case in terms of the achieved stability.

On the other hand, as a consequence of omitting the vehicle's destination location, when LoaRe is applied, there are a few vehicles which have much longer travel time than the average. Correspondingly, the trip duration distribution shown in Fig. 8 reveals that LoaRe has a significantly longer right tail than ConRe. Thus LoaRe shows a much lower trip time reliability performance improvement (i.e., 16.96% only, as compared to ConRe's 41.25% of improvement) and causes serious fairness issues for a certain number of vehicles.

In these tests, the routing algorithm is only invoked upon encountering an en-route event. Thus, only a small number of cars use the algorithm. In the final test, we explore the consequence of increased use of the ConRe algorithm. In particular, we modify the ORG scenario so that a certain percentage of cars recalculate their route once every second. Fig. 7 indicates the impact of penetration rate (percentage of cars employing the strategy) on Average Trip Time and Planning Time. Clearly increasing the number of vehicles using selfish rerouting has a very negative impact on performance. This is consistent with the results in [28] and in line with Braess's paradox [32].

In summary, even a small portion of roads closed in the center of a road network, can cause a substantial degradation of traffic conditions. However, neither selfish rerouting nor altruistic rerouting is suitable for improving both average trip time and trip time reliability when such events occur, especially under higher penetration rates. In the following we will demonstrate the benefits of our proposed NRR policy vs. commonly available selfish solutions.

2) Investigating NRR's Scalability: As discussed in Section III, NRR has multi-level options, i.e., the higher the level the traffic manager chooses, the more junctions with NRR-enabled iTLs around the closed road will be activated to run NRR. To find the best scalability level of NRR, we have
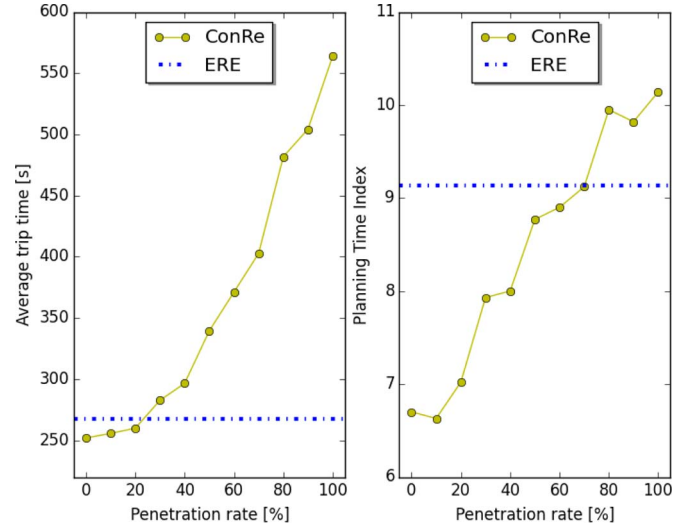

Fig. 7. Impact of the penetration rate on the performance of ConRe.

TABLE V
PERFORMANCE OF NRR UNDER DIFFERENT SCALABILITY
LEVELS IN 8 × 7 GRID MAP

NRR level	L_0	L_1	L_2	L_3	L_4
# enabled iTL	2	**8**	18	32	44
ATT	218.60	**216.09**	216.26	213.53	212.88
Percentage of ATT reduction to L0 (%)	0	**1.15**	1.07	2.32	2.62
95th Percentile Travel Time (PTT)	403.0	**396.0**	397.0	387.95	380.0
Percentage of 95th PTT reduction to L0 (%)	0	**1.74**	1.49	3.73	5.71

evaluated its performance using 8 × 7 grid maps from $Level_0$ to $Level_4$. Compared to $Level_0$ NRR, the reduction of ATT and 95th percentile trip time (expressed in percentage) achieved by NRR in all other higher levels are shown in Table V.

One important conclusion that can be drawn from this table is that the upgrade from $Level_0$ to $Level_1$ brings enough performance enhancement while upgrades to $Level_2$, $Level_3$ and even $Level_4$ bring only minor additional improvements. In order to minimize operational costs (i.e., the number of NRR enabled iTLs), we suggest implementation of $Level_1$ NRR only.

3) NRR vs. The Existing Solutions: To show the performance gain when applying NRR, the two most commonly used solutions in practice, namely Fastest Rerouting and Shortest Rerouting, are implemented in this evaluation.

Fastest rerouting (FasRe): During the road closure time period in ERE scenario, all vehicles that have the closed road

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TABLE VI
COMPARISON OF VARYING WEIGHT ALLOCATIONS STRATEGIES' IMPACT
ON NRR (COLOGNE CENTER/8×7)

	w	TTI	PTI	SI
NRR_ada	adaptive	1.42 / 2.79	2.85 / 5.12	0.81 / 0.63
NRR_even	$(\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4})^T$	1.44 / 2.82	2.85 / 5.22	1.04 / 0.67
NRR_oc	$(1, 0, 0, 0)^T$	1.43 / 2.82	2.85 / 5.25	0.90 / 0.67
NRR_tt	$(0, 1, 0, 0)^T$	2.04 / 2.83	6.53 / 5.26	2.70 / 0.67
NRR_gd	$(0, 0, 1, 0)^T$	1.67 / 2.79	3.89 / 5.15	2.06 / 0.67
NRR_gc	$(0, 0, 0, 1)^T$	1.44 / 2.86	2.91 / 5.31	0.88 / 0.73

included in their ongoing routes, reroute once according to global traffic information. This scenario aims to mimic the *fastest* route that existing VNS can provide. When a driver is notified about an event ahead, this common solution uses the on-vehicle navigation system again based on the latest global traffic information, excluding the closed road from the rerouting result since it will appear as a bottleneck.

Shortest rerouting (ShoRe): During the road closure time period in ERE scenario, all vehicles that have the closed road included in their ongoing routes, reroute once only based on the length of roads. This scenario mimics the *shortest* route that existing VNS can provide.

In practice, the drivers are usually notified about an en-route event only one junction away from the location where it has occurred. This notification can be either through temporary road signs, or the observations of the drivers of deteriorating road conditions. Therefore, in our simulation, FasRe and ShoRe are implemented as Level$_0$ rerouting strategies.

NRR: During the road closure time period in ERE scenario, our proposed Level$_1$ NRR is enabled for congestion avoidance.

Table VII compares the performance of the algorithms for the grid topology and city center of Cologne respectively (comparison of varying weight allocations strategies' impact on NRR is shown in (Table VI)). We discuss the performance according to the performance parameters of travel time index, 95th percentile travel time, planning time index and system instability.

Travel time: In terms of the reduction of the ATT, according to the evaluation results shown in Table VII, Level$_1$ NRR shows the best performance compared to ShoRe and FasRe. More precisely, in 8×7 grid map, NRR decreases the ATT by 19.25% compared to ERE, while this improvement is limited to 18.48% for ShoRe and 18.39% for FasRe. Although the advantage NRR brings is relatively marginal, less than 1% compared to ShoRe and FasRe, in realistic scenario (i.e., city center of Cologne) this advantage becomes a much more significant 32.06%, with ShoRe and FasRe perform even worse than ERE by 5.96% and 0.57% respectively. Similar conclusions can be drawn regarding the achieved TTI.

According to the trip distribution statistics plotted in Fig. 8, in both grid and city center of Cologne maps, NRR still has a long right tail similar to that of ERE, ShoRe and FasRe, due to the fact that there have been always a few vehicles already stuck in the closed road before any rerouting strategy is applied. Thus, their trip time will be severely affected but for most of the other

vehicles NRR successfully moves the trip time distribution to the left, saving more time for more trips compared to other rerouting strategies.

Travel time reliability: In terms of PTI reduction for both maps, Level$_1$ NRR performs the best among ShoRe and FasRe, and shows higher gain compared to that shown by ATT evaluation metric. Specifically, in 8×7 grid map, NRR performs 43.98% better than ERE, while ShoRe and FasRe outperform the latter by 43.00% and 42.67% respectively. In realistic scenario, NRR maintains this advantage by 58.76% compared to ERE, while, similar to ATT, ShoRe and FasRe even perform 6.66% and 0.87% worse than ERE.

All solutions perform worse in city center of Cologne than in the grid map. A reasonable explanation is that compared to 8×7 grid map, city center of Cologne scenario has almost 3 times more vehicles and larger areas, and there is only one road segment closed for both scenarios. Hence, as opposed to 8×7 grid map scenario, there are a lot more vehicles in city center of Cologne which are not or only slightly affected by the en-route event but still being counted in the overall simulation results.

Due to many direction-changing restrictions in realistic urban roads (i.e., one-way road, prohibited left/right turn), as well as the limited scalability of the two compared solutions (i.e., Level$_0$), ShoRe and FasRe always have much less rerouting choices than NRR, therefore, they tend to give the same rerouting direction to a higher percentage of vehicles, leading to more congested roads. This is the reason why ShoRe and FasRe performs even worse than ERE in which no rerouting strategy is applied, apart from the previously discussed limitations of selfish rerouting.

Other evaluation metrics: From the evaluation results of system instability we observe that NRR can also balance the traffic load on the roads better than FasRe and ShoRe. Additionally, the notable traffic improvement NRR brings is not a result of diverting event-affected vehicles to a much longer route which is usually not preferred by the drivers. There are only marginal differences among NRR, FasRe and ShoRe in terms of total travel length, maximally 5.04% in grid map and 1.91% in realistic map, nevertheless, the considerable variations of performance gain among them compared to ERE can go up to 32.06% in ATT gain and 58.76% in PTI gain in realistic scenario (see Fig. 9).

4) Study of the Impact of NRR on Both Rerouted and Non-Rerouted Vehicles: The previous results assess the impact of the strategies on all vehicles, whether they are directly impacted by having the en-route event as part of their original route, or only indirectly by potential increased traffic due to rerouted vehicles. We have further examined the rerouted and non-rerouted vehicles separately.

As shown in the Table VIII, there is a common advantage among FasRe, ShoRe and NRR which consists in the small portion of vehicles chosen to be rerouted in both grid and realistic scenario, which means that the three rerouting strategies would not affect the travel experience of the most drivers by repetitive rerouting requests. Although in grid map, they can all reduce the trip time considerably for rerouted vehicles, only NRR maintains this advantage in the city center of Cologne, while FasRe and ShoRe increase more trip times

TABLE VII
PERFORMANCE COMPARISON OF NRR, SHORE AND FASRE WITH ORG AND ERE SCENARIOS (COLOGNE CENTER/8 × 7)

|	Average Travel Time (sec)	Travel Time Index (TTI)	95th Percentile Travel Time (sec)	Planning Time Index (PTI)	System Instability	Total travel Length(km)
ORG	140.09 / 207.55	1.40 / 2.79	269.75 / 375.95	2.70 / 5.05	0.74 / 0.56	4483.79 / 2719.31
ERE	214.88 / 267.61	2.11 / 3.40	705.50 / 719.75	6.91 / 9.14	3.32 / 1.25	4483.79 / 2719.31
FasRe	216.10 / 218.39	2.12 / 2.83	711.75 / 403.95	6.97 / 5.24	3.34 / 0.69	4486.05 / 2741.18
ShoRe	227.69 / 218.15	2.25 / 2.83	746.75 / 400.95	7.37 / 5.21	3.43 / 0.66	4485.55 / 2735.48
NRR	145.98 / 216.09	1.42 / 2.79	292.0 / 396.0	2.85 / 5.12	0.81 / 0.63	4571.11 / 2873.25
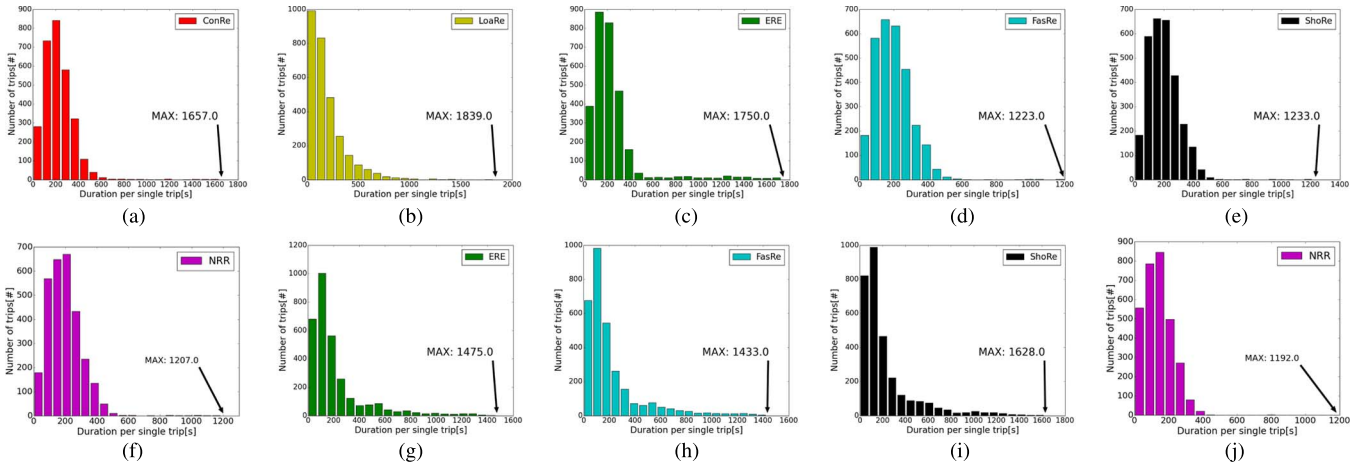
Fig. 8. Trip duration distribution of the evaluated scenarios in both 8 × 7 grid map (a)–(f) and city center of Cologne (g)–(j).

even for the rerouted vehicles. Therefore, in spite of the fact that NRR is designed for mitigating traffic congestion mainly from the global point of view, it still can provide attractive incentive for each individual driver to encourage them to accept rerouting instructions given by NRR.

If the driver do not accept the rerouting decision given by NRR, surprisingly, the results also indicate that in both maps, NRR is the only rerouting strategy that can reduce more trip time for more non-rerouted vehicles, in comparison to the number of non-rerouted vehicles which have their trip time increased. However, drivers are still being strongly encouraged to accept NRR's decision, because on average they would save up to at least 10 times more trip time than when not doing so.

Based on all the findings illustrated above, and one extra fact that even for non-rerouted vehicles the average wasted trip time is much less than the average saved trip time, the conclusion can be drawn that NRR is the only rerouting strategy that can not only bring significant benefit for rerouted vehicles, but also improve traffic which consists of non-rerouted vehicles and cause nearly no serious fairness issue.

5) Impact of Varying Weight Allocation Strategies on NRR:
In this subsection, we analyze the results of multiple NRR versions with varying weight allocations. We have compared 6 typical weight allocation strategies for NRR: one (NRR_ada) of them uses the adaptive process described with Equations (6)–(8); NRR_even is another strategy which evenly assigns weight values for all four factors of the cost function; the other four strategies assign full weight value for each of the four factors as shown in Table VI.

Table VI validates that in both 8 × 7 and center of Cologne testbeds, NRR using adaptive weight allocation can achieve the lowest congestion level (TTI) and system instability (SI) while ensuring the highest travel time reliability (PTI). Although it performs a bit worse than NRR_ada, the NRR using evenly assigned weight values can also achieve good results in both testbeds. Except for the strategy which assigns full weight to the road occupancy factor (NRR_oc), the other three weight allocation strategies do not show consistent performance in both testbeds.

V. CONCLUSION AND FUTURE WORKS

In this paper, to mitigate unpredictable traffic congestions caused by en-route events, such as accidents, we have proposed a highly practical vehicle rerouting strategy dubbed *NRR: Next Road Rerouting* based on the widely used adaptive traffic light control system and vehicle navigation system (VNS). NRR diverts each vehicle affected by an en-route event to its optimal next road considering four real time factors, namely the road occupancy, the travel time, the geographic distance to its intended destination and the geographic closeness to the blocked road. The obtained evaluation results highlight that in comparison to the commonly used existing solutions, NRR can achieve a reduction of average trip time and an improvement of travel time reliability up to 38.02% and 65.42% respectively in a realistic map. Moreover, NRR can even improve the traffic conditions for more than half of non-rerouted vehicles. Besides, our evaluation results reveal also the devastating impact on traffic

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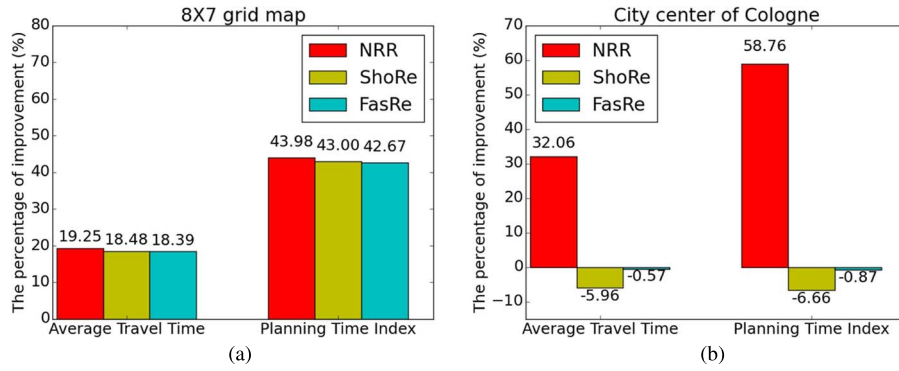

Fig. 9. Comparison of the percentage of improvement achieved by NRR, ShoRe and FasRe over ERE in terms of ATT and PTI.

TABLE VIII
IMPACT OF NRR, SHORE AND FASRE ON BOTH REROUTED AND NON-REROUTED VEHICLES (COLOGNE CENTER/8 × 7)

	Rerouted					Non-rerouted				
	# vehicles having SAME trip time	# vehicles WASTED trip time	Average WASTED trip time (s)	# vehicles SAVED trip time	Average SAVED trip time (s)	# vehicles having SAME trip time	# vehicles WASTED trip time	Average WASTED trip time (s)	# vehicles SAVED trip time	Average SAVED trip time (s)
NRR	0 / 1	**1 / 3**	40.0 / 121.0	136 / 124	558.69 / 854.35	865 / 926	**855 / 880**	4.25 / 24.05	1218 / 1008	85.65 / 62.85
ShoRe	0 / 0	**3 / 0**	152.67 / 0	3 / 117	81.33 / 896.91	854 / 855	**1284 / 1015**	39.45 / 22.15	922 / 955	12.61 / 66.04
FasRe	0 / 0	**5 / 1**	64.6 / 88.0	3 / 118	47.33 / 886.94	910 / 862	**1205 / 997**	13.67 / 23.33	943 / 964	13.72 / 65.78

when overusing selfish rerouting (i.e., VNS) and highlight the benefit of the smart altruistic rerouting strategy (i.e., NRR).

As a future work, we plan to study the impact of various parameters of the blocked roads (e.g., length, shape, relative location in road network, etc.) to find out the most appropriate time to enable NRR to achieve better performance. We can also integrate NRR with the optimization process of traffic light phase to further improve the traffic conditions.

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