Infrastructure Bandwidth Allocation for Social Welfare Maximization in Future Connected Autonomous Vehicular Networks

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ABSTRACT

Control of conventional transportation networks aims at bringing the state of the network to the *system optimal* (SO) state. This optimum is characterized by the minimality of the social cost function, i.e., the total cost of travel of all drivers. On the other hand, drivers are assumed to be rational and selfish, and make their travel decisions to optimize their own travel costs, bringing the state of the network to a *user equilibrium* (UE). In this paper, we model the behavior of users in the future connected vehicular transportation networks, where users consider both the travel cost and the utility from data communication when making their travel decisions. We divide the users into two groups based on the kind of data network they are using. We leverage the data communication aspect of the decision making to influence the user route choices, driving the UE state to the SO state. We propose a V2I bandwidth allocation scheme, which provides a guideline on how the system operator can adjust the parameters of the communication network to achieve the optimal UE.

KEYWORDS

traffic control; vehicular communication networks; system optimal; user equilibrium

1 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). Similar behavior in vehicular networks has been recently discussed in [13], where the attainable data rate is regarded as a principal metric in route selection of (human) drivers. 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 [3, 29]. 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 [6, 27]. The ratio between the social costs at UE and at SO is called the *price of anarchy* (PoA) [34].

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 [23] 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

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

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 [29]. 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 [21] and our submitted paper [22], 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 3 and Section 4, 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 5, we propose a V2I bandwidth allocation scheme in a two-route network 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 6, 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.

The remainder of this paper is organized as follows. In Section 2 we review the related work on the data communication and user behavior in vehicular communication networks. In Section 3 we divide the users into real-time user group and content user group, and present the model of the vehicular communication network. In Section 4 we model the communication utilities of different user groups, and characterize the communication equilibrium. In Section 5 we derive the relationship between the V2I bandwidth and the traffic car density at UE in a two-route 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 6. We conclude our work and discuss future extensions in Section 7.

2 RELATED WORK

Enhancing the transportation network via communication network capabilities enables a wide range of applications [14, 33], for example, interactive entertainment, urban sensing [9], collision avoidance in platoon formation [5], improving the intersection capacity via platoons [19] and via learning of congestion levels if vehicles communicate heterogeneously [35]. A wealth of research focuses on vehicle-to-vehicle (V2V) communication [32] in the transportation networks. [26] presents the network-layer V2V connectivity requirements in one-way and two-way street scenarios. In the two-way street scenario, the store-carry-forward routing model is used, where the packets are relayed by the vehicles moving in the opposite direction. A physical-layer perspective is considered in [26] which quantifies the maximum number of hops that ensure a desired bit error rate in the V2V communication. Vehicle-to-infrastructure (V2I) communication is an alternative to the V2V communication, which is also well studied in a variety of context. For example, [13] adopts the cognitive radio technology where the vehicles are the secondary users and the TV base stations are the primary users. Data rate is taken into consideration for route selecting. It provides a guideline on which spectrum sharing mode to use based on the intensity of TV base stations. [30] demonstrates a V2I-based identification system that pairs vehicles with multi-lane service stations, where transactions are made within the vehicles electronically. Considering both V2I and V2V communication, [24] studies the throughput upper bound by applying the max-flow algorithm on a time-expanded graph given the mobility trace.

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. Hierarchical caching and cache invalidation algorithms have been considered in [18] by keeping track of the location of vehicles and sending updated information of cached files to a more targeted area, instead of broadcasting. A fully distributed caching strategy is proposed in [10] using IEEE 802.11 promiscuous mode. Only the querying node can cache the queried content with the objective of differentiating its own cache from the others. Based on the information obtained from the overhearing, every vehicle's caching decision is made independently of each other. [2] studies the probability of outage under the freeway mobility model and under the random mobility model in a cooperative caching system. The outage is defined as not finding a requested data at neighboring nodes within a certain time period. It concludes that cooperative caching in a structured vehicular mobility creates an ample opportunity for improvement in outage over random mobility.

It is expected that CAV users' needs for and valuation of data service vary based on their socioeconomic characteristics and trip-related features. There is wealthy literature 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 [7], fuel costs [31], congestion level [1], reliability [20], land use [8], to advanced traveler information system [17]. 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 [16], user prior experience and habits [15], social influence [12], perceived monetary value, among others. In a recent literature review, [28] 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.

3 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 1.

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
v	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 1: 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 connect 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, for example video conference, 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. 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.

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[2] Similar distance-limited model is used in [25]

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 [11], i.e., when a vehicle is sending data via the V2V channel, all other vehicles inside its transmission range cannot send data. Therefore, 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.

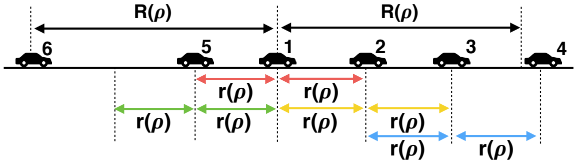

Figure 1: Part of the vehicular communication network on a link.

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, 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 to illustrate this point, we assume that the bandwidth can be adjusted by units of 10Mbps per unit of flow throughout the remainder of the sections.

4 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 4.3.

4.1 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 $\frac{\rho l(1-y)m(1-e^{-2R(\rho)\rho p})\lambda(\rho)R(\rho)/r(\rho)}{W} \le \frac{l}{2r(\rho)}$, which gives

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

Since $O(\frac{W}{R(\rho)\rho(1-y)m(1-e^{-2R(\rho)\rho p})})$ is achievable according to [25], we use the actual quantity (subject to a constant) to define the cache hit utility. Therefore, the cache hit utility is given by

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

4.2 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 v, then we have

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[3] This cache hit probability is also derived in [4]

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

4.3 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

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

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

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

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 $q_i Y_i$ is the trip rate of real-time users, and $q_i(1 - Y_i)$ is the trip rate of content users.

5 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 in a network of two routes, each consisting of one link. Finally, we propose a V2I bandwidth adjustment scheme to control the traffic flow in the two-route network.

We assume that the travel cost is a non-decreasing function of the car density, and that the link cost is the weighted sum of the travel cost and the communication cost. 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 two-route network in order to change the car density from the current value to the desired value. Consider a two-route network that has one O-D pair connected by two non-overlapping routes, each of which consists of one road segment. For the ease of discussion, we do not distinguish between "route" and "link" in this simple two-route network, and we use J_a to denote both the route cost and the link cost, where $a \in \{1, 2\}$. We assume that there are non-empty set of real-time users and non-empty set of content users on each route at equilibrium. The flow conservation constraints in terms of user groups in this network is given by

$$qY = y_1 x_1 + y_2 x_2. \tag{12}$$

At UE and at CE, $U^{V2I} = U^{V2V} = U^h$. Therefore, the route cost J_a at UE and at CE is

$$J_a = \alpha T_a(\rho_a) - (1-\alpha)U_a^h, \tag{13}$$

$$\text{or equivalently, } J_a = \alpha T_a(\rho_a) - (1-\alpha)U_a^{V2I}, \tag{14}$$

$$\text{or equivalently, } J_a = \alpha T_a(\rho_a) - (1-\alpha)U_a^{V2V}. \tag{15}$$

From Wardrop's first principle, the cost of route 1 and the cost of route 2 are the same at UE, i.e.

$$\alpha T_1(\rho_1) - (1-\alpha)U_1^h = \alpha T_2(\rho_2) - (1-\alpha)U_2^h. \tag{16}$$

Substituting the cache hit utility at CE (9) into (16) gives

$$\begin{aligned} \frac{B_1}{\rho_1} - \frac{B_2}{\rho_2} =& \frac{\alpha}{(1-\alpha)(u-v)}\Big(T_1(\rho_1) - T_2(\rho_2)\Big) - \\ & \frac{uW}{u-v}\Big(\frac{1}{R(\rho_1)\rho_1} - \frac{1}{R(\rho_2)\rho_2}\Big). \end{aligned} \tag{17}$$

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. 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

$$\begin{cases} qY = x_1^R + x_2^R, \;\; q(1-Y) = x_1^C + x_2^C \\ x_1 = x_1^R + x_1^C, \;\; x_2 = x_2^R + x_2^C \\ x_1^C = x_1^{CV} + x_2^{CI}, \;\; x_2^C = x_2^{CV} + x_2^{CI} \end{cases}. \tag{18}$$

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 (17). 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.

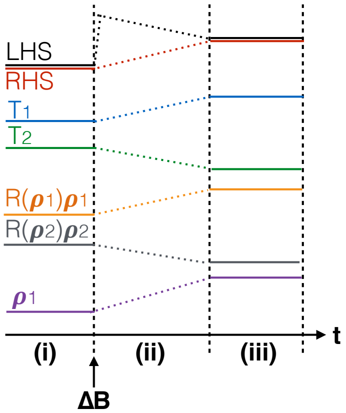

Figure 2: Dynamics of a two-route network when the V2I bandwidth on route 1 is increased, given that the searching distance $R(\rho)$ is designed in such a way that $R(\rho)\rho$ is monotonically increasing w.r.t. ρ. The dotted-lines indicate the general shape of the changes.

6 NUMERICAL RESULTS

In this section, we present the numerical results of the flow control scheme proposed in Section 5, 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. We assume that the change in the flows is linear w.r.t. the difference in the corresponding costs. Specifically, we assume

$$\begin{cases} \frac{\partial}{\partial t}x_1^R(t) = a_1(J_2^{CI} - J_1^{CI}) \\ \frac{\partial}{\partial t}x_1^C(t) = a_2\big(\min\{J_2^{CI}, J_2^{CV}\} - min\{J_1^{CI}, J_1^{CV}\}\big) \\ \frac{\partial}{\partial t}x_1^{CV}(t) = a_3(J_1^{CI} - J_1^{CV}) \\ \frac{\partial}{\partial t}x_2^{CV}(t) = a_4(J_2^{CI} - J_2^{CV}) \end{cases}, \qquad (19)$$

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 100 minutes with the initial condition $x_1^R(0) = 20/min$, $x_1^C(0) = 30/min$, $x_1^{CV}(0) = 15/min$, $x_2^{CV}(0) = 10/min$. The SO can be computed as $x_1 = 60/min$, $x_2 = 40/min$. Initially, we have $x_1 = 50/min$, $x_2 = 50/min$, so we need to increase the flow on route 1. At the beginning of the 50th minute, we change the V2I bandwidth on route 1 from 50Mbps to 60Mbps.

We solve the system (19) using MatLab ode15s solver with the following parameters.

- $q = 100/min, Y = 0.5$
  Explanation: On average, there are 100 vehicles entering the network every minute. Half of these 100 vehicles are driven by real-time users, and the other half are driven by content users.
- $\alpha = 0.6,\ p = 0.01,\ u = \$2,\ v = \$1.5, l_1 = 1200m,\ l_2 = 1000m$
  Explanation: The weight towards the travel cost is 0.6. A certain content is stored in the cache of a vehicle with probability 0.01. The intrinsic value of the data communication is 2 dollars, and the users are charged 1.5 dollars for using V2I connection. The length of route 1 and route 2 is 1200 meters and 1000 meters respectively.
- $T_1 = \frac{x_1}{600}h,\ T_2 = \frac{x_2}{400}h$
  Explanation: We adopt the travel time as the travel cost. It is known that traffic flow is the product of car density and the average speed, i.e. $x_a = \rho_a \frac{l_a}{T_a}$. Therefore, we have $T_1(\rho_1) = \sqrt{\frac{\rho_1 l_1}{600}}h,\ T_2(\rho_2) = \sqrt{\frac{\rho_2 l_2}{400}}h$. This is a simplified model, whereas in practice, the travel time is a more complicated function of the traffic flow.
- $R(\rho) = \frac{10}{\rho^{0.9}}m$
  Explanation: We assume that $R(\rho)\rho$ is non-decreasing w.r.t. ρ. Given the above design, the searching distance ranges from 10 meters to around 80 meters. In practice, the searching distance may be designed differently based on certain routing scheme or power control policy.
- $W = 40Mbps, B_1 = 50Mbps, B_2 = 48Mbps$
  Explanation: Each vehicle can support 40Mbps of data traffic. The initial V2I bandwidth on route 1 and route 2 is 50Mbps and 48Mbps respectively.
- $a_1 = 0.001, a_2 = 0.001, a_3 = 0.01, a_4 = 0.01$
  Explanation: 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 around the 20th minute. The V2I bandwidth on route 1 is changed from 50Mbps to 60Mbps at the 50th minute, 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 80th minute, the system reaches to a new UE, where the flow on route 1 and on route 2 are 60/min and 40/min respectively, 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 50th minute, 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 80th minute. This convergence is also shown in Fig. 7, where the LHS matches the RHS at UE and at CE.

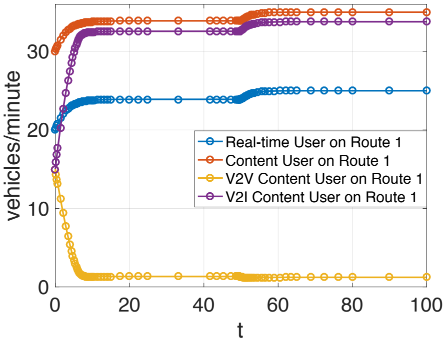

Figure 3: Flows of different user groups on route 1.

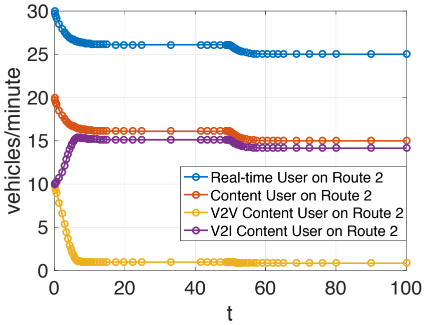

Figure 4: Flows of different user groups on route 2.

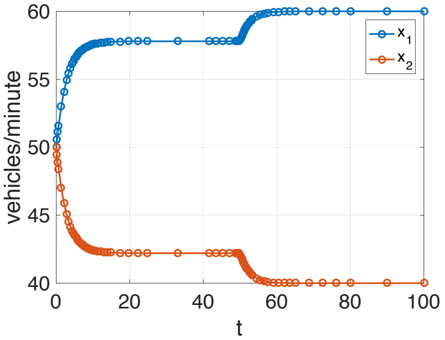

Figure 5: Convergence of flows. The system reaches to the UE, which matches the SO, at around the 80th minute.

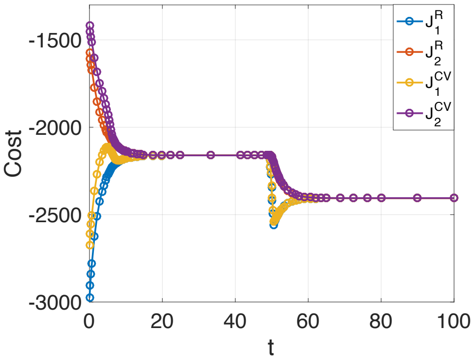

Figure 6: Total cost of different user groups.

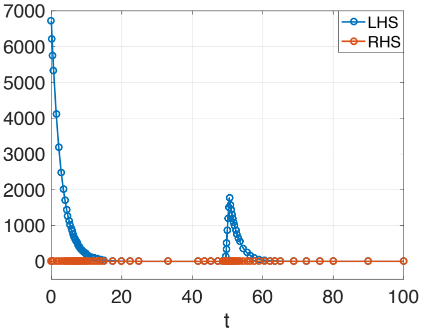

Figure 7: LHS matches RHS at UE and at CE.

We now analyze the performance of the proposed flow control scheme in terms of the achievability of the SO state and the speed of flow convergence. 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 V2I bandwidth may not incite enough users to change route or communication modes. 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. 8, we note that an increment of 5Mbps in the V2I bandwidth only pushes the flow on route 1 to 59/minute, 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. 8.

The speed of flow convergence depends on a variety of parameters. Fig. 9 and Fig. 10 show, respectively, the effect of the price of V2I connection and the effect of the weight towards the travel cost on the speed of convergence. 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. Since less users make a change in a unit time, it takes longer for the system to converge to the new UE.

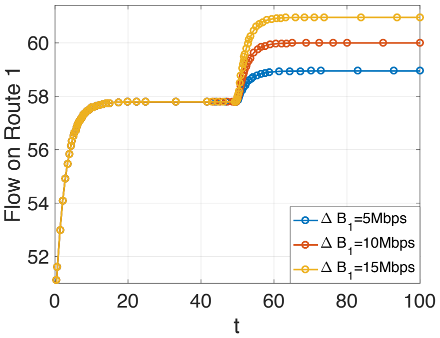

Figure 8: Achievability of SO under different V2I bandwidth adjustment.

7 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 for a two-route network, which provides a guideline on how the system operator can adjust the network parameters to achieve the optimal social

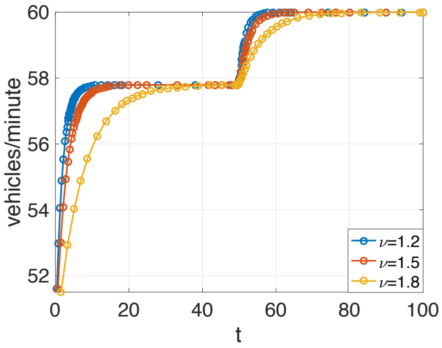

Figure 9: Flow convergence under different price of V2I connection.

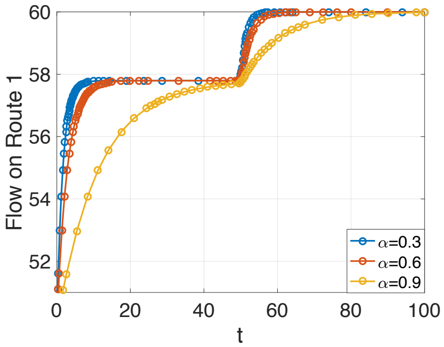

Figure 10: Flow convergence under different weights towards the travel cost.

welfare even if the users are non-cooperative. There are a number of open problems in this work. While the proposed scheme can be applied to a two-route network, its performance in a more complex network will be further studied. The existing V2I infrastructure may only allow a limited bandwidth adjustment, so the UE may never match the SO. Therefore, the solution region needs deeper analysis. Moreover, the convergence of the traffic flow in real world networks using the proposed scheme warrants further investigation.

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REFERENCES

[1] Haitham M Al-Deek, Asad J Khattak, and Paramsothy Thananjeyan. 1998. A combined traveler behavior and system performance model with advanced traveler information systems. *Transportation Research Part A: Policy and Practice* 32, 7 (1998), 479–493.

[2] Osama Attia and Tamer A. ElBatt. 2012. On the Role of Vehicular Mobility in Cooperative Content Caching. *CoRR* abs/1203.0657 (2012), 350–354.

[3] M. J. Beckman, C. B. McGuire, and C. B. Winsten. 1956. *Studies in the Economics of Transportation.* Yale University Press.

[4] Chaoyi Bian, Tong Zhao, Xiaoming Li, Xiaojiang Du, and Wei Yan. 2016. Theoretical analysis on caching effects in urban vehicular ad hoc networks. *Wireless Communications and Mobile Computing* 16 (Sept. 2016), 1759–1772. Issue 13. https://doi.org/10.1002/wcm.2651

[5] S. Biswas, R. Tatchikou, and F. Dion. 2006. Vehicle-to-vehicle wireless communication protocols for enhancing highway traffic safety. *IEEE Communications Magazine* 44, 1 (2006), 74–82.

[6] D. Braess, A. Nagurney, and T. Wakolbinger. 2005. On a Paradox of Traffic Planning. *Transportation Science* 39, 4 (2005), 446–450.

[7] Mark W Burris and Ram M Pendyala. 2002. Discrete choice models of traveler participation in differential time of day pricing programs. *Transport Policy* 9, 3 (2002), 241–251.

[8] Xinyu Cao and Daniel Chatman. 2016. How will smart growth land-use policies affect travel? A theoretical discussion on the importance of residential sorting. *Environment and Planning B: Planning and Design* 43, 1 (2016), 58–73.

[9] Felipe Domingos Da Cunha, Azzedine Boukerche, Leandro Villas, Aline Carneiro Viana, and Antonio AF Loureiro. 2014. *Data communication in VANETs: a survey, challenges and applications.* Ph.D. Dissertation. INRIA Saclay; INRIA.

[10] Marco Fiore, Francesco Mininni, Claudio Casetti, and Carla-Fabiana Chiasserini. 2009. To cache or not to cache?. In *INFOCOM 2009, IEEE.* 235–243.

[11] P. Gupta and P. R. Kumar. 2000. The capacity of wireless networks. *IEEE Transactions on Information Theory* 46, 2 (Mar 2000), 388–404. https://doi.org/10.1109/18.825799

[12] Se-Joon Hong, James YL Thong, Jae-Yun Moon, and Kar-Yan Tam. 2008. Understanding the behavior of mobile data services consumers. *Information Systems Frontiers* 10, 4 (2008), 431–445.

[13] Chunxiao Jiang, Yan Chen, and KJ Ray Liu. 2014. Data-driven optimal throughput analysis for route selection in cognitive vehicular networks. *Selected Areas in Communications, IEEE Journal on* 32, 11 (2014), 2149–2162.

[14] Kamini Kamini and Rakesh Kumar. 2010. Vanet parameters and applications: A review. *Global Journal of Computer Science and Technology* 10, 7 (2010).

[15] Byoungsoo Kim. 2012. The diffusion of mobile data services and applications: Exploring the role of habit and its antecedents. *Telecommunications Policy* 36, 1 (2012), 69–81.

[16] Byoungsoo Kim, Minnseok Choi, and Ingoo Han. 2009. User behaviors toward mobile data services: The role of perceived fee and prior experience. *Expert Systems with Applications* 36, 4 (2009), 8528–8536.

[17] David Levinson. 2003. The value of advanced traveler information systems for route choice. *Transportation Research Part C: Emerging Technologies* 11, 1 (2003), 75–87.

[18] Sunho Lim, Soo Hoan Chae, Chansu Yu, and Chita R Das. 2008. On cache invalidation for internet-based vehicular ad hoc networks. In *Mobile Ad Hoc and Sensor Systems (MASS), 2008, 5th IEEE International Conference on.* 712–717.

[19] Jennie Lioris, Ramtin Pedarsani, Fatma Yildiz Tascikaraoglu, and Pravin Varaiya. 2017. Platoons of connected vehicles can double throughput in urban roads. *Transportation Research Part C: Emerging Technologies* 77 (April 2017), 292–305.

[20] Henry X Liu, Will Recker, and Anthony Chen. 2004. Uncovering the contribution of travel time reliability to dynamic route choice using real-time loop data. *Transportation Research Part A: Policy and Practice* 38, 6 (2004), 435–453.

[21] Teng Liu, A. Alhussein Abouzeid, and A. Agung Julius. 2017. Traffic Control in Vehicular Communication Networks.. In *American Control Conference.*

[22] Teng Liu, A. Alhussein Abouzeid, and A. Agung Julius. 2017. Traffic Flow Control in Vehicular Communication Networks. *Submitted to IEEE Transaction on Mobile Computing* (2017).

[23] Nicholas Loulloudes, George Pallis, and Marios Dikaiakos. 2010. Caching dynamic information in vehicular ad hoc networks. *Euro-Par 2010-Parallel Processing* (2010), 516–527.

[24] F. Malandrino, C. Casetti, C. F. Chiasserini, and M. Fiore. 2013. Optimal Content Downloading in Vehicular Networks. *IEEE Transactions on Mobile Computing* 12, 7 (July 2013), 1377–1391. https://doi.org/10.1109/TMC.2012.115

[25] M. Nekoui, A. Eslami, and H. Pishro-Nik. 2008. Scaling Laws for Distance Limited Communications in Vehicular Ad Hoc Networks. In *2008 IEEE International Conference on Communications.* 2253–2257. https://doi.org/10.1109/ICC.2008.430

[26] Sooksan Panichpapiboon and Wasan Pattara-Atikom. 2008. Connectivity requirements for self-organizing traffic information systems. *Vehicular Technology, IEEE Transactions on* 57, 6 (2008), 3333–3340.

[27] T. Roughgarden and E. Tardos. 2002. How bad is selfish routing? *J. ACM* 49, 2 (2002), 236–259.

[28] Aijaz A Shaikh and Heikki Karjaluoto. 2015. Making the most of information technology & systems usage: A literature review, framework and future research agenda. *Computers in Human Behavior* 49 (2015), 541–566.

[29] Yosef Sheffi. 1985. Urban transportation network. *Pretince Hall* (1985).

[30] Gopi Krishna Tummala, Derrick Cobb, Prasun Sinha, and Rajiv Ramnath. 2016. Soft-swipe: Enabling High-accuracy Pairing of Vehicles to Lanes Using COTS Technology. In *Proceedings of the First ACM International Workshop on Smart, Autonomous, and Connected Vehicular Systems and Services (CarSys '16).* 62–63.

[31] Claude Weis, Kay Axhausen, Robert Schlich, and René Zbinden. 2010. Models of mode choice and mobility tool ownership beyond 2008 fuel prices. *Transportation Research Record: Journal of the Transportation Research Board* 2157 (2010), 86–94.

[32] T. L. Wilke, T. Patcharinee, and N. F. Maxemchuk. 2009. A survey of inter-vehicle communication protocols and their applications. *IEEE Communications Surveys and Tutorials* 11, 2 (2009), 3–20.

[33] J. Yao, S. S. Kanhere, and M. Hassan. 2012. Improving QoS in High-Speed Mobility Using Bandwidth Maps. *IEEE Transactions on Mobile Computing* 11, 4 (April 2012), 603–617. https://doi.org/10.1109/TMC.2011.97

[34] H. Youn, M. T. Gastner, and H. Jeong. 2008. Price of Anarchy in Transportation Networks: Efficiency and Optimality Control. *Physics Review Letters* 101, 12 (2008), 128701.

[35] Shanyu Zhou and Hulya Seferoglu. 2016. Connectivity-aware Traffic Phase Scheduling for Heterogeneously Connected Vehicles. In *Proceedings of the First ACM International Workshop on Smart, Autonomous, and Connected Vehicular Systems and Services (CarSys '16).* 44–51.