A Real-Time En-Route Route Guidance Decision Scheme for Transportation-Based Cyberphysical Systems

Jie Lin, Wei Yu, Xinyu Yang, Qingyu Yang, Xinwen Fu, and Wei Zhao

Abstract—In transportation-based cyberphysical systems (TCPS), also known as intelligent transportation systems (ITS), to increase traffic efficiency, a number of dynamic route guidance schemes have been designed to assist drivers in determining optimal routes for their travels. To determine optimal routes, it is critical to effectively predict the traffic condition of roads along the guided routes based on real-time traffic information collected by vehicular networks to mitigate traffic congestion and improve traffic efficiency. In this paper, we propose a Dynamic En-route Decision real-time Route guidance (DEDR) scheme to effectively mitigate road congestion caused by the sudden increase of vehicles and to reduce travel time and fuel consumption. DEDR considers real-time traffic information generation and transmission by vehicular networks. Based on the shared traffic information, DEDR introduces the trust probability to predict traffic conditions and to dynamically, en route, determine alternative optimal routes. DEDR also considers multiple metrics to comprehensively assess traffic conditions so that drivers can determine the optimal route with a preference to these metrics during travel. DEDR considers effects of external factors (bad weather, incidents, etc.) on traffic conditions as well. Through a combination of extensive theoretical analysis and simulation experiments, our data show that DEDR can greatly increase traffic efficiency in terms of time efficiency, balancing efficiency, and fuel efficiency, in comparison with existing schemes.

Index Terms—Communication protocols, dynamic route guidance systems, new important applications and trends, real-time traffic, transportation-based cyberphysical systems (TCPS), vehicular networks.

I. INTRODUCTION

TRANSPORTATION-BASED cyberphysical systems (TCPS), also known as intelligent transportation systems (ITS), use modern information, communication, computing, and control technologies to make transportation systems reliable, efficient, and secure [9], [19]. With integrating transportation management and control systems supported by modern computing and communication techniques [6], [7], TCPS or ITS can support a diversity of applications, including real-time traffic information collection, safety improvement, intelligent route guidance, etc. [16].

Collecting real-time traffic condition information and informing drivers about optimal routes from their initial locations to their final destinations are essential for TCPS. Therefore, vehicular networks, including vehicle-to-vehicle (V2V) and vehicle-to-roadside (V2R) communication, and route guidance systems are important components in TCPS [11]. A number of route protocols have been developed to reliably and securely deliver information or package in vehicular ad hoc networks (VANETS) and mobile wireless mesh networks [1], [13], [18], [23], [30], which can be easily used in the information collection associated with real-time traffic condition in TCPS. In our proposed scheme, the simple real-time traffic information generation and transmission is considered, and the detailed traffic route protocol is developed. The proposed scheme focuses on determining optimal guided routes for drivers from their current locations to their final destinations based on the real-time traffic condition information collected by vehicular networks, with low traffic congestion and great traffic capability.

Low traffic congestion and great road capacity are essential for TCPS. To achieve this goal, with the advance of modern sensor and communication technology, there has been a considerable amount of research made on dynamic route guidance schemes, which can provide drivers with optimal routes by using real-time traffic information [2], [3], [5], [10], [12], [14], [15], [20], [21], [24], [26], [27], [32], [34]–[36]. Nonetheless, most of these dynamic route guidance schemes do not consider the generation and transmission of real-time traffic information in TCPS. Existing dynamic route guidance schemes also collect real-time traffic information and determine the optimal route before vehicles depart, but these do not effectively predict.
the traffic condition of roads along the guided routes using real-time traffic information during travel to mitigate traffic congestion. In this case, some roads would suffer from traffic congestion due to the sudden increase of vehicles on these roads, where traffic conditions are great before these vehicles depart and later deteriorates when vehicles enter these roads. In addition, few efforts have considered the effects of external factors (weather, incidents, etc.) on determining optimal routes for drivers. Thus, this calls for an effective dynamic route guidance scheme, which can dynamically and effectively predict the traffic condition of roads along the guided routes by considering the real-time traffic information and external factors, while determining alternative guided routes to mitigate traffic congestion and improve traffic efficiency.

In this paper, we propose a novel dynamic en-route decision real-time route guidance scheme (also called DEDR) for a TCPS, which can dynamically, en route, adjust the optimal route from its current location to the destination during travel. Our proposed scheme can effectively mitigate road congestion raised by the sudden increase of vehicles on a road and can also reduce the amount of time spent on traveling, vehicle fuel consumption, and traffic balance in a TCPS. During travel, DEDR can dynamically determine whether the current guided route remains optimal from the current location to the destination and can, en route, determine an alternative optimal route for drivers based on the collected real-time traffic information.

In particular, DEDR first considers the generation and transmission process of real-time traffic condition information. Based on the generated and shared traffic information, DEDR introduces trust probability to declare the probability of determining whether the current guided route remains optimal. In our scheme, the current guided route will not be considered as the optimal route, and the alternative optimal route will be generated when the trust probability of the current guided route based on the real-time traffic condition is lower than the predefined threshold. In addition, DEDR considers metrics (e.g., travel time, fuel consumption, and vehicle density) to assess traffic conditions. DEDR can determine the optimal route according to the drivers’ preference determined by the aforementioned metrics. DEDR also considers the effects of external factors (weather, incidents, etc.) on determining the optimal route and formulates external factors as travel time delay. Thus, DEDR can, en route, dynamically adjust the optimal route from the current location to the destination during travel by considering both real-time traffic information and external factors, leading to the reduction of road congestion and the increase of traffic efficiency.

Through a combination of theoretical analysis and simulation experiments, we evaluate the effectiveness of DEDR, in comparison with the shortest distance route guidance (SDRG), the shortest time route guidance (STRG), and the dynamic real-time route guidance (RTRG) schemes, with respect to time efficiency, balance efficiency, and fuel efficiency. STRG, SDRG, and RTRG represent the shortest path scheme [8], [29], [31] with various weights (i.e., static travel time, travel distance, and dynamic real-time travel time). Our data show that DEDR achieves better performance than existing schemes. For example, the average travel time of DEDR is always less than that of existing schemes. When 3000 vehicles are deployed in the evaluated system, the average travel time of DEDR is 152 s, which is 459.5, 221.2, and 51.1 s less than that of SDRG, STRG, and RTRG, respectively. When drivers’ preference metric is the fuel consumption, DEDR can achieve the reduction of fuel consumption, and the total fuel consumption of DEDR is 78.3, 161.6, and 252.6 L less than that of SDRG, STRG, and RTRG, respectively. DEDR can also achieve great traffic balance, and the maximum number of jammed roads is 10, which is less than 34 in SDRG, 31 in STRG, and 23 in RTRG. Our data show that DEDR achieves better traffic balance than existing schemes. Our data also show that DEDR can effectively mitigate road congestion and improve traffic efficiency, in comparison with existing schemes.

The remainder of this paper is organized as follows: We introduce system models in Section II. We present our scheme in Section III. We analyze the effectiveness of our scheme in Section IV. We show experimental results to validate our findings in Section V. We review related works in Section VI and conclude this paper in Section VII.

II. SYSTEM MODEL

In a TCPS, each vehicle is deployed with a global positioning system (GPS), sensors, and a wireless device. The GPS is used to determine the current position of the vehicle during travel, and sensors are used to measure the characteristics of the vehicle (speed, fuel consumption, etc.). All wireless devices in TCPS can organize a vehicular network to share the real-time traffic information measured on a vehicle along with other vehicles on the road. One critical service of a TCPS is the information sharing among vehicles. The shared traffic information can guide vehicles to determine the optimal route from its current location to its destination, dynamically, during travel.

We consider that each road or street is divided into multiple segments with a fixed length. We assume that each road or street has a unique road ID and each segment of the road has a unique segment ID. As shown in Fig. 1, road Rd_{AB} is divided into three segments, which are denoted by segment_{1}, segment_{2}, and segment_{3}. Road Rd_{AB} is not equal to road Rd_{BA} because road Rd_{AB} represents the road that vehicles can only travel from position A to B and road Rd_{BA} represents the road that the vehicle can only travel from position B to A. In Fig. 1, vehicle v
travels in segment \( s \) of \( R_d_{BA} \), and vehicle \( u \) and \( w \) travel in segment \( s \) of \( R_d_{AB} \).

The vehicles that travel in the same segment are organized as a cluster, and the vehicle that is the closest to the center of the segment is considered as a cluster-head vehicle. Obviously, the members of a cluster will change as vehicles move, and the cluster-head vehicle will change as vehicles move. Vehicles in the same cluster measure real-time traffic conditions (speed, fuel consumption, vehicle density, incidents, etc.) associated with their current segment and send the measured traffic information to the cluster-head vehicle in the same segment through wireless communication. After receiving measured traffic information from cluster members, the cluster-head vehicle aggregate the received traffic information and establishes the real-time traffic information message for its segment and shares this message with other cluster-head vehicles in neighboring road segments via vehicular networks. Our scheme can use V2V communication without deploying roadside units.

The cluster-head vehicle not only can generate the real-time traffic information message for its own road segment but also can forward the received real-time traffic information messages from other road segments. In this way, the real-time traffic condition of a location can be quickly propagated through the network without a fixed infrastructure that normally incurs a higher cost. We also assume that all vehicles are always steered as quickly as possible to reduce travel time and improve traffic efficiency. To simplify our analysis, we focus on one lane on each road or street. Our proposed scheme can be extended to a road with multiple lanes. All notations used in this paper are shown in Table I.

### III. Our Approach

Here, we first present the basic idea of our approach and then introduce the main components.

#### A. Basic Idea

In DEDR, vehicles measure the real-time traffic information of current positions through deployed GPS and sensors and share the measured traffic information by using wireless communications. Vehicles traveling on the same road segment are organized as a cluster, and the vehicle that remains closest to the center of the segment is considered as the temporary cluster-head vehicle and is responsible for aggregating the received traffic information shared by other cluster members. The cluster-head vehicle then generates a message for the real-time traffic information in its segment and shares this message with the cluster-head vehicles in other segments. A cluster-head vehicle can forward the received traffic information message from other segments and share it with its cluster members. By doing so, the real-time traffic information of a segment can be quickly propagated through the vehicular network.

When a vehicle receives messages for the traffic information of roads in its current guided route, DEDR assists the vehicle in predicting the trust probability (TP) of these roads and determines whether the TP of the current guided route is smaller than the predefined threshold. If it is smaller than \( \Phi \), DEDR will, en route, determine an alternative optimal route with a higher TP from the current location to the destination based on the collected traffic information. By doing so, DEDR can, en route, determine and alter its real-time optimal route and reduce the traffic congestion.

DEDR considers three different metrics, i.e., travel time, fuel consumption, and vehicle density, to comprehensively assess the TP of each road segment and determine the optimal routes, while considering drivers’ preference of these metrics. Based on the desirable preference, time efficiency, balance efficiency, and fuel efficiency can be achieved by DEDR. In addition, external factors (weather, incidents, etc.) are considered in DEDR when determining optimal routes to improve traffic efficiency.

Our proposed approach consists of the following key components: 1) Real-time traffic information measurement is used to sense and measure the required traffic information based on current traffic conditions; 2) real-time traffic information message generation and propagation is used to generate the traffic information message and share this with other vehicles; 3) determination of traffic states is used to determine the trust probability of all road segments; and 4) en-route route alteration and decision is used to, en route, determine and alter the real-time optimal route during travel. In the following, we present these main components in detail.

#### TABLE I

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T )</td>
<td>Slot time.</td>
</tr>
<tr>
<td>( R_d )</td>
<td>Road or street ID.</td>
</tr>
<tr>
<td>( S_{Rd} )</td>
<td>Segment ID of road ( R_d ).</td>
</tr>
<tr>
<td>( S_{Rd}^{T} )</td>
<td>Travel speed at segment ( R_d ) at time ( T ).</td>
</tr>
<tr>
<td>( T_{Rd} )</td>
<td>Travel time needed to pass segment ( S_{Rd} ) at time ( T ).</td>
</tr>
<tr>
<td>( W_{Rd} )</td>
<td>Width of road ( R_d ).</td>
</tr>
<tr>
<td>( L_{Rd} )</td>
<td>Length of road ( R_d ).</td>
</tr>
<tr>
<td>( L_{Rd}^{S} )</td>
<td>Length of segment ( S_{Rd} ).</td>
</tr>
<tr>
<td>( Num_{Rd}^{S} )</td>
<td>The number of vehicles that travel on segment ( S_{Rd} ) at time ( T ).</td>
</tr>
<tr>
<td>( D_{Rd}^{S} )</td>
<td>Vehicle density at segment ( S_{Rd} ) at time ( T ).</td>
</tr>
<tr>
<td>( C_{F}^{S} )</td>
<td>Fuel Consumption when vehicle travels in segment ( S_{Rd} ) at time ( T ).</td>
</tr>
<tr>
<td>( P_{in}^{Rd} )</td>
<td>The number of vehicles that entry road ( R_d ) at time ( T ).</td>
</tr>
<tr>
<td>( P_{out}^{Rd} )</td>
<td>The number of vehicles that leave road ( R_d ) at time ( T ).</td>
</tr>
<tr>
<td>( Inc_{Rd}^{S} )</td>
<td>The effect degree of incidence in segment ( S_{Rd} ) at time ( T ).</td>
</tr>
<tr>
<td>( W_{ea}^{S} )</td>
<td>The effect degree of weather in segment ( S_{Rd} ) at time ( T ).</td>
</tr>
<tr>
<td>( u, v, w )</td>
<td>Vehicle ID.</td>
</tr>
<tr>
<td>( V_{u} )</td>
<td>Travel speed of vehicle ( u ).</td>
</tr>
<tr>
<td>( F_{u} )</td>
<td>Fuel consumption of vehicle ( u ).</td>
</tr>
<tr>
<td>( G )</td>
<td>Vehicle gravity (N).</td>
</tr>
<tr>
<td>( f )</td>
<td>Rolling resistance coefficient.</td>
</tr>
<tr>
<td>( C_{D} )</td>
<td>Air resistance coefficient.</td>
</tr>
<tr>
<td>( A )</td>
<td>Drive tire contact area.</td>
</tr>
<tr>
<td>( \eta_{r} )</td>
<td>Transmission efficiency.</td>
</tr>
<tr>
<td>( g_{e} )</td>
<td>Engine fuel Consumption.</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Fuel density.</td>
</tr>
<tr>
<td>( P_{e} )</td>
<td>Engine consumption power.</td>
</tr>
<tr>
<td>( r )</td>
<td>Wheel radius.</td>
</tr>
<tr>
<td>( \tau_{g} )</td>
<td>Transmission gear ratio.</td>
</tr>
<tr>
<td>( \tau_{o} )</td>
<td>Main reducer transmission ratio.</td>
</tr>
<tr>
<td>( n_{e} )</td>
<td>Engine speed corresponding to the transmission gear ratio.</td>
</tr>
<tr>
<td>( Q_{s} )</td>
<td>Fuel consumption in 100 kilometers.</td>
</tr>
<tr>
<td>( T_{P}^{Rd} )</td>
<td>The trust probability of road ( R_d ) at time ( T ).</td>
</tr>
<tr>
<td>( \Phi )</td>
<td>The pre-defined trust threshold.</td>
</tr>
<tr>
<td>( \alpha, \beta, \gamma )</td>
<td>Individual preference factors of travel time, fuel consumption and vehicle density, respectively.</td>
</tr>
</tbody>
</table>
B. Real-Time Traffic Information Measurement

The real-time traffic information measurement of DEDR consists of the following four steps: vehicle initialization, operation parameters measurement, road state measurement, and measurement aggregation and sharing.

1) Step 1 — Vehicle Initialization: In our scheme, each vehicle is assigned with a vehicle ID that can be its license plate number, which is denoted by $u$. Before the vehicle departs, DEDR determines its current location, which is denoted by $SN_u$, and the traveler inputs the destination, which is denoted by $DN_u$, and preference factors $\alpha$, $\beta$, and $\gamma$ for travel time, fuel consumption, and vehicle density, respectively.

In this stage, DEDR only collects information, including vehicle ID, current position, destination, and preference setting, and stores them in its memory. After collecting the information, DEDR determines an initial optimal route from the current position to the destination based on the preference set by the traveler. Then, the vehicle travels along the initially settled optimal route. The detailed route determination process will be described in Section III-D and E.

2) Step 2 — Operation Parameters Measurement: In this stage, DEDR measures and collects operation parameters by sensors deployed on vehicle $u$ during travel, including the current slot time $T$, vehicle average speed $V_u$ at time $T$, fuel consumption $F_u$, vehicle rolling resistance coefficient $f_u$, vehicle engine fuel consumption $ge_u$, fuel density $\rho$, vehicle engine consumption power $P_{ea_u}$, vehicle engine speed $n_{ea_u}$, vehicle transmission gear ratio $i_{tu}$, and vehicle main reduced transmission ratio $i_{ou}$. DEDR stores these parameters in the memory, which will be further used to determine the real-time traffic condition of current position and determine the total travel time and fuel consumption for completing the travel.

3) Step 3 — Road State Measurement: In this stage, DEDR determines the road state of current vehicle traveling position, including road ID $Rd$, road segment ID $Sg_{Rd}$, width of road $W_{Rd}$, length of road $L_{Rd}$, the effect degree of incidence $Inc_{Sg_{Rd}}$, and weather conditions $Weda_{Sg_{Rd}}$. The measurements associated with the road state will be used in assessing real-time traffic conditions. DEDR also measures the distance from the current vehicle position to the center of current segment $Sg_{Rd}$. The distance, which is denoted by $Ds_{uSg_{Rd}}$, is used to determine the cluster-head vehicle in this segment.

4) Step 4 — Measurement Aggregation and Sharing: In this stage, vehicle $u$ aggregates the measurement obtained from Step 2 and Step 3 and generates a traffic information report $r_u$, which is constructed by $r_u = (u|T|Rd|Sg_{Rd}|V_u|F_u|W_{Rd}|L_{Rd}|Inc_{Sg_{Rd}}|Weda_{Sg_{Rd}}|Ds_{uSg_{Rd}})$, where $|$ is the concatenate operation, and other notations are defined in Table I.

After generating the local traffic information report $r_u$, vehicle $u$ shares the report $r_u$ to other vehicles through the wireless communication network and receives the traffic information report from other vehicles in the same segment. We have $Sg_{Rd}$, $u \rightarrow * : r_u$ and $* \rightarrow u : r_u$, where $*$ represents other vehicles in the same segment as vehicle $u$.

C. Real-Time Traffic Information Message Generation and Propagation

In our scheme, a road is divided into multiple segments with a fixed length, and vehicles in the same segment are organized as a cluster. Cluster members jointly measure and determine real-time traffic conditions in their current segment. This stage consists of the following three steps: cluster organization, traffic information message generation, and traffic information message propagation, which will be further described as follows.

1) Cluster Organization: In our scheme, the traffic conditions of one segment are measured by vehicles in that segment, which are organized as a cluster. Those vehicles communicate with each other through wireless communications and share a local traffic information report $r$. After receiving traffic information reports from other vehicles in the same segment, vehicle $u$ will determine whether it is closest to the center of current segment by comparing $Ds_{uSg_{Rd}}$ and $Ds_{uSg_{Rd}}$ of other vehicles. If vehicle $u$ is the closest one, $u$ will be considered as the cluster-head vehicle of current segment. Otherwise, the closest one, which is denoted by $v$, can be selected by comparing $Ds_{uSg_{Rd}}$ and vehicle $v$ is notified as a cluster-head vehicle, and the segment ID is selected as the cluster ID. As vehicles move, cluster members and cluster heads of segments will be changed over time.

2) Traffic Information Message Generation: After receiving all traffic information reports generated by cluster member vehicles, the designated cluster-head vehicle aggregates reports $r$, and merges the real-time traffic information into an integrated traffic information message (TIM) associated with the current segment at time $T$. In our scheme, there are two types of TIMs: normal and exigence.

The normal TIM is used to show real-time traffic conditions of current segment in the normal case and is formed by $N_T = (T|Sg_{Rd}|W_{Rd}|L_{Rd}|Inc_{Sg_{Rd}}|Weda_{Sg_{Rd}}| Den_{Sg_{Rd}})$, where $|$ is the concatenate operator, and $Den_{Sg_{Rd}}$ is the total number of vehicles in this segment that can be derived by counting the number of received traffic information reports of cluster-head vehicles. $Den_{Sg_{Rd}}$ represents the vehicle density of this segment at time $T$, which can be derived by $Den_{T} = Num_{T} / W_{Rd}$. $Sg_{Rd}$ is the speed that vehicles in this segment can achieve at time $T$, which can be obtained by $Sd_{T_{Sg_{Rd}}} = (1 / Num_{T_{Sg_{Rd}}}) \cdot \sum Sd_{uSg_{Rd}}$. In addition, $Q_T$ is the fuel consumption economy that vehicles in this segment can achieve at time $T$, which can be obtained by $Q_T = (1 / Num_{T_{Sg_{Rd}}}) \cdot \sum Q_{uT_{Sg_{Rd}}}$.

Exigence TIM is used to inform the exigent traffic condition information (bad weather, incidents, etc.). Exigent TIM can be formed by $E_T = (T|Sg_{Rd}|Weda_{Sg_{Rd}}| Inc_{Sg_{Rd}}| Delay)$, where $Weda_{Sg_{Rd}}$ and $Inc_{Sg_{Rd}}$ represent the effect degree of bad weather and incidents, respectively. The effect degree consists of the number of lane reductions, the vehicle pass, and so on. $Delay$ represents the remaining time delay caused by bad weather and incidents (i.e., the time taken to recover the traffic conditions).

In practice, the frequency of updating the road state measurement and exchanging the information with other vehicles in the same cluster is flexible, changing dynamically based on the speed of vehicles. In each time interval, vehicles first update their road state measurement and then exchange the information with other vehicles in the same cluster. As the speed of the vehicles is increased, updating the road state measurement...
and exchanging information become more frequent. Because vehicles moving at a higher speed will traverse a greater distance in a time interval and will change the traffic state more rapidly, we intentionally increase the update time frequency to maintain a number of data points per unit distance. On the other hand, if the speed of vehicles is lower, updating the road state measurement and exchanging information become less frequent. Overall, the basic principle for choosing the time duration, for each combination of road state measurement and exchanging information, will be how often a vehicle can achieve a new traffic state.

3) Traffic Information Message Propagation: In our scheme, both normal and exigent TIMs at different segments will be propagated by cluster-head vehicles. In this way, the communication and computation overhead, as well as energy, can be reduced, and the throughput capacity of vehicular networks can be increased. After generating normal TIM \( NR_{Sg}^{Rd} \), and exigent TIM \( ER_{Sg}^{Rd} \), the cluster-head vehicle broadcasts the information to all cluster-head vehicles in neighboring segments. The normal TIM is broadcasted once by the cluster-head vehicle in each time slot, and the exigent TIM is broadcast only if the weather becomes bad or an incident occurs.

The cluster-head vehicle in one segment can also serve as the relay nodes to receive and forward the TIMs of other segments. When a cluster-head vehicle receives a TIM from other segments, it determines whether the roads and the segment in which TIM is generated are part of the current guided route. If so, the cluster-head vehicle first stores the received TIM in the memory and then forwards this to its nearby neighboring cluster-head vehicles. Otherwise, the cluster-head vehicle only forwards the received TIM. In this way, EDER can quickly propagate the TIM of a road segment over the network, making it available to other vehicles, which assess the traffic conditions of target roads and segments. In this way, our approach does not rely on a fixed infrastructure that is costly to deploy. The stored TIM can be used to assess traffic conditions of roads and segments that the vehicle will go to next.

Notice that the vehicles, except the cluster-head vehicle in a road segment, could miss the information if the cluster-head vehicle only stores and shares the information associated with the segments in its own (the cluster-head vehicle’s) route. To make the information fully useful, the cluster-head vehicle can store the TIM and distribute this to all other vehicles in the cluster, whether the corresponding segment of the TIM is in its route or not. In our analysis and evaluation, we consider the case where the TIM is stored and the information is distributed to the cluster.

In our scheme, we divide the road into several segments, and we determine the frequency of reporting measurement based on the length of the segments. The cluster-head broadcasts a message in each time slot, and then, the new cluster-head of a segment is selected. For the system to be viable, there must be a balance between the quantity of real-time information and the network stability. More accurate real-time information can be obtained when the frequency of reporting measurement is higher (i.e., the length of segment is smaller), while the network is more stable when the frequency of reporting measurement is smaller (i.e., the length of segment is larger). Therefore, we vary the frequency of reporting measurement (determined by the length of a segment) to find a proper balance to achieve both the appropriate frequency of real-time information and the stability of the network. As the cluster-head vehicle only needs to broadcast the road state measurement generated by itself and receive and broadcast the measurement generated by neighboring cluster members, the communication overhead and computation overhead are not high. Thus, we are able to vary the frequency of reporting measurement to find a balance in which both the accurate real-time information can be obtained and the stable network can be achieved.

D. Determination of Traffic States

In the following, we first determine the metrics and then introduce trust probability (TP) to determine traffic states.

1) Metrics Considered in DEDR: In our scheme, we consider the following three metrics: a) Travel time (TT) is defined as the time taken to complete the travel, b) vehicle density (VD) is defined as the number of vehicles in each square meter in the road of guided route during travel, and c) fuel consumption (FC) is defined as the quantity of fuel needed to complete the travel. Obviously, travelers always prefer to take a route with the lowest amount of time traveled, together with low fuel consumed and low vehicle density. In the following, we describe how to determine these metrics.

Travel Time (TT): Assume that there are \( n \) remaining roads that vehicle \( u \) needs to travel along the current guided route from its current location to the destination. The remaining \( n \) roads can be denoted by \( \{ Rd_1, Rd_2, \ldots, Rd_n \} \). Then, \( TT \) of vehicle \( u \) is \( TT_u = TT_u^{\text{passed}} + TT_u^{\text{unpassed}} \), where \( TT_u^{\text{passed}} \) represents the traveled time of vehicle \( u \) from the initial position to its current location and can be easily concluded through a vehicle-mounted stopwatch, and \( TT_u^{\text{unpassed}} \) represents the time that is still needed to approach the destination from its current location and can be derived by

\[
TT_u^{\text{unpassed}} = \sum_{i=1}^{n} (\sum_{j=1}^{m} T_{R_{d_i}}^{S_{g_{d_i}}} + T_{R_{d_i}}^{S_{g_{d_i}}}) - \sum_{i=1}^{n} S_{d_i}/S_{d_i}^{T_{R_{d_i}}}, \quad \text{where} \quad n = \text{number of remaining roads}, \quad m = \text{number of segments divided in road } R_{d_i}, \quad L_{g_{d_i}}^{T_{R_{d_i}}} \text{ represents the length of the } j\text{th segment of road } R_{d_i}, \quad T_{R_{d_i}}^{S_{g_{d_i}}} \text{ represents the time slot that vehicle } u \text{ will drive on the } j\text{th segment of road } R_{d_i}, \quad S_{g_{d_i}}^{T_{R_{d_i}}} \text{ represents the travel speed that a vehicle can achieve on the } j\text{th segment of road } R_{d_i}, \quad T_{R_{d_i}}^{S_{g_{d_i}}} \text{ represents the time slot that vehicle } u \text{ passes the } j\text{th segment of road } R_{d_i}, \quad \text{at time } T_{R_{d_i}}.
\]

Vehicle Density (VD): Based on the received real-time TIM of targeted roads and segments, \( VD \) of a segment at time \( T_{R_{d_i}} \) is equal to \( VD_{R_{d_i}}^{T_{R_{d_i}}} = \frac{\text{Num}_{T_{R_{d_i}}}^{S_{g_{d_i}}}}{W_{R_{d_i}} \times L_{g_{d_i}}^{T_{R_{d_i}}}} \), which is equal to \( \text{Num}_{T_{R_{d_i}}}^{S_{g_{d_i}}} / W_{R_{d_i}} \times L_{g_{d_i}}^{T_{R_{d_i}}} \). For a road \( R_{d_i} \) at time \( T_{R_{d_i}} \) can be determined by

\[
VD_{R_{d_i}}^{T_{R_{d_i}}} = \sum_{j=1}^{m} \left( \frac{\text{Num}_{T_{R_{d_i}}}^{S_{g_{d_i}}}}{L_{g_{d_i}}^{T_{R_{d_i}}} \times W_{R_{d_i}}} \right).
\]

Fuel Consumption (FC): With considering the same assumption in determining \( TT \), the \( n \) roads (denoted by \( \{ Rd_1, Rd_2, \ldots, Rd_n \} \)) remaining for a vehicle \( u \) to pass the FC of vehicle \( u \) can be determined by

\[
F_u = F_u^{\text{passed}} + F_u^{\text{unpassed}},
\]
where $F_{\text{u passed}}$ represents the quantity of fuel that vehicle $u$ has consumed, and it can be obtained by the vehicle-mounted fuel meter. $F_{\text{un passed}}$ represents the quantity of fuel that vehicle $u$ needs to complete the travel, which is determined by $F_{\text{un passed}} = \sum_{i=1}^{n} (\sum_{j=1}^{m} Q_{T_j}^{S_{\text{hd}}_j})$ and $Q_{T_j}^{S_{\text{hd}}_j} = Q^{S_{\text{hd}}_j} \cdot L_{S_{\text{hd}}_j}$, where $Q^{S_{\text{hd}}_j}$ represents the fuel consumption at 100 km that changes over time as traffic conditions change. Based on real-time normal TIM and fuel consumption [22], [33], DEDR can predict $Q_S$ of a road segment in a time slot by

$$Q^{S_{\text{hd}}_j} = \frac{g_v \cdot P_e}{1.02 \cdot S_{\text{hd}}_j \cdot S_{\text{hd}}_j \cdot \rho} \cdot \frac{S_{\text{hd}}_j}{3600 (1 + 3776140)}$$

(1)

where all notations are defined in Table I.

2) Determination of Traffic Conditions: According to the aforementioned analysis, we can find that the number of vehicles and the speed of vehicles in segment $S_{\text{hd}}_j$ at time $T_j$ are very important to assess and predict the traffic conditions of $S_{\text{hd}}_j$ at time $T_j$, in terms of $TT$, $FC$, and $VD$. In our scheme, the TIMs of segment $S_{\text{hd}}_j$ and its neighboring segments generated at time $T_i$ are used to predict traffic conditions at time $T_j$. DEDR introduces trust probability $(TP)$ to measure the predicted traffic conditions. The definition of trust probability $(TP)$ is described in Definition 1.

**Definition 1—Trust Probability $(TP)$**: is defined as the probability that the traffic conditions of a segment at time $T_j$ are not worse than the traffic condition of the segment at current time $T_i$ as time goes on, where $T_j$ is larger than $T_i$.

$TP$ represents the probability that the traffic condition of a segment in time $T_j$ is not worse than the previous traffic condition of the segment. Taking metric $TT$ as an example, $TP$ of segment $S_{\text{hd}}_j$ at time $T_j$ can be derived by

$$TP^{S_{\text{hd}}_j} = P(T_{T_j}^{S_{\text{hd}}_j} \leq T_{T_i}^{S_{\text{hd}}_j})$$

(2)

where $T_i$ represents the current time slot, and other notations are defined in Table I. Based on the definition, $TP$ of a segment is not constant and will change over time as the traffic conditions of the segment change. $TP$ of a segment in different time slots will be different as well.

Based on the analysis shown in the previous subsection, the key problem of assessing and predicting traffic conditions (i.e., $TP$) of a segment is to predict the possible vehicle speed that vehicles can move on the segment. Vehicle speed is dependent on the vehicle density of the current segment of road. For a road segment, the following three types of density threshold should be considered, namely, 1) unimpeded density, 2) stable density, and 3) jammed density, which are denoted by $K_p$, $K_s$, and $K_m$, respectively. The unimpeded density represents the minimum density, in which vehicle speed can achieve the maximum limited speed of the segment or road; the stable density represents the interim density, in which vehicles can pass the segment with stable speed; and the jammed density represents the maximum density, in which vehicles only can remain static or move with extremely low speed due to clogged traffic. Based on the fastest limited speed of a segment and operation parameters of vehicles, $K_p$ and $K_m$ of the segment can be derived by $K_p = 1/(S_{\text{hd}}_j^2/2a_d + b \cdot S_{\text{hd}}_j + c)$ and $K_m = 1/c$, where $S_{\text{hd}}_j$ is the fastest limited speed of segment $S_{\text{hd}}_j$, and $a$, $b$, and $c$ are operation parameters. Here, $a_d$ is the vehicle braking deceleration, $b$ is the response time, and $c$ is the total length of vehicle length and save braking distance. $K_s$ relies on the driver’s operation habits and can be only obtained by observation.

Based on the rand-size relationship among real-time vehicle density, $K_p$, $K_s$, and $K_m$, the real-time vehicle speed of a segment can be determined by the following four cases.

Case 1: If the current vehicle density of a segment is smaller than $K_p$, the segment, the current vehicle speed of the segment can achieve the fastest limited speed of the segment, which is derived by

$$S_{\text{hd}}_j = S_{\text{hd}}_j = \left(\frac{S_{\text{hd}}_j^2}{K_p}\right)^{0.377}$$

(3)

Case 2: If the current vehicle density of a segment is larger than $K_p$ and smaller than $K_s$, the segment, the current vehicle speed of the segment is dependent on current vehicle density, which is given by

$$S_{\text{hd}}_j = \frac{1}{a \cdot \left(S_{\text{hd}}_j^2 + b \cdot S_{\text{hd}}_j + c\right)^{0.377}}$$

(4)

where $S_{\text{hd}}_j$ represents the vehicle density of segment $S_{\text{hd}}_j$ at time $T_j$; $S_{\text{hd}}_j$ represents the current-achieved speed; and $a$, $b$, and $c$ are operation parameters. Here, $a$ is the vehicle braking deceleration, $b$ is the response time, and $c$ is the total length of vehicle length and save braking distance. $K_s$ relies on the driver’s operation habits and can be only obtained by observation.

Case 3: If the current vehicle density of a segment is larger than $K_s$ and smaller than $K_m$, the segment, the current vehicle speed of the segment is dependent upon current vehicle density. Then, we have

$$S_{\text{hd}}_j = \frac{1}{b \cdot S_{\text{hd}}_j + c}$$

(5)

Case 4: If the current vehicle density of a segment is smaller than $K_m$ of the segment, the segment will be jammed and the vehicle speed should be “0,” i.e.,

$$S_{\text{hd}}_j = 0$$

(6)
Therefore, to predict the vehicle speed on a road in a time slot, the number of vehicles on a road \( R_d \) at the next time \( T_j \) can be derived by

\[
Num_{T_j}^{R_d} = \sum_{k=1}^{m} Num_{T_j}^{Sg_{hd_i}} + Pin_{R_d}^{T_j} - Pout_{R_d}^{T_j} \tag{9}
\]

where \( T_i \) is the current time and is equal to \( (T_j - 1) \), \( Num_{T_i}^{Sg_{hd_i}} \) is the number of vehicles in each segment of road \( R_d \), \( Pin_{R_d}^{T_j} \) is the number of vehicles which will enter road \( R_d \), and \( Pout_{R_d}^{T_j} \) is the number of vehicles which will leave road \( R_d \) at time \( T_j \). Because \( Num_{T_i}^{Sg_{hd_i}} \) can be obtained by the normal TIMs of \( Sg_{hd_i} \) at time \( T_i \), we only need to determine \( Pin_{R_d}^{T_j} \) and \( Pout_{R_d}^{T_j} \).

For a road that includes a road head and a road tail, a vehicle can only be steered from road head to road tail or enters the road from the road head and leaves the road from the road tail. In our scheme, we assume that only vehicles in the last segment of a road should leave the road in the next time. Thus, \( Pout_{T_j}^{R_d} \) and \( Pin_{T_j}^{R_d} \) can be formed by

\[
Pout_{T_j}^{R_d} = Num_{T_j}^{Sg_{hd_i}^{last}} \tag{10}
\]

\[
Pin_{T_j}^{R_d} = \theta \cdot \sum_{x \in N_{R_d}} Num_{T_j}^{Sg_{Rd_x^{last}}} \tag{11}
\]

where \( R_{dx} \) represents neighboring roads of \( R_d \) and connects to the road head of \( R_d \), \( Sg_{Rd_x^{last}} \) represents the last segment of road \( R_{dx} \), and \( \theta \) is the ratio of vehicles that enter into \( R_d \) and the ratio of vehicles that leave \( R_d \). All parameters in (10) and (11), except \( \theta \), can be obtained by the real-time TIM at time \( T_j \). Here, \( \theta \) is determined by the vehicle density of road \( R_d \) at time \( T_j \) and can be derived by

\[
\theta = \begin{cases} 
\frac{L_{R_d} \cdot W_{R_d} \cdot K_p - Num_{T_j}^{R_d} + Num_{T_j}^{Sg_{hd_i}^{last}}}{\sum_{x \in N_{R_d}} Num_{T_j}^{Sg_{Rd_x^{last}}}} & (Den_{T_j}^{R_d} \leq K_p) \\
\frac{\sum_{x \in N_{R_d}} Num_{T_j}^{Sg_{Rd_x^{last}}}}{\sum_{x \in R_{dx}} Num_{T_j}^{Sg_{Rd_x^{last}}}} & (Den_{T_j}^{R_d} > K_p)
\end{cases}
\tag{12}
\]

Here, \( Num_{T_j}^{R_d} \) is the total number of vehicles in road \( R_d \) and is equal to the sum of vehicles in all segments of \( R_d \). Equation (12) represents that, if the vehicle density in road \( R_d \) is smaller than the unimpeded density of \( R_d \), the vehicle density of \( R_d \) in the next time slot can achieve unimpeded density without affecting traffic conditions of \( R_d \). Otherwise, the number of entering vehicles must be no more than the number of leaving vehicles to keep the traffic conditions of road \( R_d \).

Recall that \( T_j \) is the next time slot of time \( T_i \) (i.e., \( T_j = T_i + 1 \)). Thus, we can use the real-time TIM at time \( T_i \) to predict the traffic conditions at time \( T_j \). Based on the aforementioned analysis, we can find that no matter which metrics (travel time, vehicle density, fuel consumption, etc.) are used to assess traffic conditions, the number of vehicles is the key parameter. All metrics associated with a road will get worse as the number of vehicles increases.

Based on the definition of trust probability (TP) in Definition 1 and (4), \( TP_{Sg_{hd_i}^{last}}^{R_d} \) is defined as the probability that the vehicle speed at time \( T_j \) is slower than that at time \( T_i \). According to the relationship between vehicle speed and vehicle density analyzed in (5)-(8), vehicle speed is monotonically nonincreasing with vehicle density. Thus, \( TP_{Sg_{hd_i}^{last}}^{R_d} \) can be considered as the probability that the number of vehicles that enter a road at next time \( T_j \) is no more than the number of vehicles that leave this road at current time \( T_i \).

It is possible that there are many segments in the current guided route for a long route. To reduce computation and communication overhead, in this paper, we only choose TP of a road, which is denoted by \( TP_{R_d}^{Rd_i} \), to represent TP of all segments in the road. In our scheme, we assume that vehicles in the last segment of a road must leave this road at the current time, and vehicles in the last segment of a road have an equal probability to enter any of the neighboring roads connected to the current road. Thus, \( TP_{R_d}^{Rd_i} \) can be represented as

\[
TP_{R_d}^{Rd_i} = P \left( Pin_{T_j}^{Rd_i} \leq Pout_{T_j}^{Rd_i} \right)
\]

\[
= \sum_{n=0}^{Pout_{T_j}^{Rd_i}} C^n \left( \sum_{x \in R_{dx}} Num_{T_j}^{Sg_{Rd_x^{last}}} \left( \frac{1}{|N_{R_d}|} \right) \right)^n \cdot \left( 1 - \frac{1}{|N_{R_d}|} \right)^{\sum_{x \in R_{dx}} Num_{T_j}^{Sg_{Rd_x^{last}}} - n} \tag{13}
\]

where \( 1/|N_{R_d}| \) is the number of neighboring roads connected to the road head of road \( R_d \), and \( Pout_{T_j}^{Rd_i} \) can be obtained by (10).

Notice that (13) considers the case where the number of vehicles that may enter road \( R_d \) is larger than the number of vehicles that would leave road \( R_d \). When the number of vehicles that may enter road \( R_d \) is smaller than the number of vehicles left, \( TP_{Sg_{hd_i}^{last}}^{R_d} \) can be considered to be 100%. This is because the number of entering vehicles in road \( R_d \) will be always smaller than that of left vehicles, even if all vehicles in the last segment of all neighboring roads of \( R_d \) enter into road \( R_d \).

\( TP_{Sg_{hd_i}^{last}}^{R_d} \) can effectively reflect the probability that real-time traffic conditions are not worse than the previous traffic condition. The use of \( TP_{Sg_{hd_i}^{last}}^{R_d} \) can effectively help travelers to, en route, decide the alternative optimal route to the destination when traffic conditions of the current guided route becomes worse and the current guided route is degenerated to a non-optimal route. The detailed process of en-route route alteration and decision will be described next.

In our analysis, we assume that vehicles are equally likely to enter one of the neighboring roads. This assumption is used to simplify the theoretical analysis. In practice, vehicles could enter one of the neighboring roads with different probabilities in various scenarios. Thus, the derivation of TP would use conditional probability, and this can be easily extended based
on (13). Here, the only change to deriving \( TP \) in this extended scenario is to replace the equal probability \( 1/[|N_{Rd_i}|] \) with conditional probability. The conditional probability of a vehicle entering one of the neighboring roads with a given destination can be obtained via the historical data analysis, based on the driver’s preferences, or other methods. Notice that deriving \( TP \) with conditional probability will only affect the probability of selecting the neighboring road, and this will not affect the route alteration and decision process in our scheme. To summarize, the derivation of \( TP \) in our scheme, which is simplified in the interest of theoretical analysis, can be easily extended to the scenario, in which vehicles enter one of the neighboring roads with conditional probability.

E. En-Route Route Alteration and Decision

Here, we describe the detailed process en-route route alteration and decision of DEDR, which considers the following metrics: travel time (\( TT \)), fuel consumption (\( FC \)), and vehicle density (\( VD \)).

1) Route Alteration and Decision With Single Metric: Assume that vehicle \( u \) is steered along the current guided route to the destination, and the current guided route is denoted by \{\( Rd_1, Rd_2, \ldots, Rd_n \)\}. When vehicle \( u \) receives the real-time TIMs of roads in the current guided route at time \( T_l \), DEDR predicts time slots that vehicle \( u \) enters each road of the current guided route, based on the real-time vehicle speed. For example, the time slot that vehicle \( u \) enters road \( Rd_i \) can be derived by \( T_l = T_l + (L_{Rd_i} - L_{\text{passed}}/Sd_{Rd_i}) + \sum_{x=2}^{n-1} (L_{Rd_x}/Sd_{Rd_x}) \), where \( L_{Rd_i} \) is the current road on which vehicle \( u \) is steered on, \( T_l \) is the current time slot, \( L_{\text{passed}} \) is the length that vehicle \( u \) has been steered on road \( Rd_1 \), and \( Sd_{Rd_i} \) is the real-time vehicle speed on road \( Rd_i \). Notice that the vehicle speed on a road is equal to the average vehicle speed of all segments divided in the road. All these parameters can be obtained based on TIMs.

After obtaining the predicted time slots that vehicle \( u \) enters each road in the current guided route, DEDR predicts the traffic conditions of each road in corresponding time slots, i.e., trust probability (\( TP \)). Based on (13), DEDR can predict \( TP \) of a road at the next time slot by analyzing real-time TIM at the current time slot. Through iteration, DEDR can obtain the \( TP \) of a road at a latter time slot based on TIMs at the current time slot. That is, for the current guided route \{\( Rd_1, Rd_2, \ldots, Rd_n \)\}, DEDR can predict and determine the corresponding \( TP \) of these road, which is denoted by \( \{TP_{Rd_1}^{\text{current}}, TP_{Rd_2}^{\text{current}}, \ldots, TP_{Rd_n}^{\text{current}} \} \).

Because traffic conditions of roads in the current guided route are relevant, the \( TP \) of the current guided route can be obtained by the product of \( TP \) of all roads, which is \( TP_{\text{current}} = \prod_{x=2}^{n} TP_{Rd_x}^{\text{current}} \). After obtaining \( TP_{\text{current}} \), DEDR determines whether the current guided route still remains an optimal one by comparing \( TP_{\text{current}} \) with the predefined trust threshold, which is denoted by \( \Phi \). If \( TP_{\text{current}} \) is not smaller than \( \Phi \), the current guided route remains optimal. Otherwise, the current guided route is a non-optimal route. As the traffic conditions change over time, an alternative optimal route is needed.

To determine the alternative optimal route, DEDR considers the following three metrics to assess traffic conditions: travel time (\( TT \)), fuel consumption (\( FC \)), and vehicle density (\( VD \)). Considering travel time (\( TT \)) as a metric to assess traffic conditions, the predicted \( TT \) of the current guided route can be derived by

\[
TT_{\text{current}} = \sum_{x=2}^{n} \frac{L_{Rd_x}}{Sd_{Rd_x}} \cdot TP_{Rd_x}^{\text{current}}.
\]

(14)

DED can also determine an alternative optimal route by using Floyd’s shortest path [4], [29], by treating travel time as weight. The travel time \( TT_{\text{alter}} \) of alternative optimal route, which is denoted by \{\( Rd_{1_2}, Rd_{2_2}, \ldots, Rd_{n_2} \)\}, should be smaller than \( TT_{\text{current}} \), where \( TT_{\text{alter}} \) can be obtained in the same way in (14). After obtaining an alternative optimal route, vehicle \( u \) will be steered along the alternative optimal route.

Considering fuel consumption (\( FC \)) and vehicle density (\( VD \)) to assess traffic conditions, the predicted \( FC \) and \( VD \) of the current guided route can be derived in the same way as deriving \( TT \), i.e.,

\[
FC_{\text{current}} = \sum_{x=2}^{n} \frac{Q_{Rd_x}}{TP_{Rd_x}^{\text{current}}},
\]

\[
VD_{\text{current}} = \sum_{x=2}^{n} \frac{\text{Den}_{Rd_x}}{TP_{Rd_x}^{\text{current}}}.
\]

(15)

(16)

In these cases, DEDR can determine an alternative optimal route, by using Floyd’s shortest path mechanism, by considering the weight as fuel consumption and vehicle density, respectively, based on real-time TIMs on roads.

Based on the definition and formalization of \( TP \), as mentioned earlier, when DEDR predicts the future road conditions, it considers that the future road conditions can be predicted based on the current road conditions divided by trust probability (\( TP \)). Here, the road conditions consider the metrics \( TT, VD, \) and \( FC \) in (14)–(16), respectively.

2) Route Alteration and Decision With Merged Metrics: DEDR can assess not only traffic conditions with one metric but also traffic conditions with multiple metrics and determine the optimal route with drivers’ preference of multiple metrics during travel. In this paper, we only consider three metrics, namely, \( TT, FC, \) and \( VD \), as an example to assess traffic conditions.

To consider drivers’ preferences, DEDR introduces preference factors of travel time, fuel consumption, and vehicle density, which are denoted by \( \alpha, \beta, \) and \( \gamma \), respectively. Thus, the combined weight of road \( Rd_x \) can be formed by

\[
\text{Weight}_{\text{merged}}^{Rd_x} = \alpha \cdot \text{Weight}_{TT}^{Rd_x} + \beta \cdot \text{Weight}_{FC}^{Rd_x} + \gamma \cdot \text{Weight}_{VD}^{Rd_x}.
\]

(17)

where \( \alpha, \beta, \) and \( \gamma \) can be considered as the proportion weight of \( TT, FC, \) and \( VD \) in the total weight, and travelers can determine them based on their preferences; \( \text{Weight}_{TT}^{Rd_x}, \text{Weight}_{FC}^{Rd_x}, \) and \( \text{Weight}_{VD}^{Rd_x} \) represent the normalized weight of \( TT, FC, \) and \( VD \), respectively. Because the units of \( TT, FC, \) and \( VD \) are different, the weights of \( TT, FC, \) and \( VD \) must be
normalized before being used to assess comprehensive traffic conditions.

To normalize the weights of TT, FC, and VD on each road, routes with maximum TT, FC, and VD should be selected from all routes from its current location to the destination, respectively. As the traffic conditions change over time, the route with the maximum weight from the current location to the destination is difficult to obtain. Thus, in our scheme, the local maximum weight is used to replace the global maximum weight, so that the normalized weights of TT, FC, and VD can be obtained.

To obtain the local maximum weight, DEDR predicts travel time, fuel consumption, and vehicle density of a route from its current location to the destination by considering time, fuel consumption, and vehicle density, respectively. Notice that assessing traffic conditions with different metrics may obtain different routes from the current location to the destination in DEDR.

The local maximum weight of TT in DEDR is the maximum of TT_{TT}, TT_{FC}, and TT_{VD}. Similarly, the local maximum weight of FC and VD can be obtained as well. Then, the combined weight of road Rd can be formalized by

\[
\text{Weight}_{\text{merged}}^{Rd} = \alpha \cdot \frac{TT^{Rd}}{\max(PTT, TT_{\text{FC}}, TT_{\text{VD}})} + \beta \cdot \frac{FC^{Rd}}{\max(FC_{TT}, FC_{\text{FC}}, FC_{\text{VD}})} + \gamma \cdot \frac{VD^{Rd}}{\max(VD_{TT}, VD_{\text{FC}}, VD_{\text{VD}})}.
\]

Everything mentioned previously is en-route route alteration and determination when vehicles receive the normal TIM. Recall that there is also another message in our scheme, which is called the exigent TIM discussed in Section III-C2, which is used to inform the exigent traffic conditions (bad weather, incidents, etc.). Exigent TIM can inform drivers on the remaining time delay raised by bad weather and incidents (i.e., the time to restore the traffic conditions). When drivers receive the exigent TIM, if the current time is before the restored time, the weight of this road is considered as infinity. Otherwise, the traffic conditions of the road are considered to be restored, and the traffic conditions can be reset to the initial value until the fresh normal TIM of road is received by the vehicles. Based on the obtained weight of road, DEDR can, en route, determine and alter the optimal route in the same way as it receives the normal TIM.

IV. ANALYSIS

We now analyze the performance of our proposed scheme to guide travels. The performance metrics include the following: 1) time efficiency is defined as the ratio of the travel time of the expected shortest route to the travel time of DEDR, 2) balance efficiency is defined as the probability of vehicle shunt, and 3) fuel efficiency is defined as the ratio of the fuel consumption of the expected shortest route and the fuel consumption of DEDR.

A. Time Efficiency

Based on the length and the limited speed of a road, the smallest time to drive over the road can be obtained. With the smallest time as weight, the expected travel time and the expected shortest route from the initial location to the destination can be obtained by the shortest distance scheme, which can be denoted by \(TT_{\text{total}}^{\text{exp}}, \{Rd_1^{\text{exp}}, Rd_2^{\text{exp}}, \ldots, Rd_n^{\text{exp}}\}\), respectively.

In DEDR, when the travel is completed, the traveled route from the initial location to the destination based on DEDR can be obtained, which can be denoted by \(\{Rd_1^{\text{DED}}, Rd_2^{\text{DED}}, \ldots, Rd_m^{\text{DED}}\}\). The time that is used to drive over each road can be concluded. The total travel time of DEDR can be formed by

\[
TT^{\text{DED}}_\text{total} = (L_{Rd_1^{\text{DED}}} / Sd_{T_1^{\text{exp}}}) + (L_{Rd_2^{\text{DED}}} / Sd_{T_2^{\text{exp}}}) + \cdots + (L_{Rd_m^{\text{DED}}} / Sd_{T_m^{\text{exp}}}),
\]

where \(Sd_{T_i^{\text{exp}}}^{\text{DED}}\) is the average speed when vehicles traveled on the road \(Rd_i^{\text{DED}}\).

In our analysis, we consider the time efficiency of DEDR in the following three traffic cases: 1) light traffic, 2) moderate traffic, and 3) heavy traffic.

Case 1—Light Traffic: In this case, a few vehicles are steered on the road, and the average vehicle speed on all roads is currently the speed limit set on these roads. Then, the expected route \(\{Rd_1^{\text{exp}}, Rd_2^{\text{exp}}, \ldots, Rd_n^{\text{exp}}\}\) is the best route from the initial position to the destination, and the expected time \(TT^{\text{exp}}_\text{total}\) is the time to complete the travel with limited speed. The core idea of DEDR is to determine traffic conditions, and the route is determined by the shortest distance scheme. Thus, the guided route determined by DEDR in this case should be equal to the expected route \(\{Rd_1^{\text{exp}}, Rd_2^{\text{exp}}, \ldots, Rd_n^{\text{exp}}\}\). This is because traffic conditions of all roads are great, and the guided route is not required to be altered while traveling. Thus, the travel time of DEDR is equal to the expected smallest time, i.e., \(TT^{\text{DED}}_\text{total} = TT^{\text{exp}}_\text{total}\), and the time efficiency of DEDR is

\[
\text{TE}^{\text{DED}} = \frac{TT^{\text{exp}}_\text{total}}{TT^{\text{DED}}_\text{total}} = 1.
\]

Case 2—Moderate Traffic: In this case, a moderate number of vehicles are driving on the roads, and some roads may show traffic congestions. Thus, the expected time becomes

\[
TT^{\text{exp}}_\text{total} = (L_{Rd_1^{\text{exp}}} / Sd_{T_1^{\text{exp}}}) + (L_{Rd_2^{\text{exp}}} / Sd_{T_2^{\text{exp}}}) + \cdots + (L_{Rd_n^{\text{exp}}} / Sd_{T_n^{\text{exp}}}).
\]

The initial guided route obtained by DEDR is also considered as the expected route. The trust probability \(\Phi\) of each road in the expected route is concluded en route, and the TP of the expected route can be obtained as well. If the TP of expected route is larger than the predefined threshold \(\Phi\), the vehicle remains steered along the expected route. Otherwise, the vehicle is steered on road \(Rd_i\), and the TP of all rest roads in the expected route is less than \(\Phi\). Then, DEDR determines an alternative optimal route, which can be denoted by \(\{Rd_1^{\text{DED}}, Rd_2^{\text{DED}}, \ldots, Rd_m^{\text{DED}}\}\), where the travel time of the alternative route should conform to

\[
\sum_{x=1}^{m} (L_{Rd_i^{\text{DED}}} / Sd_{T_x^{\text{exp}}}) \cdot TP_{Rd_i^{\text{DED}}} < \sum_{y=1}^{n} (L_{Rd_y^{\text{exp}}} / Sd_{T_y^{\text{exp}}}) \cdot TP_{Rd_i^{\text{exp}}}.
\]
Based on the basic idea of DEDR, the predicted travel time of a road in an alternative route can be formalized by

\[
TT_{DEDR}^{Rd} = \frac{L_{Rd}^{DEDR}}{Sd_{T_y}^{Rd}^{DEDR}} \cdot TP_{T_y}^{Rd}^{DEDR}
\]

Based on the previous two equations, we have

\[
TT_{total}^{DEDR} = TT_{passed} + \sum_{x=1}^{m} TT_{Rd}^{DEDR}
\]

\[
< TT_{passed} + \sum_{y=1}^{n} TT^{exp}_{Rd^{exp}} = TT_{total}^{exp}.
\] (19)

Thus, the time efficiency of DEDR for this case is

\[
P_{TE}^{DEDR} = \frac{TT_{total}^{exp}}{TT_{total}^{DEDR}} > 1.
\]

**Case 3—Heavy Traffic:** In this case, a large number of vehicles currently driving on roads and most of the roads show traffic congestion. As most roads are congested, DEDR cannot choose an alternative route, in which the TP of alternative route is larger than the predefined threshold \( \Phi \). Thus, vehicles should be steered along the expected route and the travel time of DEDR is equal to the expected travel time, and the time efficiency of DEDR should be “1.”

Notice that Case 1 and Case 3 will occur with a low probability due to the increasing number of vehicles, while also factoring in road construction. Then, the traffic conditions, most of the time, can be represented by Case 2. Thus, DEDR can achieve greater time efficiency in a TCPS and assist travelers in saving travel time in comparison to existing route guidance schemes.

### B. Balance Efficiency

DEDR can achieve vehicle shunting during travel. Assume that the expected route from the initial location to the destination can be denoted by \( \{R_1^{exp}, R_2^{exp}, \ldots, R_n^{exp}\} \). When the number of vehicles on the designated route is small, DEDR will not alter the route and will steer vehicles along with the expected route. When vehicles are steered on road \( R_i^{exp} \) and the traffic conditions of the expected route become worse as traffic congestion occurs on the expected route, DEDR will determine an alternative route from the road \( R_d \) to the destination. The alternative route can be denoted by \( \{R_1^{DEDR}, R_2^{DEDR}, \ldots, R_m^{DEDR}\} \). Based on DEDR, the predicted travel time of alternative route should be smaller than that of the expected route, i.e., conforming to (19).

Notice that the alternative route can be determined if and only if the criteria stated in (19) can be achieved. Thus, there could be no alternative route from its current location to the destination existing in a TCPS under the current traffic conditions. That is, there can be only one route from the current location to the destination existing in a TCPS or other routes are congested under real-time traffic conditions. In this case, as vehicle shunting cannot increase traffic capacity, there is no need to shunt vehicles.

If alternative routes exist, DEDR can shunt vehicles from its current guided route to the alternative route with a probability, given by \( P_{BE}^{DEDR} = \frac{\text{Route}_{Alter}}{\text{Route}_{Total}} \), where \( \text{Route}_{Alter} \) and \( \text{Route}_{Total} \) represent the number of existing alternative routes and the number of total routes from the current location to the destination, respectively.

For an area, the number of total routes from one location to another location should be constant and the number of alternative routes changes as the traffic conditions change over time. Based on \( P_{BE}^{DEDR} \), DEDR can shunt vehicles to alternative routes with a greater probability when the traffic capacity of the current guided route is low. As the number of vehicles shunted to alternative routes is increased, the number of alternative routes can be decreased as the traffic capacity of altered routes becomes worse, reducing the available traffic capacity of current guided routes. Until the number of alternative routes approaches zero or the traffic capacity of the current guided route is restored, DEDR stops vehicle shunting. Thus, when traffic congestion exists in the current guided route, DEDR can effectively determine alternative routes and achieve traffic balance.

### C. Fuel Efficiency

Based on fuel consumption efficiency, there has always been a speed, which consumes the lowest fuel to drive on a road. This speed is referred to as economic speed. Travel speed that is larger and lower than economic speed can lead to the increase of fuel consumption. As such, fuel consumption increases as the speed increases or decreases in comparison with economic speed. Based on operation parameters of the vehicle, the economic speed and economic fuel consumption per 100 km can be concluded.

Considering fuel consumption as a metric to assess traffic conditions and determine the guided route, vehicles can obtain an expected route by the shortest distance scheme (e.g., Floyd [4], [29] and Dijkstra [8], [31]) with weight as fuel consumption. The expected route from the initial location to the destination can also be denoted by \( \{R_1^{exp}, R_2^{exp}, \ldots, R_n^{exp}\} \).

If no traffic congestion occurs in the current guided route, there is no alternative route needed during travel, and the total fuel consumption of DEDR is equal to the total consumption of completing the travel along the expected route. Nonetheless, when the traffic conditions of the current guided route worsens and the TP of all remaining roads is less than \( \Phi \), DEDR can determine an alternative route by using fuel consumption as a metric. The alternative route should be conforming to

\[
\sum_{x=1}^{m} \frac{L_{Rd}^{DEDR} \cdot Q_{Sd}^{Rd}^{DEDR}}{TP_{T_x}^{Rd}} < \sum_{y=1}^{n} \frac{L_{Rd}^{exp} \cdot Q_{Sd}^{Rd^{exp}}}{TP_{T_y}^{Rd^{exp}}}
\] (20)

where \( Q_{Sd}^{Rd^{DEDR}} \) is the economic fuel consumption of road \( Rd^{DEDR} \) and relies on the real-time vehicle speed \( Sd_{Rd^{DEDR}} \) of the road. Then, the fuel efficiency of DEDR becomes

\[
P_{FE}^{DEDR} = \frac{\sum_{y=1}^{n} L_{Rd^{exp}} \cdot Q_{Sd}^{Rd^{exp}}}{\sum_{x=1}^{m} L_{Rd}^{DEDR} \cdot Q_{Sd}^{Rd^{DEDR}}}
\] (21)
As the vehicle speed $S_d^{DEDR}$ in an alternative route should be larger than the speed $S_d^{exp}$ in the expected route, $S_d^{DEDR}$ should be closer to the economic speed than $S_d^{exp}$. As mentioned earlier, a speed that is closer to the economic speed will lead to lower economic fuel consumption. Thus, economic fuel consumption $Q_s^{DEDR}$ in an alternative route should be less than the economic fuel consumption $Q_s^{exp}$ in the expected route. Thus, according to (21), the fuel consumption in an alternative route should be less than that in the expected route when the length of the alternative route is nearly to the length of the expected route (i.e., $P_{DEDR}^{FE} > 1$). In practice, the lengths of routes from the same initial location to the same destination are almost equal to each other, i.e., DEDR can achieve great fuel efficiency.

V. PERFORMANCE EVALUATION

Here, we will show the simulation results of DEDR in comparison with the SDRG, STRG, and RTRG schemes [8], [29], [31] with respect to the time efficiency, balance efficiency, and fuel efficiency stated in Section IV. Here, STRG and SDRG belong to the shortest path scheme (e.g., Dijkstra [8], [31] and Floyd [29]) with weight as static travel time and static distance, respectively. RTRG is a shortest path scheme with weight as dynamic real-time travel time.

We conducted performance evaluation based on a simplified version of partial traffic map of Xi’an, China, as shown in Fig. 3. The data sets used for the simulation consists of road distance and the limited speed of each road in Fig. 3. These two data sets can be easily obtained by the traffic map of Xi’an. To simplify our evaluation, we consider that all roads in Fig. 3 have a dual carriageway and only one lane existing in each direction. Each road is divided into several segments with a fixed segment length of 50 m. In each evaluation, a number of vehicles are randomly selected to join in the transportation system, and the maximum number of vehicles that can be included in our simulation is 3000. The initial location and final destination of a vehicle are randomly selected from 45 nodes in Fig. 3. To obtain the operation parameters of vehicles, YC6L260-40 engine is chosen as an example in our experiments, as shown in Fig. 2 [33], and the operation parameters of vehicles used to derive fuel consumption are shown in Table II. In addition, the predefined trust probability threshold is 50% in our evaluation.

In our evaluation, the performance of DEDR is evaluated by assessing not only traffic conditions with single metric but traffic conditions with travelers’ preference of multiple metrics as well. All simulations in this paper were completed by MATLAB (see Fig. 3).

Time Efficiency: Fig. 4 illustrates the number of vehicles increasing as the time goes, when the travel time is used as a metric to assess traffic conditions. As we can observe, the arrived number of vehicles with DEDR is always larger than the number of vehicles when other route guidance schemes are used. This indicates that, given the same traffic condition, DEDR can effectively reduce the travel time of vehicles.

Fig. 5 shows the average delay of all vehicles with different route guidance schemes. The average delay is equal to the time difference between the expected shortest time and the consumed time. As we can observe, regardless of the traffic conditions in each situation, DEDR can always achieve the lowest average time delay in comparison with other schemes. Fig. 6 shows the number of vehicles that complete their travels with increased travel time. From the figure, in DEDR, the increased time of most vehicles is 30 time slots, and no increased time of a vehicle is larger than 50.

Balance Efficiency: Fig. 7 shows the number of jammed roads in the experiment as the time passes. As we can observe, when the increasing ratio of vehicle numbers is high (say 100 per time slot in our experiment setting), the highest numbers of
Fig. 4. Arrived number versus time.

Fig. 5. Average delay.

Fig. 6. Vehicle number versus increased time.

jammed roads in DEDR, RTRG, SDRG, and STRG are 10, 23, 34, and 30, respectively. Thus, DEDR can effectively mitigate traffic congestions in comparison with existing schemes.

Fig. 7. Number of jammed roads versus time (vehicle increasing ratio at 100 per time slot).

Fig. 8. Vehicle number versus vehicle density.

to assess traffic conditions. We can observe that in the initial stage, as shown in Fig. 8(1), no road is jammed, regardless of whether which route guidance scheme is used. As the time passes, as shown in Fig. 8(2)–(4), the vehicle densities of most roads in DEDR (including both DEDR-T and DEDR-D) are only 20% of the jammed density of these roads, while the vehicle density of most roads in other schemes is not balanced as a number of jammed roads exist when these schemes are used.

Fuel Efficiency: Fig. 9 shows the total fuel consumption of completing the travel in these route guidance schemes. Similarly, DEDR-T means that vehicles use DEDR with travel time ($TT$) to assess traffic conditions, and DEDR-F means that vehicles use DEDR with fuel consumption ($FC$) to assess traffic conditions. As we can observe, DEDR-F can always achieve low fuel consumption in these four cases. In addition, SDRG can achieve low fuel consumption because the fuel consumption is increased when the traveled distance is increased.

Efficiency With Considering Traveler’s Preference: DEDR can not only assess traffic with single metric but use multiple metrics to comprehensively assess traffic conditions as well. Then, drivers can determine optimal routes with the preference...
of these metrics during travel, as indicated in (17) and (18). In
this evaluation, we consider the mean values of \( TT \), \( VD \), and \( FC \) to assess traffic conditions, i.e., \( \alpha : \beta : \gamma = 1/3 : 1/3 : 1/3 \) in (17). In this evaluation, DEDR-T, DEDR-D, DEDR-F, and DEDR-C represent the DEDR that determines the guided route with considering \( TT \), \( VD \), \( FC \), and all three metrics to assess traffic conditions, respectively.

Fig. 10 shows the number of vehicles that complete their travel with increased time. As shown in Fig. 10, the arrived number of vehicles in DEDR-C is close to that in DEDR-T and DEDR-D and is larger than the arrived number in DEDR-F. Fig. 11 shows the average delay in DEDR-T, DEDR-D, DEDR-F, and DEDR-C, respectively. As we can observe in the figure, DEDR-C can also achieve a lower time delay. Therefore, DEDR-C can achieve greater time efficiency in comparison with DEDR-F and DEDR-D.

Fig. 12 shows the number of jammed roads in different time slots. As we can observe, the number of jammed roads in DEDR-C is close to that in DEDR-T and DEDR-D and is less than the number of jammed roads in DEDR-F. Fig. 13 shows the number of roads in different vehicle densities. We observe that, regardless of which time slots, the number of roads with high vehicle density (i.e., the vehicle density is larger than 30%) in DEDR-C is always not more than that in DEDR-T, DEDR-D, and DEDR-F. Thus, DEDR-C can achieve great balance efficiency with considering traveler’s preference.

Fig. 14 shows that total fuel consumption. In the figure, we can observe that the fuel consumption in DEDR-C is larger than that in DEDR-F as well as less than that in DEDR-T and DEDR-D. Thus, DEDR-C can achieve greater fuel efficiency in comparison with DEDR-T and DEDR-D.

To summarize, through our evaluation results, we observe that DEDR-C can balance time efficiency, balance efficiency, and fuel efficiency, by considering traveler’s preferences so that travelers can achieve the preferred performance efficiency by choosing different \( \alpha \), \( \beta \), and \( \gamma \).

VI. RELATED WORKS

To increase the traffic capability of TCPS or ITS, a number of route guidance schemes (RGSs) have been developed [2],
Existing RGSs can be divided into two categories: static and dynamic. Most of the existing static RGSs rely on the shortest distance mechanisms (e.g., Dijkstra [8], [31] and Floyd [4], [29]) to obtain the optimal route by converting travel time or travel distance as the link weight of graphs [25]. Because static RGSs only use fixed road parameters to determine an optimal route, traffic efficiency will be limited as road congestions occur. Thus, static RGSs are not suitable for TCPS.

To overcome this issue, a number of dynamic RGSs have been developed to determine optimal routes based on real-time traffic conditions. According to different methods of information transmission, dynamic RGSs can be divided into two categories: infrastructure-based RGS [2], [10], [12], [27], [35], [36] and infrastructure-free RGS [3], [5], [14], [15], [21], [24]–[27], [32], [35], [36].

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To determine optimal routes and reduce computation and communication overhead, a number of infrastructure-free RGSs have been developed. In such a system, traffic conditions are measured by computing equipment deployed in individual vehicles, so that vehicles can communicate with each other through wireless communication without deploying dedicated infrastructure devices. For example, Ding et al. [3] developed a V2V real-time routing (V2R2) scheme, which can effectively determine a route with less time and bypass defined areas. Nonetheless, these schemes do not consider the effect on the route determination of vehicles during travel. Khanjary et al. [10] presented five traffic rerouting strategies to reduce travel time. Nonetheless, few existing schemes considered the effect of external factors (bad weather, incidents, etc.) on route determination, as well as the real-time information generation and transmission. In addition, some strategies were developed to minimize the fuel consumption in real-time operations [28]. They did not focus on minimizing fuel consumption via altering optimal routes and did not consider other metrics to balance drivers’ individual preference.

Unlike existing schemes, in this paper, we developed an end-to-end real-time RGS, which is denoted by DEDR, which considers both the information generation and transmission and the optimal route determination and alteration. This paper is the extended version of our conference version published in [17]. Based on the short conference version, we have made substantial extensions and revisions in the extended version. The extensions include a description of metrics determination and formalization, the description of vehicle speed determination and formalization, an explanation of route alteration and decision with integrated metrics, the analysis on fuel efficiency of our proposed scheme (DEDR), an additional performance evaluation, and an extensive review of related research efforts, etc.

VII. CONCLUSION

In this paper, we have proposed a novel scheme that can effectively mitigate traffic congestions and improve the traffic efficiency of a TCPS (or an ITS). DEDR adopts the trust probability (TP) to assess real-time traffic conditions with multiple metrics and, en route, alter the optimal route from the current location to the destination during travel. DEDR is capable of assessing real-time traffic conditions with multiple metrics and determine optimal routes, leading to travel time reduction, traffic balance, and fuel consumption reduction. Through a combination of both theoretical analysis and simulation experiments, our data show that our developed scheme achieves better traffic efficiency, in terms of time efficiency, balance efficiency, and fuel efficiency, in comparison with existing schemes.
REFERENCES


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