Traffic Flow Control in Vehicular Multi-Hop Networks with Data Caching and Infrastructure Support

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***Abstract*—This work studies the user equilibrium (UE) state and the system optimal (SO) state in vehicular communication networks that support both V2V and V2I communication. Each user in this network is assumed to make route choice that optimizes a utility function that involves the traditional travel cost and the data communication utility. The overall social cost is minimized when the network is in the SO state. However, the rational and selfish user behavior brings the network to the UE state. It is well known that, in general, the UE state does not necessarily coincide with the SO state. In this paper, we leverage the data communication aspect of the decision making to influence the users' route choices, driving the UE state to the SO state. We provide a guideline for the system operator on how to drive the network towards the SO state using the V2I bandwidth allocation scheme developed in the paper. The model and the proposed algorithm are validated using Veins simulation under IEEE 802.11p protocol. In the simulation, we also show that the system cost can be lowered compared with the UE state if the bandwidth allocation is close to the optimal solution under the proposed algorithm.**

***Index Terms*—traffic control; vehicular communication networks; system optimal; user equilibrium; bandwidth allocation**

I. INTRODUCTION

IN transportation systems, the prospect of wide-scale connected autonomous vehicles (CAVs) is approaching its realization, due to the advances in control and communication. In a traditional transportation network, the drivers make travel decisions (e.g., route choices, travel timing) that minimize the transportation related costs, such as travel time, travel distance, etc. With the emergence of CAVs that form vehicular ad-hoc networks (VANETs), data communication network connectivity is not only going to be an important factor for enabling vehicular control, but also going to change the CAV users traveling behavior. Some CAV users will expect the type of data communication service they are accustomed to at their homes and offices. Thus, CAV users may choose routes not only depending on travel time and costs, but also based on the quality of data service (QoS) that will be provided on the route, since this directly affects their productivity and/or quality of life. CAV users may choose to take a route with longer travel time in order to have a better data communication network connectivity (just as travelers may choose a more expensive hotel, or a less convenient hotel location, if it offers a high speed WiFi connection).

We envision that CAV users will consider data communication cost and quality as a factor in making their travel decision, thus breaking away from the traditional traffic network theory where travelers consider only travel time and costs (e.g., road pricing) in shaping their behavior. Evidence of this behavior has been recently reported in a case study [1] where drivers changed their travel routes depending on the availability of data connectivity on the highways available for the alternative routes that can be chosen by the drivers. This behavior enables the shaping of vehicular traffic patterns by modulating parameters of the data communication network. For regulators, this offers an opportunity to align social utility with personal utility in vehicular traffic networks. For the transportation infrastructure operators this can lead to better infrastructure usage (e.g. more balanced load leading to more balanced road pavement deterioration, etc.) and maintenance planning. Hereafter in this paper, we will refer to the travel decision makers (i.e., drivers or CAV users/systems) as "users."

Travel decision making among users can be analyzed in a game theoretical setting [2], [3]. The travel decision of each user impacts the state of the transportation network, and thereby may also impact the transportation costs of all users. The Nash equilibrium of this game is referred to as the *Wardrop equilibrium* or the *user equilibrium* (UE). Thus, UE occurs if no user can be better off by unilaterally changing his travel decision. In a traditional transportation network, the UE state[1] is achieved if every user tries to minimize his/her travel cost (e.g., travel time).

In contrast to UE, we can also consider the system optimal (SO) state. The system optimal state occurs if the social cost function, typically the total of the travel costs of all users, is minimized. In general, under the assumption that the users are selfish and rational, it is known that UE and SO are not the same. This phenomenon is sometimes referred to as the Braess' paradox [4], [5]. The ratio between the social costs at UE and at SO is called the *price of anarchy* (PoA) [6].

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[1] i.e., the state of the transportation network if the game is at UE.

In order to decrease the Price of Anarchy (PoA) in traditional transportation networks, road pricing, fuel costs, congestion level, etc., have been proposed and are currently adopted in practice [7], [8], [9], [10]. For example, a wealth of research has been done on the design of congestion tolls. Marginal cost pricing is a well-known approach for steering the user equilibrium to the system optimal, which has been proposed in [2]. However, no existing study has explored the problem of exploiting the communication aspect to maximize the social welfare when users are faced with the joint choice of transportation and data service, which is the key feature of CAV users, and is the focus of this paper.

In this paper, we model the users behavior in the vehicular communication network, where the inter-dependency between the network condition (including vehicular traffic network condition and communication network condition) and the users' valuation of the cost (including travel cost and communication cost) leads to a different UE. We assume all the vehicles are cache-enabled, and can communicate via vehicle-to-vehicle (V2V) connections and via vehicle-to-infrastructure (V2I) connections (see [11] for the evaluation of utilizing caching techniques in V2V communication with the presence of V2I infrastructure). The data connectivity depends on a variety of parameters, such as the car density, V2V/V2I bandwidth, caching ratio, etc. The connectivity dynamics, coupled with the traffic condition, affects users' route planning. For example, a dense traffic flow in a road segment leads to a longer travel time on that segment, but can potentially enhance the communication utility if the benefit of the V2V caching gain dominates the loss of the V2I QoS. On the other hand, as more users choose to use the road segment with low travel cost and low communication cost, congestion may occur on that segment in both the vehicular traffic and the communication traffic, which will discourage other users from using this road segment.

The interaction between the transportation network and the users decisions has been thoroughly studied [3]. However, the effect of network communications, both from a connectivity dynamics point of view, and from a path decision point of view, have not been considered. In this work, we focus on the influence of the data service on users route planning. We adopt the notion that the system operator can use the communication network parameters as a knob to be leveraged so as to push the user equilibrium (UE) closer to the system optimal (SO). This paper is an extension of our previous conference paper [12], with the main key contributions being that we model both V2V and V2I traffic, and we model two types of network users. Specifically, we make the following contributions:

(a) In Section III and Section IV, we incorporate the data communication aspect, including V2I bandwidth and content caching in V2V communication, in the modeling of the trip cost of different user groups, and characterize the UE states of the vehicular communication network. We also characterize the communication equilibrium, which is the equilibrium of the users choice of communication mode (V2V v.s. V2I).

(b) In Section V, we propose a V2I bandwidth allocation scheme to drive the traffic flows at UE closer to the traffic flows at SO, and therefore decrease the price-of-anarchy. We also derive the relationships between the V2I bandwidth and the traffic car density at the equilibrium, which provides a guideline on how to adjust the V2I bandwidth if the V2V routing policy and the travel cost function are known.

(c) In Section VI, we present some numerical results for the performance of the proposed scheme, given a specific model of the users' decision making process as an example. We also discuss the insights drawn from the analysis regarding how the the travel cost and the communication utility influence the users behavior based on the numerical results.

(d) In Section VII, we validate the proposed model via Veins simulation under **IEEE** 802.11p protocol. The simulation results show that the utility predicted by the proposed model generally matches the utility in the simulation, and that the V2I bandwidth allocation can be leveraged to change users' behavior such that the system cost is lowered under **IEEE** 802.11p protocol.

The remainder of this paper is organized as follows. In Section II we review the related work on the data communication and user behavior in vehicular communication networks. In Section III we divide the users into real-time user group and content user group, and present the model of the vehicular communication network. In Section IV we model the communication utilities of different user groups, and characterize the communication equilibrium. In Section V we derive the relationship between the V2I bandwidth and the traffic car density at UE in a general network, and propose a V2I bandwidth allocation scheme to drive the flows at UE closer to the flows at SO. The numerical results and the performance analysis of the proposed scheme are presented in Section VI. The proposed model is validated via Veins simulation in Section VII. We conclude our work and discuss future extensions in Section VIII.

II. RELATED WORK

Enhancing the transportation network via communication network capabilities enables a wide range of applications [13], [14], for example, interactive entertainment, urban sensing [15], collision avoidance in platoon formation [16], improving the intersection capacity via platoons [17] and via learning of congestion levels if vehicles communicate heterogeneously [18]. A wealth of research focuses on vehicle-to-vehicle (V2V) communication in the transportation networks [19], [20]. Vehicle-to-infrastructure (V2I) communication is an alternative to the V2V communication, which is also well studied in a variety of contexts [1], [21], [22], [23]. Content caching in vehicular networks has been considered in the past, which takes use of the large storage space of vehicles and the dynamic topology of the networks [24], [25], [26]. Offloading V2I communication to V2V communication with in-vehicle caching can improve service quality due to the high speed and the high communication demand

in vehicular communication networks [27]. In this paper, we consider a transportation network that supports both V2V and V2I communication, where V2V communication relies on data caching.

It is expected that CAV users' needs for and valuation of data service vary based on their socioeconomic characteristics and trip-related features. There are several studies on people's behavior in response to transportation service and data communication service. These studies, however, reside in different research fields. Transportation studies typically focus on traveler behavior including mode choice, route choice, departure time choice, etc. For traveler route choice, the main focus ranges from the effects of road pricing [28], fuel costs [9], congestion level [10], reliability [29], land use [30], to advanced traveler information system [31]. In related recent work, [32] proposed a scheme in which independent power and transportation system operators can collaborate to manage each network towards a socially optimum operating point. This is somewhat synergistic to our work in that the effect of power consumption impacts the trip choice of travelers. However, arguably, our work is more challenging since the network quality is also a function of traffic. Furthermore, the dynamics of the interaction between network quality and traffic is quite different from the case of power-traffic interactions. User responses to cost and quality of data communication service have been investigated in a wide spectrum of fields including information system, psychology, and business management. Studies have looked into effects of perceived fee [33], user prior experience and habits [34], social influence [35], perceived monetary value, among others. In a recent literature review, [36] summarized main areas and methods on research related to people's data communication behavior in the past decade. However, no existing study has explored the user behavior when facing the joint choice of transportation and data service, which is the key feature of CAV users and is the main focus of this work.

This work extends our previous work [12]. The key extensions and improvements are summarized as follows. We generalize the condition for the system to be at equilibrium from two-road networks to general networks. In addition, we use a generalized empirical travel time function from Bureau of Public Roads as the travel cost function. We also changed certain parameters in the case study to be consistent with the simulations in Section VII. The numerical results from Section VI are similar to the simulation results in Section VII in terms of user behavior, which justifies the proposed V2I bandwidth allocation scheme. Moreover, we validate the proposed model via simulations in Veins. This involved substantial extension of the functionality of the Veins simulator in order to support real-time data and route-selection decisions and tracing. The simulation results show that the V2I utility predicted by the proposed model generally matches the simulated cache hit utility. We show, via simulations in Veins, that V2I bandwidth allocation can be leveraged to change users' behavior such that the system cost is lowered under **IEEE** 802.11p protocol. Compared with our related work [37] and [38], this paper considers a more general and realistic scenario, where the network supports both V2V and V2I communication, and the system operator can leverage the V2I bandwidth to drive the network towards the SO state.

III. SYSTEM MODEL

In this section, we model the transportation network and the communication network. We divide the users into two groups, and model the V2V communication and the V2I communication separately. For ease of reference, key notations are summarized in Table I.

Notation	Description
A	set of links (road segments)
N	set of all origin-destination (O-D) pairs
K_i	set of all routes connecting O-D pair $i \in N$
q_i	trip rate between O-D pair $i \in N$
x_a	flow on link $a \in A$
$\delta_{i,k}(a)$	=1, if link a is on route k between O-D pair i; =0, otherwise
B_a	V2I bandwidth allocation on link $a \in A$
W	data traffic that a vehicle can support in unit time
$T_a(\cdot)$	travel cost of link $a \in A$
$\mathbb{J}_{i,k}$	route cost of route $k \in K_i$ that connects O-D pair $i \in N$
J_a	link cost of link $a \in A$
U_a^h	cache hit utility on link $a \in A$
U_a^{V2I}	V2I utility on link $a \in A$
U_a^{V2V}	V2V utility on link $a \in A$
Y_i	fraction of real-time users who travel between the O-D pair $i \in N$
y_a	fraction of real-time users on link $a \in A$
$x_{i,k}^R/x_{i,k}^C$	flow of real-time/content users who choose route $k \in K_i$ between O-D pair $i \in N$
$x_{i,k}^{CV}/x_{i,k}^{CI}$	flow of the V2V/V2I content users on route $k \in K_i$ between O-D pair $i \in N$
m_a	fraction of content users who chooses V2V connection on link $a \in A$
u	intrinsic value of data
ν	price for using V2I connection
l_a	length of link $a \in A$
p_a	caching ratio on link $a \in A$
ρ_a	car density of link $a \in A$
$r(\rho_a)$	transmission range. $r(\rho_a) << l_a, \ \forall a \in A$
$R(\rho_a)$	searching distance. $R(\rho_a) < l_a/2, \ \forall a \in A$

TABLE I: Table of Notations

The transportation network consists of a number of road segments which we refer to as links. Infrastructure related parameters, such as the free-flow speed, stay the same throughout a link. The set of all links in the transportation network is denoted by A. Each vehicle in this transportation network travels from an origin to a destination via a set of links. We refer to a set of links that connects an origin and a destination as a route. The set of all possible origin-destination pairs (O-D pairs) is denoted by N. There is/are one or more routes between each O-D pair. The set of routes between the O-D pair i is represented by K_i. We assume that the trip rate q_i for every O-D pair $i \in N$ can be drawn from historical data, and thus is known to the operator apriori. Without loss of generality, we only consider one-way traffic, i.e. all links are directed, since any two-way link can be equivalently replaced by two one-way directed links. The indicator variable $\delta_{i,k}(a)$ is defined such that $\delta_{i,k}(a) = 1$ if link a is passed by the traffic along route $k \in K_i$, otherwise $\delta_{i,k}(a) = 0$. The vehicles travel along the links and form the link flow vector $\mathbf{x}$, where the entry x_a represents the traffic flow on link a.

In order to model the data communication, we divide the users into two groups based on the kind of data network applications they are using. If a user needs real-time data communication, he/she will require V2I connection. We refer to these users as real-time users, and we denote the fraction of real-time users on link a by y_a. **We define real-time data as interactive content that cannot be satisfied from other vehicles' caches, e.g. video conferencing, online gaming, etc. Real-time data communication, as defined in this paper, may not have guaranteed bandwidth or strong real-time requirements, but it requires an interactive response from an end-user or server in the Internet rather than a cached content from another vehicle.** On the other hand, if a user prefers content that does not necessarily require a backbone connection to the Internet, for example movies and music, he/she may choose to use V2V connection or V2I connection. We refer to these users as content users. The fraction of content users on link a is thus $1-y_a$. Let m_a denote the fraction of the content users who choose V2V connection on link a, and we refer to these users as the V2V content users. The fraction of the content users who choose V2I connection on link a is thus $1-m_a$, and we refer to these users as the V2I content users. For V2V content users, if the requested content is not found in the neighboring vehicles due to cache miss, this user then turns to use V2I connection. We assume that both the real-time users and the content users will participate in serving and forwarding the content requests. The position of the users on link a, including the real-time users and the content users, is assumed to follow a Poisson distribution with the density parameter ρ_a. For modeling simplicity, we assume that a user stays as either a real-time or content user throughout the duration of their trip.

The data communication is modeled as follows. In V2V communication, each vehicle sends requests to the neighboring vehicles in a multi-hop fashion. The searching distance is denoted [2] by R. Given a certain power control scheme or a routing protocol, R is a function of the car density ρ_a, hence, $R(\rho_a)$. Similarly, the one-hop transmission range is denoted by $r(\rho_a)$. When a vehicle receives a request, it sends the data (e.g., via the reverse path) to the querying vehicle if the requested data is stored in the cache. Otherwise, the vehicle forwards the request to its neighboring nodes. If none of the vehicles within the querying vehicle's searching distance has the requested content, the querying vehicle turns to use V2I connection. We assume that a vehicle's transmission range is limited to the same road segment, and the searching distance does not reach any other roads. **Our model currently is most suitable to one-way roads without too many intersections, eg. highways. The model would need to be generalized to model more specific or complex road situations such as intersections in city road environment. Existing work has studied this problem (e.g. [18], [39]), where the model is heavily dependent on particular intersection types, which is a different line of work that could be pursued. Our model however provides a first step in that direction, and also lends insight on the tradeoff between connectivity value and traditional travel cost.**

The cache hit probability can be derived as follows. Let p denote the probability that a certain content is stored in the cache of a vehicle. The density of the vehicles that have a certain content in the cache is ρp. Since the position of the vehicles is assumed to follow a Poisson distribution, the probability that there is no cache hit in the searching distance of a querying vehicle is $e^{-2R(\rho)\rho p}$. Therefore, the cache hit probability is $1-e^{-2R(\rho)\rho p}$ for every content user on the link[3].

We adopt the protocol interference model [41], i.e., when a vehicle is sending data via the V2V channel, all other vehicles inside its transmission range cannot send data. **The effect of any additional modes of interference that we do not model is that the cache hit probability will be lower than those provided by the analytical results, and hence our results provide a best case scenario with respect to the hit probability. In the future work, the impact of interference can be incorporated in the analytical results cache hit probability. Specifically, if interference within the transmission range is considered under a more complicated interference model (e.g. physical interference model [42]), then the cache hit probability would be reduced.** Under the protocol model, there are at most $\frac{l_a}{2r(\rho_a)}$ simultaneous transmissions on a road segment with length l_a. For simplicity, we drop the subscript a when there is no confusion. Fig. 1 shows a part of the vehicular network, where all nodes are V2V users. To illustrate the V2V communication model, consider the communication between the following pairs of nodes:

- Node 1 and Node 2: Node 2 is within the transmission range of Node 1 (and vise versa). Therefore, they can communicate with each other directly in one hop. This is also true between Node 1 and Node 5, Node 2 and Node 3, Node 3 and Node 4.
- Node 1 and Node 3: Node 3 is within the transmission range of Node 2 and is within the searching distance of Node 1. Therefore, Node 1 and Node 3 can communicate with two hops, where Node 2 is the intermediate forwarding node.
- Node 1 and Node 4: Node 4 is outside of Node 1's searching distance. Therefore, although Node 4 is within Node 3's transmission range, Node 1 and Node 4 are not able to communicate with each other.
- Node 1 and Node 6: Node 6 is within Node 1's searching distance, however, there is no intermediate node to forward requests or to relay data between them. Therefore, Node 1 and Node 6 are not able to communicate with each other.

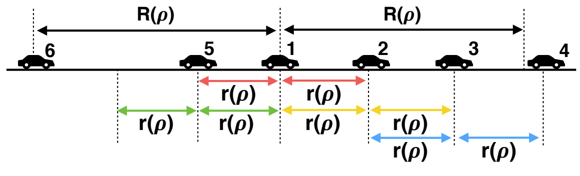

Fig. 1: Part of the vehicular communication network on a link.

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[2] Similar distance-limited model is used in [39]

[3] This cache hit probability is also derived in [40]

In V2I communication, we consider the ideal scenario where all vehicles on a road segment can communicate with the Road Side Units (RSUs) on that segment at any time via V2I connection. We assume that all requests can be served by V2I connection. Let B_a denote the V2I bandwidth (bit/second) shared by the users within a unit length on road segment a, which is adjustable by the network operator in real-time with certain limits. In practice, the system operator is a certain "coordinator", for example the Federal Highway Administration, which coordinates highway transportation programs in cooperation with states and other partners to enhance the country's safety, economic vitality, quality of life, and the environment. This "coordinator" will provide incentives to the network operator in order to maximize the social welfare. But how this coordination is done is beyond the scope of the paper. In practice, it may not be possible for the operator to accurately adjust the V2I bandwidth, but rather there could be a more course grain level of control of the bandwidth. However, this is not a restriction for the model, and we will show in the simulation in Section VII that the proposed scheme can lower the system cost under **IEEE** 802.11p protocol, where the bandwidth allocation can only take eight different values.

IV. COMMUNICATION UTILITIES

In this section, we first model the cache hit utility, the V2V utility, and the V2I utility. Based on the communication utilities of different user groups, we introduce the communication equilibrium in Section IV-C.

A. Cache Hit Utility

Let U^h and $\lambda(\rho)$ denote the cache hit utility and the throughput per node due to cache hit respectively. We also assign the data with an intrinsic value u. Then, the cache hit utility can be defined as the expected value of the throughput due to cache hit, weighted by the intrinsic value of data, i.e.,

$$U^h = u\lambda(\rho). \tag{1}$$

We derive $\lambda(\rho)$ as follows. Since the request packet is relatively short, we only consider the data packets. A road segment has $\rho l(1-y)m$ V2V users and each V2V data packet traverses at most $R(\rho)/r(\rho)$ hops. Therefore the total V2V data traffic on a road segment with $\rho l(1-y)m(1-e^{-2R(\rho)\rho p})$ V2V connections is $\rho l(1-y)m(1-e^{-2R(\rho)\rho p})\lambda(\rho)\frac{R(\rho)}{r(\rho)}$ bits/second. We assume that each vehicle can support a W bits/second traffic, then we need at least $\frac{\rho l(1-y)m(1-e^{-2R(\rho)\rho p})\lambda(\rho)R(\rho)/r(\rho)}{W}$ concurrent transmissions. There are at most $\frac{l}{2r(\rho)}$ concurrent transmissions on a road segment, therefore $\frac{\rho l(1-y)m(1-e^{-2R(\rho)\rho p})\lambda(\rho)R(\rho)/r(\rho)}{W} \leq \frac{l}{2r(\rho)}$, which gives

$$\lambda(\rho) = O(\frac{W}{R(\rho)\rho(1-y)m(1-e^{-2R(\rho)\rho p})}). \tag{2}$$

Since $O(\frac{W}{R(\rho)\rho(1-y)m(1-e^{-2R(\rho)\rho p})})$ is achievable according to [39], we use the actual quantity (subject to a constant) to define the cache hit utility. Therefore, the cache hit utility is given by

$$U^h = \frac{uW}{R(\rho)\rho(1-y)m(1-e^{-2R(\rho)\rho p})}. \tag{3}$$

B. V2V and V2I Utilities

We define the V2V utility as the expected value of the throughput of a V2V content user. If a vehicle chooses to use V2V connection, it is possible that the requested content is not cached in any of the vehicles within its searching distance. Upon a cache miss, the querying vehicle turns to use the V2I connection. Therefore, the V2V utility is the weighted sum of the cache hit utility U^h and the V2I utility U^{V2I}:

$$U^{V2V} = (1-e^{-2R(\rho)\rho p})U^h + e^{-2R(\rho)\rho p}U^{V2I}. \tag{4}$$

We define the V2I utility as the throughput of a vehicle that uses the V2I connection, weighted by the difference between the intrinsic value of the data and the price for using V2I connection. As mentioned before, the V2I bandwidth is defined as the channel capacity that is shared by the V2I users within a unit length. The V2I users consist of all real-time users, the V2V content users who encounter cache misses, and all V2I content users. The number of those three groups of V2I users in a unit length is, respectively, ρy, $\rho(1-y)me^{-2R(\rho)\rho p}$, and $\rho(1-y)(1-m)$. We assume that the V2I channel capacity is divided equitably among the V2I users. Denote the price charged for using the V2I connection by ν, then we have

$$U^{V2I} = \frac{(u-\nu)B}{\rho(y+(1-y)me^{-2R(\rho)\rho p}+(1-y)(1-m))}. \tag{5}$$

C. Communication Equilibrium

A real-time user can only choose V2I connection, while a content user chooses the communication mode (V2V or V2I) that has the higher utility. If both V2V connection and V2I connection are used by a non-empty set of content users, by Wardrop's first principle, the V2V utility and the V2I utility for the content users are equal at equilibrium, hence equating (5) and (4)

$$(1-e^{-2R(\rho)\rho p})U^h + e^{-2R(\rho)\rho p}U^{V2I} = U^{V2I}, \tag{6}$$

which yields

$$U^h = U^{V2I}. \tag{7}$$

We refer to this state as the communication equilibrium (CE). Therefore, at CE, the fraction of V2V content users is

$$(1-y)m = \frac{uW/(1-e^{-2R(\rho)\rho p})}{R(\rho)(u-\nu)B+uW}. \tag{8}$$

Substituting (8) into (3), then at CE we have

$$U^h = \big((u-\nu)B + \frac{uW}{R(\rho)}\big)\frac{1}{\rho}. \tag{9}$$

We assume that the fraction of real-time users and the fraction of the content users for every O-D pair are fixed. Let Y_i denote the fraction of the real-time users that travel between O-D pair $i \in N$, hence q_iY_i is the trip rate of real-time users, and $q_i(1-Y_i)$ is the trip rate of content users.

V. FLOW CONTROL VIA V2I BANDWIDTH ALLOCATION

In this section, we first introduce the route cost function, then we derive a formula that can be used for V2I bandwidth allocation. Finally, we propose a V2I bandwidth adjustment scheme to control the traffic flow.

We assume that the traditional travel cost is a non-decreasing function of the car density[4]**, and that the link cost is the weighted sum of the travel cost and the communication cost. Note that the travel cost is defined per link. If a driver enters a link, the travel cost may change only when he/she exists this link**. Denote the weight towards the travel cost by α. Denote the link cost of the real-time users, the V2V content users, and the V2I content users on link a by J_a^R, J_a^{CV}, and J_a^{CI} respectively. We have

$$\begin{cases} J_a^R = \alpha T_a(\rho_a) - (1-\alpha)U_a^{V2I} \\ J_a^{CV} = \alpha T_a(\rho_a) - (1-\alpha)U_a^{V2V} \\ J_a^{CI} = \alpha T_a(\rho_a) - (1-\alpha)U_a^{V2I} \end{cases}. \tag{10}$$

We define the route cost as the sum of the cost of the links along that route. The cost of route $k \in K_i$ for real-time users, V2V content users, and V2I content users are, respectively,

$$\begin{cases} \mathbb{J}_{i,k}^R = \sum_{a\in A} \delta_{i,k}(a) J_a^R \\ \mathbb{J}_{i,k}^{CV} = \sum_{a\in A} \delta_{i,k}(a) J_a^{CV} \\ \mathbb{J}_{i,k}^{CI} = \sum_{a\in A} \delta_{i,k}(a) J_a^{CI} \end{cases}. \tag{11}$$

We now derive a formula that can be used for V2I bandwidth allocation in a general network in order to change the car density from the current value to the desired value. We assume that there are non-empty set of real-time users and non-empty set of content users on each used route at equilibrium. Consider a used route $l \in N_i$ that connects the O-D pair $i \in N$, at UE and at CE, we have $U_{i,l}^{V2I} = U_{i,l}^{V2V} = U_{i,l}^h$. Therefore, the route cost $J_{k,i}$ at UE and at CE is

$$J_{i,l} = \alpha T_{i,l}(\rho_{i,l}) - (1-\alpha)U_{i,l}^h, \tag{12}$$

$$\text{or equivalently, } J_{i,l} = \alpha T_{i,l}(\rho_{i,l}) - (1-\alpha)U_{i,l}^{V2I}, \tag{13}$$

$$\text{or equivalently, } J_{i,l} = \alpha T_{i,l}(\rho_{i,l}) - (1-\alpha)U_{i,l}^{V2V}. \tag{14}$$

Consider a pair of any used route $k, l \in N_i$ that connects the same O-D pair $i \in N$, from Wardrop's first principle, the cost of route k and the cost of route l are the same at UE, i.e.

$$\alpha T_{i,k}(\rho_{i,k}) - (1-\alpha)U_{i,k}^h = \alpha Ti,l(\rho i,l) - (1-\alpha)U^h i,l. \tag{15}$$

Substituting the cache hit utility at CE (9) into (15) gives

$$\begin{aligned} \frac{B_{i,k}}{\rho_{i,k}} - \frac{B_{i,l}}{\rho_{i,l}} = & \frac{\alpha}{(1-\alpha)(u-\nu)}\big(T_{i,k}(\rho_{i,k}) - T_{i,l}(\rho_{i,l})\big) - \\ & \frac{uW}{u-\nu}\big(\frac{1}{R(\rho_{i,k})\rho_{i,k}} - \frac{1}{R(\rho_{i,l})\rho_{i,l}}\big). \end{aligned} \tag{16}$$

In order to analyze the users behavior in response to the adjustment of the V2I bandwidth, we now discuss how the users make route decisions and communication decisions. All users entering the network are presented with the travel costs and the V2I utilities. In addition, the content users are also presented with the V2V utilities. After observing the costs and utilities, the users choose which routes to take. After a V2V content user enters a certain route, he/she can switch to use V2I connection, thus becomes a V2I content user, and vice versa. Consider a network with two routes connecting a single O-D pair. For a route $k \in \{1,2\}$, let x_k^R, x_k^C, x_k^{CV}, and x_k^{CI} denote, respectively, the flow of real-time users who choose route k, the flow of content users who choose route k, the flow of the V2V content users on route k, and the flow of the V2I content users on route k. The flows of different user groups in this two-route network should satisfy

$$\begin{cases} qY = x_1^R + x_2^R, \quad q(1-Y) = x_1^C + x_2^C \\ x_1 = x_1^R + x_1^C, \quad x_2 = x_2^R + x_2^C \\ x_1^C = x_1^{CV} + x_2^{CI}, \quad x_2^C = x_2^{CV} + x_2^{CI} \end{cases}. \tag{17}$$

The V2I bandwidth adjustment scheme is stated as follows. The system operator can increase the car density on a route by increasing the V2I bandwidth of that route, given that the searching distance $R(\rho)$ is designed in such a way that $R(\rho)\rho$ is monotonically increasing w.r.t. ρ. Fig. 2 shows the dynamics of the two-route network when the V2I bandwidth on route 1 is increased, where LHS and RHS denotes the left hand side and the right hand side of (16). Since the actual shape of the dependencies are unknown, we use the dotted-lines to indicate the general shape of the changes. For ease of discussion, we divide the time into three intervals:

(i) The system is at UE, where the cost of route 1 is the same as the cost of route 2. The system is also at CE, where the LHS matches the RHS.
(ii) The system operator increases the V2I bandwidth on route 1 by ΔB, so there is a sudden increase in the V2I utility on route 1 and in the LHS. After observing this change, more real-time users choose route 1, and the car density on route 1 increases. As a result, the LHS gradually decreases. The change in the travel costs and in the searching distances lead to a gradual increase in the RHS.
(iii) The LHS matches the RHS. The system reaches a new UE state, where the car density on route 1 is higher than the original car density.

The effect of decreasing the V2I bandwidth can be analyzed in a similar manner.

VI. CASE STUDY

In this section, we present the numerical results of the flow control scheme proposed in Section V, which can provide insights into how the travel cost and the communication utility influence the users' behavior. We also discuss its performance in terms of the achievability of the SO and the speed of the convergence.

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[4] This is a common assumption in the study of transportation networks, e.g. [43], [6]

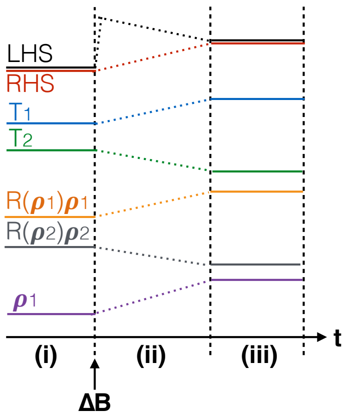

Fig. 2: Dynamics of a two-route network when the V2I bandwidth on route 1 is increased, given that the searching distance $R(\rho)$ is designed in such a way that $R(\rho)\rho$ is monotonically increasing w.r.t. ρ. The dotted-lines indicate the general shape of the changes.

We assume that the change in the flows is linear w.r.t. the difference in the corresponding costs. Specifically, we assume

$$\begin{cases} \frac{\partial}{\partial t}x_1^R(t) = a_1(J_2^{CI} - J_1^{CI}) \\ \frac{\partial}{\partial t}x_1^C(t) = a_2\big(\min\{J_2^{CI}, J_2^{CV}\} - \min\{J_1^{CI}, J_1^{CV}\}\big) \\ \frac{\partial}{\partial t}x_1^{CV}(t) = a_3(J_1^{CI} - J_1^{CV}) \\ \frac{\partial}{\partial t}x_2^{CV}(t) = a_4(J_2^{CI} - J_2^{CV}) \end{cases}, \tag{18}$$

where a_1, a_2, a_3, and a_4 are constant. The cost functions J_i^{CV} and J_i^{CI} are defined in (10). We solve for $x_1^R(t), x_1^C(t), x_1^{CV}(t)$, and $x_2^{CV}(t)$ over 500 s with the initial condition $x_1^R(0) = 100$vehs/h, $x_1^C(0) = 300$vehs/h, $x_1^{CV}(0) = 200$vehs/h, $x_2^{CV}(0) = 350$vehs/h. The SO can be computed as $x_1 = 816.3$vehs/h, $x_2 = 1183.7$vehs/h using any convex programming method. Initially, we have $x_1 = 400$vehs/h, $x_2 = 1600$vehs/h, so we need to increase the flow on route 1. At the beginning of the 200th second, we change the V2I bandwidth on route 1 from 3Mbps to 35Mbps.

We solve the system (18) using MatLab ode15s solver with the following parameters.

- $q = 2000$vehs/h, $Y = 0.5$.
  On average, there are 2000 vehicles entering the network every hour. Half of these 2000 vehs/h are driven by real-time users, and the other half are driven by content users.
- $\alpha = 0.3,\ p = 0.1,\ u = \$3,\ v = \$2, l_1 = 1200m,\ l_2 = 1000m.$
  The weight towards the travel cost is 0.3. A certain content is stored in the cache of a vehicle with probability 0.1. The intrinsic value of the data communication is 3 dollars, and the users are charged 2 dollars for using V2I connection. The length of route 1 and route 2 is 1200 meters and 1000 meters respectively.
- $T_1 = \frac{l_1}{v_1}(1 + \gamma(\frac{x_1}{P_1})^\beta),\ T_2 = \frac{l_2}{v_2}(1 + \gamma(\frac{x_1}{P_2})^\beta).$
  The travel time is assumed to follow the Bureau of Public Roads (BPR) function $T(x) = \frac{l}{v_{max}}(1 + \gamma(\frac{x}{P})^\beta)$, where v_{max} is the speed limit, and P is the capacity of a link. This BPR function is widely used in civil engineering [6]. We will use the same empirical parameters as in [6] hereinafter. Specifically, we set $v_1 = v_2 =$ 35mph (15.6464m/s), $\gamma = 0.2$, and $\beta = 10$. In order to simulate traffic congestion and avoid corner cases in Section VII, we set $P_1 = P_2 = 1500$vehs/h per lane.
- $R(\rho) = r = 907m.$
  We assume that the searching distance is the same as the one-hop communication range. In practice, the searching distance may be designed differently based on certain routing scheme or power control policy. Since we will use Veins simulator to validate our model in the next section, here we adopt the free space path loss formula used in Veins, and set transmit power to 20mW and sensitivity threshold to -94dBm, which results in a communication range of 907m.
- $W = 27Mbps, B_1 = 3Mbps, B_2 = 3Mbps.$
  Each vehicle can support 27Mbps of data traffic. The initial V2I bandwidth on route 1 and route 2 is 3Mbps and 3Mbps respectively. We will change B_1 from 3Mbps to 35Mbps at the 200th second in order to push the new UE closer to the SO.
- $a_1 = 1, a_2 = 1, a_3 = 100, a_4 = 100.$
  The real-time users only make route choice. The content users not only make route choice, they can also switch between communication modes while traveling. We assume that when there is a change in the route costs, the content users can switch between communication modes more rapidly than the incoming flow can make route choice. Therefore, we assign smaller values to a_1 and a_2 than to a_3 and a_4.

Fig. 3 and Fig. 4 shows, respectively, the flows of different user groups on route 1 and on route 2. The flows converge to UE after around 100 seconds. The V2I bandwidth on route 1 is changed from 3Mbps to 35Mbps at the 200th second, so there is a sudden increase in the V2I utility on route 1, which attracts more real-time users and V2I content users. Some V2V content users on route 1 also switch to V2I connection due to the higher V2I utility compared to the original V2V utility. As a result, the V2I utility on route 1 gradually decreases and the V2V utility on route 1 gradually increases. After around the 400th second, the system reaches to a new UE, where the flow on route 1 and on route 2 are around 820 vehs/h and 1180 vehs/h respectively (close to the SO), as shown in Fig. 5.

Fig. 6 shows that at UE and CE, the route costs of real-time users, V2I content users, and V2V content users are the same. At the 200th second, the increase of the V2I bandwidth on route 1 causes the sudden decrease of J_1^{CV} and J_1^R. After observing the difference in the route costs, the users adjust their route choice and communication modes, which leads to the convergence of the route costs after around the 400th second. This convergence is also shown in Fig. 7, where the LHS matches the RHS at UE and at CE. Fig. 8 shows that the system cost is significantly decreased after the changed of the V2I bandwidth on route 1.

We now analyze the performance of the proposed flow control scheme under different bandwidth changes, V2I price, and weights towards travel cost. The adjustment of the V2I bandwidth should be within a certain range due to the physical limitation of the V2I infrastructure. A small increase in the

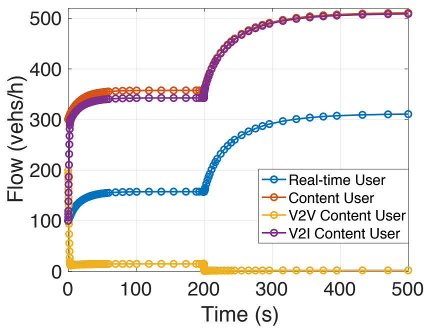

Fig. 3: Flows of different user groups on route 1.

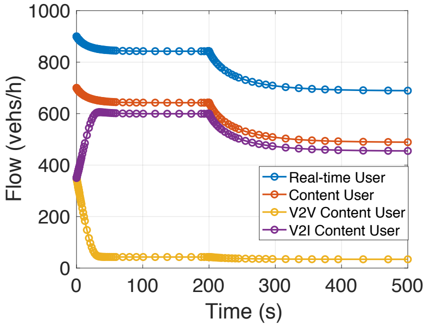

Fig. 4: Flows of different user groups on route 2.

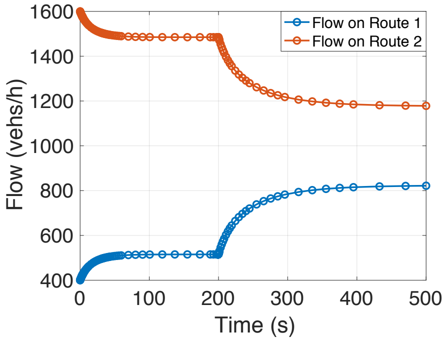

Fig. 5: Convergence of flows. The system reaches to the UE, which matches the SO, at around the 80th minute.

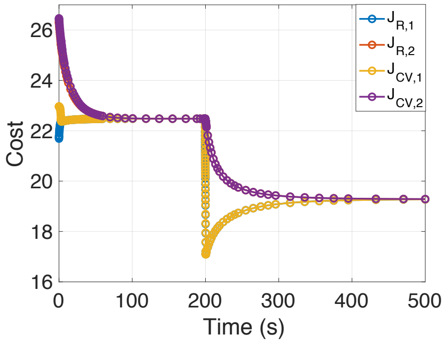

Fig. 6: Total cost of different user groups.

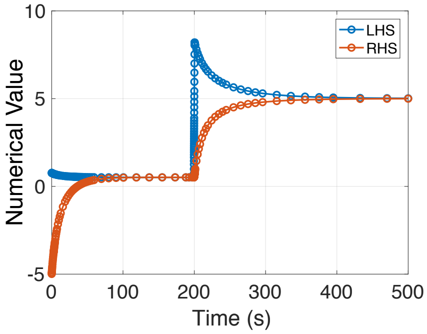

Fig. 7: LHS matches RHS at UE and at CE.

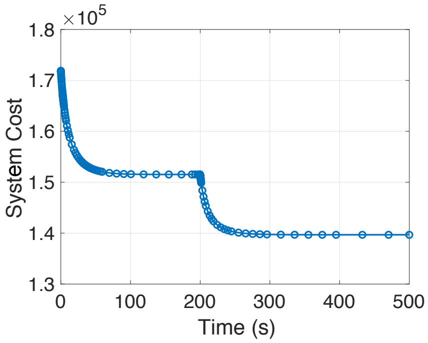

Fig. 8: System cost is significantly decreased after the V2I bandwidth on route 1 is increased from 3Mpbs to 24Mbps at the 200th second.

V2I bandwidth may not incite enough users to change route or communication modes. Similarly, as shown in Fig. 10 and Fig. 11, if the users are charged more for using V2I connection, or if the users are more concerned about travel cost than data communication, then they are more reluctant to change route choices or switch between communication modes when the V2I utility varies. In this case, a more complicated adjustment scheme can be adopted, for example, decreasing the V2I bandwidth of another route simultaneously. On the other hand, if the V2I bandwidth is increased too much, the high V2I utility may attract too many users to choose this route. In Fig. 9, we note that an increment of 16Mbps in the V2I bandwidth only pushes the flow on route 1 to around 600vehs/h, which is less than the flow at SO. A higher V2I bandwidth increment attracts more users to choose route 1, but may overshoot, as demonstrated by the yellow curve in Fig. 9. Similar effect can be observed when the users are charged less for using V2I connection, or if the users are less concerned about travel cost than data communication, as shown in Fig. 10 and in Fig. 11 respectively.

VII. SIMULATION RESULTS

In this Section, we first validate the proposed communication utility model by comparing the cache hit utility from the simulation with the V2I utility from the model at the communication equilibrium. Then we consider a two-route network and show that the system cost can be lowered by the proposed V2I bandwidth allocation scheme under **IEEE** 802.11p protocol. We use Veins[5] as the vehicular network

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[5] http://veins.car2x.org

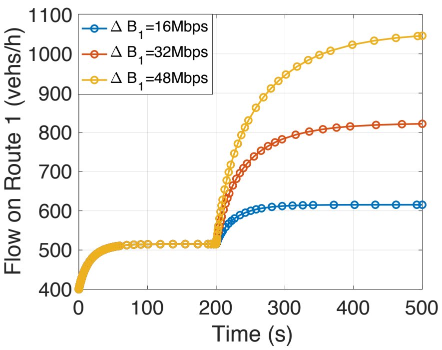

Fig. 9: Achievability of SO under different V2I bandwidth adjustment.

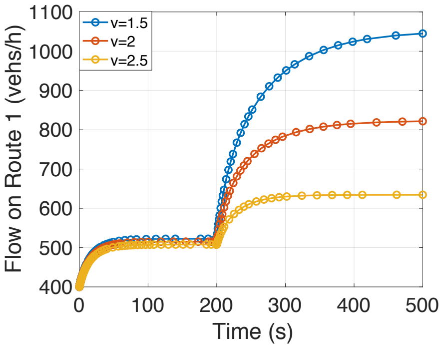

Fig. 10: Flow convergence under different price of V2I connection.

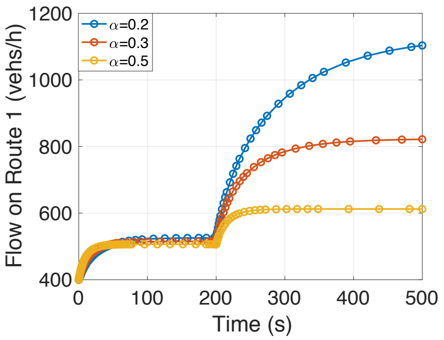

Fig. 11: Flow convergence under different weights towards the travel cost.

simulator. Veins is an open source framework based on the network simulator OMNeT++[6] and the road traffic simulator SUMO[7]. We use **IEEE** 802.11p protocol in the simulation, which is implemented in Veins and combined with the vehicular traffic simulations. **The reason that we rely on software simulation instead of a full scale real-world demonstration is that evaluation in real scenarios under a variety of traffic scenarios is not practically possible at this point, where the deployment of technologies for customized road-side units and cache-enabled vehicles is still in the emergent phase. Furthermore, since, up to our knowledge, there are no related works in the literature, we can not compare against any prior algorithm. Hence we focus on comparing between analytical results and realistic event-driven simulations that combine realistic vehicular traffic flow simulations with realistic wireless protocol simulation.**

A. Communication Cost

To validate the proposed model of the communication utility, we construct a simple network that has only one road with length 1000m. All vehicles enter the system from one end and leave the system at the other end. We use the empirical BPR function introduced in Section VI in the computation of the speed, which is then used to compute the traffic flow in the model. As discussed in Section IV-C, communication utility is different for different user groups, however at communication equilibrium, the cache hit utility and the V2I utility are the same (see Eq. (7)). In the simulation, we measure the cache hit throughput and use it to compute the cache hit utility. We record the flow of V2V content users in real time, which is then used to compute the V2I utility using Eq. (5). The cache hit ratio p is set to 0.1, and the communication range r is set to 360m. **The sensitivity is set to a non-zero value (-86dBm), which has a similar effect as interference. According to the documentation of OMNeT++, the sensitivity describes the minimum strength a signal must have to be received.** Other relevant parameters are shown in Table II. For each data point (i.e. flow), we average the throughput of 10 runs. In each run, we simulate the system for 500s with a warm-up period of 50s. As shown in the simulation result in Fig. 12, the V2I utility predicted by the proposed model generally matches the simulated cache hit utility. Since the proposed model is asymptotic, the predicted V2I utility fits the simulated cache hit utility better under larger traffic flows.

Parameter	Value	Parameter	Value
Transmission Power Content Size	20mW 256KB	Sensitivity Request Interval	-86dBm 1s

TABLE II: Relevant Parameters

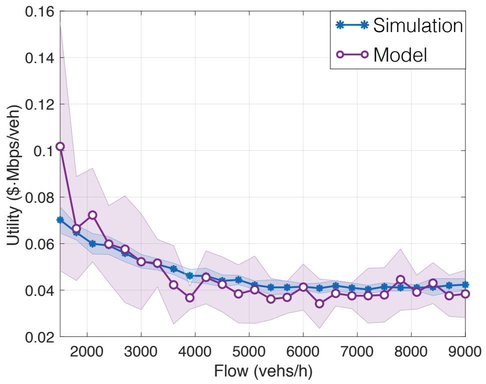

Fig. 12: Cache hit utility from Simulation v.s. V2I utility from model. The shaded area denotes the standard deviation of each data point.

B. V2I Bandwidth Allocation

In practice, the V2I bandwidth may only take certain values in vehicular communication networks. For example, in **IEEE** 802.11p the bandwidth can take eight different values. Therefore, in order to move the UE closer to the SO, the system operator can set the V2I bandwidth on a link to the next higher value under **IEEE** 802.11p protocol to encourage

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[6] https://omnetpp.org

[7] http://sumo.dlr.de/index.html

more users to travel on this link. In this section we show, via Veins simulation, that the system cost can be lowered when we change the V2I bandwidth allocation under **IEEE** 802.11p protocol. We use the same two-route network in Section VI, as shown in Fig. 13). When a vehicle enters the network, information on the current V2V throughput, V2I throughput, and the current travel time of both routes is provided. Then the user chooses the route with the smaller cost according to his/her user group (Eq. (11)). Real time throughput is computed by averaging the throughput recorded in the last 20s, and the current travel time can be obtained directly from the Veins simulator. Related parameters are the same as listed in Section VI, except for the V2I bandwidth on route 1. If the V2I bandwidth on both routes are 3Mbps, the UE state is $x_1 = 515, x_2 = 1485$, which can be read from Fig. 5. The system operator can push this UE state closer to SO by increasing the V2I bandwidth on route 1 in order to encourage more users to use route 1. We measure the system cost and the traffic flow under three different V2I bandwidth allocation policies: $\mathbf{b} = [6\ 3]^T$, $\mathbf{b} = [12\ 3]^T$, and $\mathbf{b} = [24\ 3]^T$ (with the unit of Mbps). As shown in Fig. 14, when $b_1 = 24Mbps$, the system cost is the lowest after around 300s. Therefore, if the flow on a link falls below the optimal value (e.g. 816.3 vehs/h on route 1 in this case), the system operator can increase the V2I bandwidth on this link to the next higher value under **IEEE** 802.11p protocol to attract more users, and vice versa.

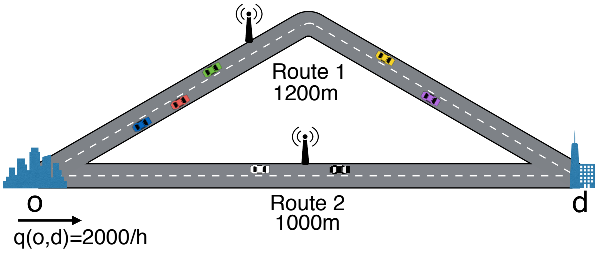

Fig. 13: Topology of the transportation network in the simulation.

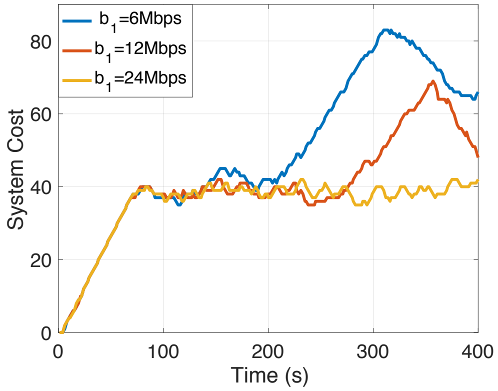

Fig. 14: System cost under different V2V bandwidth allocation policies. Bandwidth is specified according to **IEEE** 802.11p protocol.

VIII. CONCLUSION AND FUTURE WORK

In this paper, we model the user trip planning when both the traffic condition and the data communication influence user trip decision. A V2I bandwidth allocation scheme is proposed, which provides a guideline on how the system operator can adjust the network parameters to achieve the optimal social welfare even if the users are non-cooperative. We conducted a case study to show the dynamics when changing the V2I bandwidth. The proposed model is validated by Veins simulation under **IEEE** 802.11p protocol. The simulation results also show that the proposed scheme can lower the system cost even if the bandwidth allocation does not exactly match the optimal value.

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