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Emerging Applications for Cyber Transportation Systems

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Abstract Recent advances in connected vehicles and autonomous driving are going to change the face of ground transportation as we know it. This paper describes the design and evaluation of several emerging applications for such a cyber transportation system (CTS). These applications have been designed using holistic approaches, which consider the unique roles played by the human drivers, the transportation system, and the communication network. They can improve driver safety and provide on-road infotainment. They can also improve transportation operations and efficiency, thereby benefiting travelers and attracting investment from both government agencies and private businesses to deploy infrastructures and bootstrap the evolutionary process of CTS.

Keywords emerging technology, application, algorithm/protocol design and analysis, cyber transportation system

1 Introduction

Connected vehicles and autonomous driving have been rapidly gaining momentum in recent years. The next generation transportation system using these cyber technologies, which we call cyber transportation systems (CTS), can potentially result in significant improvements in safety, transportation efficiency, and on-road entertainment. Past research has focused independently on different aspects of CTS such as vehicular communications[1], transportation operations, and efficiency[2-3]. These efforts have resulted in features such as lane departure warning, blind spot monitoring, automated parking, and adaptive cruise control, in a number of high-end cars, as well as traffic monitoring, video vehicle detection, and other electronic sensors on the road today. These applications, however, represent just the beginning of the CTS era. Advanced research projects, such as the US DOT's SafetyPilot[4] and Google's self-driving car[5], hold a lot of promises for connected vehicles and autonomous driving. However, in order to facilitate the adoption and fully realize the potentials of the advanced technologies, we need to take a more holistic approach that considers multiple aspects of the CTS, including human-factors (or user experience)[6-7] and economics (or the business models).

In this work, we introduce a number of different connected vehicle applications that aim at providing safety warnings or alert messages to drivers, infotainment (a portmanteau of information and entertainment) like video streaming, and advertisement delivery. In addition, we will also describe applications geared towards improving transportation operations and efficiency via efficient carpooling and taxi dispatching, which can not only provide incentives for the government agencies and

Survey

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businesses to invest in the connected vehicle technologies, but also help travelers.

We will begin with a detailed discussion of an application that focuses on on-road safety by efficiently delivering warnings or other alert messages to drivers in Section 2. We consider a number of human factors (HFs) aspects such as message processing delay, reaction delay, and information overload (which results in lost messages) in our approach. Based on these models, we propose a number of strategies to maximize the usefulness of the messages that are finally delivered to the driver.

Section 3 will look at an infotainment service that delivers streaming video from the Internet to vehicles using a heterogeneous network consisting of both Wi-Fi access points and the cellular network (3G/4G). Here we will examine how to provide travelers with a good (and fair) quality of experience with limited coverage of Wi-Fi access points (APs) and limited cellular data usage by minimizing factors such as initial buffering delay and playback interruptions.

Next, in Section 4, we will describe an on-road "for-sale advertisements" (or Ads for short) delivery service which considers commuters' route and shopping preferences, with the objective being to schedule an appropriate subset of Ads for transmission such that given a limited communication bandwidth, the possibility of attracting the commuters to go shopping along their ways is maximized.

We will look at a new taxi dispatch service and rideshare service in Section 5; like the previous on-road video streaming and Ads delivery services, these aforementioned applications will not only benefit the travelers, but also cater to the needs of emerging business and service providers. In addition, some of these applications can improve the sustainability and efficiency of the transportation system by reducing congestion and delays (resulting in less fuel consumption and emission), thereby providing strong incentives for government and private businesses to invest in the infrastructure and technologies needed to deploy connected vehicles.

Finally, Section 6 summarizes our findings and concludes the paper.

2 Human Factors Aware Service Scheduling

Human drivers will continue to play a key role in connected vehicle systems in the foreseeable future. Previous human factors (HFs) research has examined the effects of various components ranging from road signage to different types of warning messages on drivers[6]. The work in [8] studied the effects of audio alerts on perceived importance and annoyance. Researchers have also looked at driver overload under multiple tasks and examined methods dealing with driver distraction[9-11]. Additionally, message priorities have been proposed for vehicular messages, with the Society of Automotive Engineers (SAE) standard proposing static priorities[12] and Sohn *et al.* making a case for real-time situation-based dynamic priorities[13]. However, not much work has considered HFs in the context of connected vehicles. In this section, we will examine ways of delivering services (such as warning messages from on-board vehicular safety applications) to human drivers in an efficient manner.

2.1 Introduction to Service Delivery

Traditionally, Vehicular Ad Hoc Network (VANET) research has focused on addressing V2V/V2I communication issues that have very little to do with human drivers. However, when delivering safety or alert messages, any delay due to either wireless communication or information overload to the human drivers might lead to serious injury or even loss of life. Therefore, it is important to address HFs in such service delivery.

We model the driver's interaction with the vehicular on-board system based on prior research on HFs. [14] explores how information processing in the human brain could be simulated by a queuing network with perceptual (visual/auditory processing), cognitive (modeling the central executive) and motor sub-networks (sending instruction to the relevant body parts). Each sub-network is responsible for its specific task and requires a certain amount of processing time. Using this study as a guideline, we model our service delivery as a three-step process as shown in Fig.1(a) which includes 1) sending a service from the service provider (or sender) to the driver (or receiver), 2) the driver's processing of the message, and 3) the driver's response to the message via the appropriate actions. Each of these steps requires a certain amount of time and must be performed with little to no distraction in order to successfully utilize the service. For example, a driver who is driving without any distraction is assigned the IDLE state. A vehicle in front of the driver notices an obstacle on the road and engages its brakes, sending a hard braking warning message to the vehicles around it. When the driver receives this message, his/her state switches to BUSY1 as he/she attempts to understand the contents of the message. On determining an appropriate response such as slowing down and switching the lane, the driver's state switches to BUSY2 as he/she responds to the situation and finally returns back to IDLE after completing his/her task. Note that disrupting the driver in either BUSY1 or BUSY2 will either cause him/her to get confused and might impact the timeliness and quality of his/her response. We assume that it takes a time slot to move between any two states. Using this framework for service utilization, we can now define a family of HF-aware Service Scheduling (HFSS) problems that focus on successfully delivering such services.

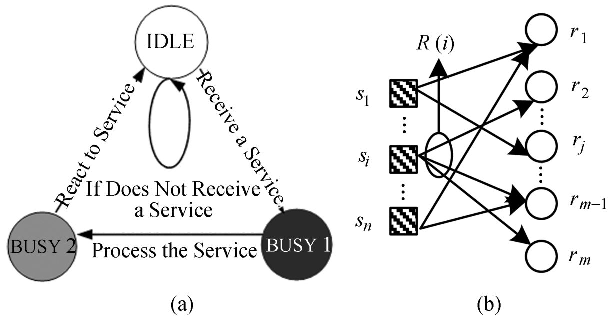

Fig.1. (a) Services delivery process. (b) Service senders and receivers.

Before moving ahead, we would like to note that different types of HF-based models need to be developed for connected vehicles based on the nature of the services that we wish to provide. In the following subsection, we will focus primarily on safety-oriented services. In such situations, ensuring the safety of the road users is paramount and we must focus on the quality and timing of the human driver's responses to our service. For infotainment applications (e.g., video delivery), on the other hand, our focus will be on the quality of the services and user experiences rather than the driver's response time and reactions.

2.2 HF-Aware Service Scheduling Family of Problems

As shown in Fig.1(a), a service must go through each of the three steps defined above in order to be useful. We assign a utility value to each service that is received successfully. More formally, we define the utility of a service i as a non-increasing utility function of the time slot t as:

$$\mu(i,\, t) = C_i \text{ if } 1 \leqslant t \leqslant n, \quad \text{and 0 otherwise,} \qquad (1)$$

where C_i is a positive integer ranging in $[1, C]$, and C is the upper bound of service utility.

Note that during the service delivery process, a number of things might go wrong: a service might be delayed, thereby decreasing its effectiveness; multiple services might arrive at the same time and collide; a driver might already be busy responding to a previous service and might not be able to focus on the new service. Accordingly, we model the losses in utility due to such processes as delay-induced, collision-induced, and driver-induced utility losses respectively.

Definition 1 (Type 1 Utility Loss (UL_1)). *To simplify our presentation, we refer to the driver-induced utility loss as type* 1 *or* UL_1. *We define* $UL_1(i,j,t) = \mu(i,t) = C_i$ *if the sender sends a service* s_i *to receiver* $r_j \in R(i)$ *during time slot* t, *while* r_j *is in either of the two BUSY states; otherwise,* $UL_1(i,j,t) = 0$ (*refer to Fig.*1(*b*)).

We also define the total utility loss (TUL) as the sum total of all individual UL_1 losses as:

$$TUL = \sum_{i=1}^{n}\sum_{t=1}^{n}\sum_{j\in R(i)} UL_1(i,j,t). \qquad (2)$$

Based on (1) and (2), we can now formally define the basic version of our problem in which we will only consider type 1 utility loss.

Definition 2 (Basic HF-Aware Service Scheduling Problem (BHFSSP)). *Assuming a single sender and* (1), *find a service schedule to minimize TUL* (*solely considering* UL_1).

Note that the timeliness of the service is not considered in this version of the problem. We study its effects in the next problem, which we refer to as Time-Variant HFSS problem (THFSSP). More specifically, the non-increasing utility function assumed in THFSSP is modeled as:

$$\mu(i,t) \geqslant \mu(i,t') \geqslant 0 \text{ for } 1 \leqslant t \leqslant t' \leqslant n \text{ and } \mu(i,1) = C_i. \qquad (3)$$

Accordingly, we can define a type 2 UL (corresponding to a time-induced utility loss).

Definition 3 (Type 2 Utility Loss (UL_2)). *We define* $UL_2(i,j,t) = C_i - \mu(i,t)$ *if and only if the sender sends a service* s_i *to receiver* $r_j \in R(i)$ (*and possibly other receivers*) *during time slot* t, *while* r_j *is in the IDLE state.*

Note that if r_j is in one of the two BUSY states, we will model the loss as UL_1 $(i,j,t) = C_i$ instead. We can now redefine TUL to include UL_1 and UL_2, similar to (2). We thus have:

Definition 4 (Time-Variant HF-Aware Service Scheduling Problem (THFSSP)). *Assuming a single sender and* (3), *find a service schedule so that TUL can be minimized* (*considering both* UL_1 *and* UL_2).

Finally, we consider the most general problem in the family of HFSS problems, called GHFSSP, which expands on THFSSP by allowing multiple service senders. Each sender has a disjoint subset of services to deliver, and the union of these subsets contains the n services. In GHFSSP, each sender can deliver a service in each time slot; multiple senders may also choose to send services in the same time slot. Accordingly, we define a type 3 UL corresponding to collision-induced utility loss.

Definition 5 (Type 3 Utility Loss (UL_3)). *Assuming that more than one services (denoted by set $S(j,t)$) are sent to a receiver r_j who is in the IDLE state during time slot t, we define UL_3 at r_j to be ΣC_i, where $s_i \in S(j,t)$.*

Note that as with THFSSP, if r_j is in BUSY 1 or BUSY 2, there would be a driver-induced utility loss of ΣC_i, not UL_3.

Definition 6 (Generalized HF-Aware Service Scheduling Problem (GHFSSP)). *Assuming multiple senders, find a schedule so that the TUL can be minimized (by considering UL_1, UL_2, and UL_3).*

In [15] we have shown that there is an Integer Linear Programming (ILP) formulation for BHFSSP. We also provide reductions from the Hamiltonian path problem to prove that our HFSS family of problems is NP-complete.

2.3 Solutions to HFSS Family

We first propose a number of solutions to the BHFSSP. Three solutions are drawn from existing approaches: one modeled using linear programming (LP-based); two others are based on approaches to the traveling salesman problem, and use the nearest neighbor approach (TSP-NN and TSP-ENN). Finally we also propose three heuristics-based solutions that attempt to minimize utility loss (Utility Loss-Dominant Strategy or ULDS), maximize utility income (Utility Income-Dominant Strategy or UIDS), and maximize utility profit (Utility Profit-Dominant Strategy or UPDS). We will briefly examine the last three solutions since they were found to be the most effective. Further details on all solutions can be found in [15].

The first of the three, ULDS, incrementally selects an unscheduled service for each time slot based on the total loss incurred by its transmission in that particular slot, i.e., for a given time slot t we rank each unscheduled service s_i with a set of intended receivers $R(i)$ by computing its total UL_1 utility loss ($UL(t,i)$) as follows:

$$UL(i,t) = \sum_{j \in R(i)} UL_1(i,j,t). \tag{4}$$

Tie breaking is performed by selecting the service with the highest utility income (UI) that is defined as:

$$UI(i,t) = \sum_{j \in R(i)} (\mu(i,t) - UL_1(i,j,t)). \tag{5}$$

The second solution, UIDS, works by reversing the selection criteria for ULDS, i.e., it uses (5) to select the service with the highest utility in each time step and breaks ties using the service with the least utility loss as described in (4). Finally, UPDS ranks the services by the utility profit or $UP(i,t)$ in each time slot, which is defined as the difference between the utility income and loss.

$$\begin{aligned} UP(i,t) &= UI(i,t) - UL(i,t) \\ &= \sum_{j \in R(i)} (\mu(i,t) - UL_1(i,j,t)) - \\ &\quad \sum_{j \in R(i)} UL_1(i,j,t). \end{aligned} \tag{6}$$

To compare the performance of our algorithms, we propose a normalized metric called the utility-loss ratio (ULR) which is defined as the ratio of the total utility lost through an algorithm (TUL_A) to the total utility lost by a random scheduling of services (TUL_{RAN}).

$$ULR = \frac{TUL_A}{TUL_{RAN}}. \tag{7}$$

The ULR is averaged over 1 000 simulations for each set of parameters to yield the average ULR (AULR), which is then used as the comparison metric. The evaluation of our BHFSSP algorithms is shown in Figs. 2(b)∼2(d). Using the parameters listed in Table 1, we compare the performance of our algorithms with variations in the number of services, receivers, service utility, etc.

Table 1. Default Experiment Parameters

Number of services	$n = 20$
Number of total receivers	$m = 30$
Avg. Number of receivers per service	$w = 9$
Utility range	$[1, C], C = 100$

As seen in Fig.2(b), we observe that our heuristic algorithms generally perform better than the others. Furthermore, the AULR of these algorithms increases with a corresponding increase in the number of receivers that are interested in each service. However, an increase in the number of services itself does not have a significant bearing on the algorithms as seen from Fig.2(c). Fig.2(d) shows that UPDS comes close to optimal performance (OPT) with an increase in the number of receivers.

These algorithms can also be modified to work with THFSSP and GHFSSP. In THFSSP, we consider both driver-induced (UL_1) and delay-induced (UL_2) utility losses. Accordingly we consider only unscheduled services with non-zero utilities in each time step. Additionally for a service that is about to expire in the next time step, its current utility is counted towards its UL_2 loss. We introduce a new metric to estimate the UL_2 loss for a service s_i if it is to be delivered in the current slot t because other services ($s_{i'}$) may have to be postponed to at least the next time slot to accommodate for this.

$$\Delta(i,t) = \sum_{i' \neq i} (|R(i')| \times (\mu(i',t) - \mu(i',t+1))). \tag{8}$$

Based on (8), we redefine (4) and (6) to get their THFSSP versions.

$$UL(i,t) = \sum_{j \in R(i)} UL_1(i,j,t) + \Delta(i,t), \tag{9}$$

$$UP(i,t) = \sum_{j \in R(i)} (\mu(i,t) - 2\,UL_1(i,j,t)) - \Delta(i,t). \tag{10}$$

Note that (5) still holds as before. We additionally model the utility loss in each time step by incorporating a number of factors such as the number of time slots that have passed, the total number of services that are available, and a utility decreasing factor that allows us to control the rate of utility decay. From Figs.2(e)~2(g) we can see that UPDS continues to outperform the other algorithms as before.

For solutions to GHFSSP, we must consider all three types of utility losses. Accordingly, we propose multi-sender version of UPDS (M-UPDS) and UIDS (M-UIDS) to handle multiple senders that can send different services in one time slot. In a given time slot, M-UPDS selects only a service s_i belonging to the same sender by comparing a calculated metric and a preset threshold, while M-UIDS uses an ILP formulation to determine the optimal schedule that will maximize the UI during that time slot, given the information on the state of each receiver in that time slot. We compare their performances in Fig.2(h). Detailed versions of both algorithms and additional simulation results are available in [15].

In general, UPDS or its variants perform better than the others. Additionally, UPDS is computationally less expensive than the other non-heuristic solutions.

Having examined safety warning and alert message delivery, we will look at on-road video streaming as a prime example of an infotainment service in the next section.

3 Streaming Video Delivery Using Heterogeneous Networks

With the popularity of smart phones and availability of Wi-Fi hotspots and cellular Internet access, streaming movies or videos from websites such as Netflix, YouTube, and Facebook have become very commonplace. In this section, we will examine how a heterogeneous network with Wi-Fi APs and 3G/4G availability can be efficiently leveraged to serve streaming video content from the Internet to travelers in connected vehicles for the duration of their journey (refer to Fig.3).

Researchers have previously studied infotainment delivery on the road[16-19]. However, they have either considered only single-hop networks or focused on non-streaming content. Other work such as the one by Bucciol *et al.*[20] has explored video streaming over 802.11 but focused more on the vehicle-to-vehicle aspects.

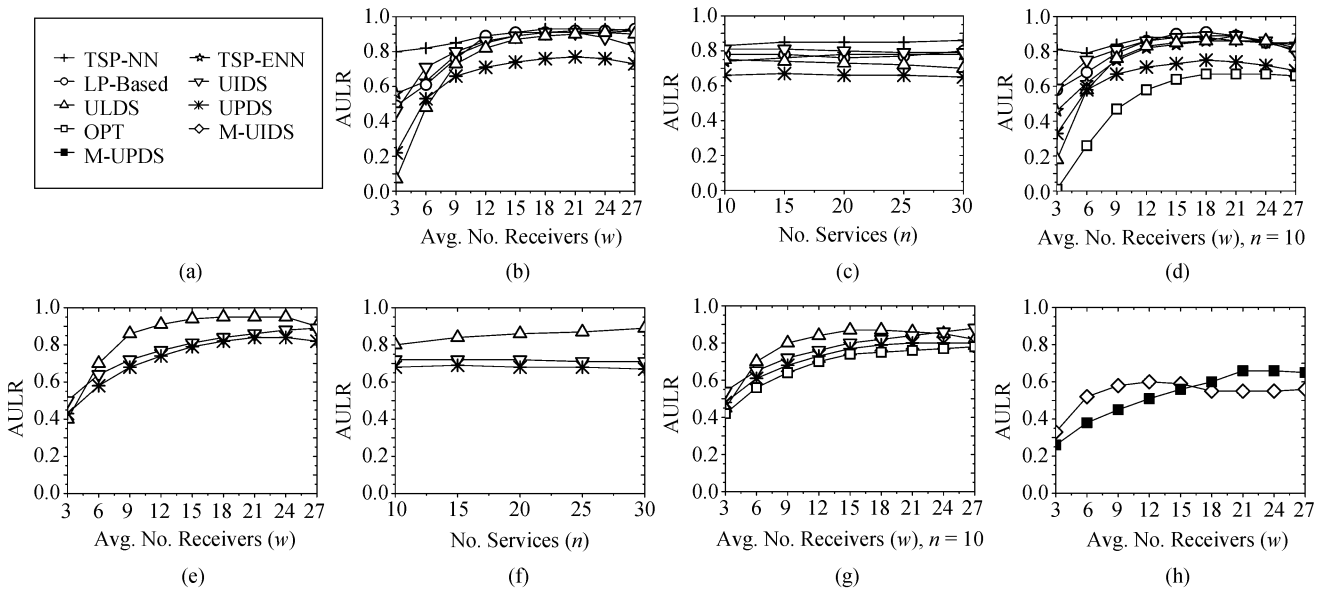

Fig.2. Performance evaluation of HFSS solutions. (a) Algorithm legends. (b)~(d) Algorithms for BHFSSP. (e)~(g) Algorithms for THFSSP algorithms. (h) Algorithms for GHFSSP.

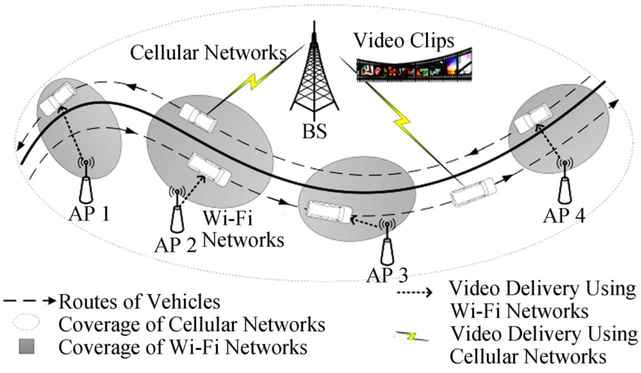

Fig.3. On-road video delivery with integrated heterogeneous networks.

3.1 Streaming Video to Vehicles

Streaming a relatively long (e.g., 10 minutes or more) video to a vehicle on the road is a non-trivial task. First, we need to stream the video with a small initial delay and a smooth playback to provide a good user experience. While aggressively prefetching video content for caching during playback is desirable, we notice that the downloaded content may be wasted since the users will stop watching the video at the end of their journey.

Secondly, we also need to deal with the limited wireless network resources that are shared among multiple users on the road. In particular, we need to carefully consider the typical characteristics of both the Wi-Fi and cellular networks: on one hand, while Wi-Fi has a high bandwidth and is free, it has a limited coverage; on the other hand, the cellular provides an almost universal coverage on the road but it has a low bandwidth and limited budget for the amount of data that can be used for video streaming by both the user and the service providers.

Additionally, due to the high moving speed of vehicles, the impact on the quality of video streaming due to non-negligible delays involved in associating with a new Wi-Fi needs to be considered. Accordingly, we need an appropriate metric to maintain and regulate the quality of the video being delivered to the user. Xue and Chen[21] proposed a perceptual quality metric to evaluate video quality from the user perspective but did not consider the additional challenges of on-road video services. Song[22] studied how zooming and ROI-enhancement coding could affect the user experience of mobile sports videos. Dobrian *et al.* analyzed the impact of video quality on user engagement based on large-scale user data[23]. However, the metrics proposed in these studies are not fit for our scenario; we thus propose a new metric that uses some of their insights and applies them to the heterogeneous vehicular network.

3.2 Assumptions and Proposed Solutions

As per [24], we consider a realistic Wi-Fi AP reception model by dividing the coverage area into zones as shown in Fig.4. The actual bandwidth available to the user depends on their current zone. For example, the two edge zones experience more interference and thus cannot deliver video at the same rate as the center zone. Additionally, switching between the Wi-Fi and the cellular at the edge of the AP zones is not instant and must be offset via caching.

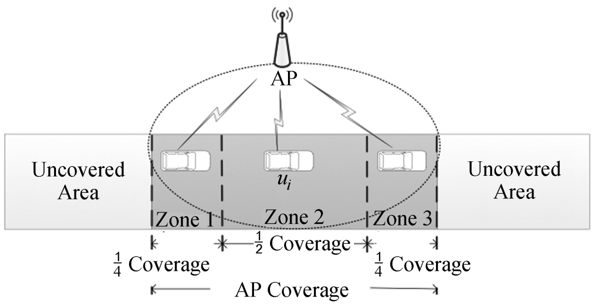

Fig.4. Realistic AP reception model.

In order to quantify the user's experience when watching a video, we propose a user experience index (UEI) metric by taking in account three factors: the duration of the video, the possible interruptions in the playback, and the initial delay before the video starts playing. The UEI is designed by taking into account the driver's perspective and is consequently improved when we are able to stream video for the length of the entire journey with minimal interruptions and start the process in a timely fashion.

In this problem, we attempt to maximize the average UEI (AUEI) across all the users in the system. Accordingly we propose two different strategies to meet this goal: 1) in the greedy divide and conquer strategy (DCS), we compute AP and cellular allocations separately by ranking the users' requirements across both and then attempt to satisfy as many requests as possible; while 2) in the integrate-and-cooperate strategy (ICS), we allow for more dynamic switching between the two networks while allocating the resources. In ICS, each user's road trip is translated into a series of overlapping trips starting at the original source and ending at each individual AP's coverage limit as shown in Fig.5. We set up additional checkpoints to mark the be ginning of the AP's coverage. ICS determines the appropriate network to use at each such checkpoint in order to satisfy the upcoming trip. Further details on these strategies can be found in [25].

We evaluate the effectiveness of our algorithms by calculating their improvement over a benchmarking algorithm called Random Wi-Fi (RW). Under RW, each AP randomly selects the commuters it wishes to serve.

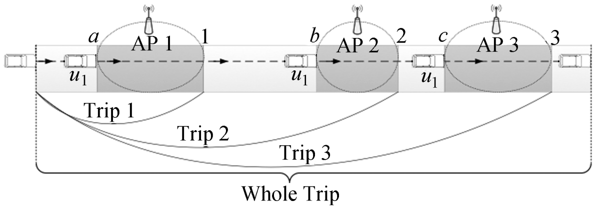

Fig.5. Example of Integrate-and-Cooperate Strategy (ICS).

We additionally average each experiment over 2 000 test cases to calculate the average performance improvement ratio (APIR), which is used as the final comparison metric. We also implement an enhanced version of the random algorithm called Random Wi-Fi + Cellular (RWC) which can additionally use the cellular network to serve more commuters. We test the performances of DCS, ICS, and RWC by varying different parameters such as the cellular and Wi-Fi coverage, the cellular download bandwidth and budget, and the number of users in the system. The default set of testing parameters for our experiments is presented in Table 2.

We can see from Figs. 6(a)~6(f) that ICS consistently outperforms DCS and RWS across the experiments. We can further state that there are significant advantages to using a heterogeneous approach to video streaming than solely relying on Wi-Fi APs, even when the cellular budget is quite limited.

Table 2. Default Values of Parameters

Category	Default Value
Number of users (n)	20
Number of APs (m)	4
Speed range	20 km/h~40 km/h
Road length	6 km
AP coverage	300 m
Distance between APs	1 000 m~1 500 m
Video play rate (pr_i)	1 Mbps~3 Mbps
AP total bandwidth (ap_b_j)	20 Mb
Cell. Net. bandwidth ($cell\_b_i$)	0.5 Mb
Total cellular budget (Ω)	500 Mb per hour
Wi-Fi assoc. time (ap_assoc_time)	7 s
Cell. assoc. time ($cell\_assoc\_time$)	2 s
Video caching threshold	$cach\_play_i = 1$ Mb
	$cach\_stop_i = 0$ Mb
Loss factor in AP reception model (θ)	0.5

So far, we have examined CTS applications in the fields of safety, and infotainment from the end-user (driver) perspective. In the subsequent sections we will focus on a more business-oriented approach to connected vehicles which will encourage users to adopt the technology and provide incentives for government and private businesses to invest in deploying the CTS infrastructure.

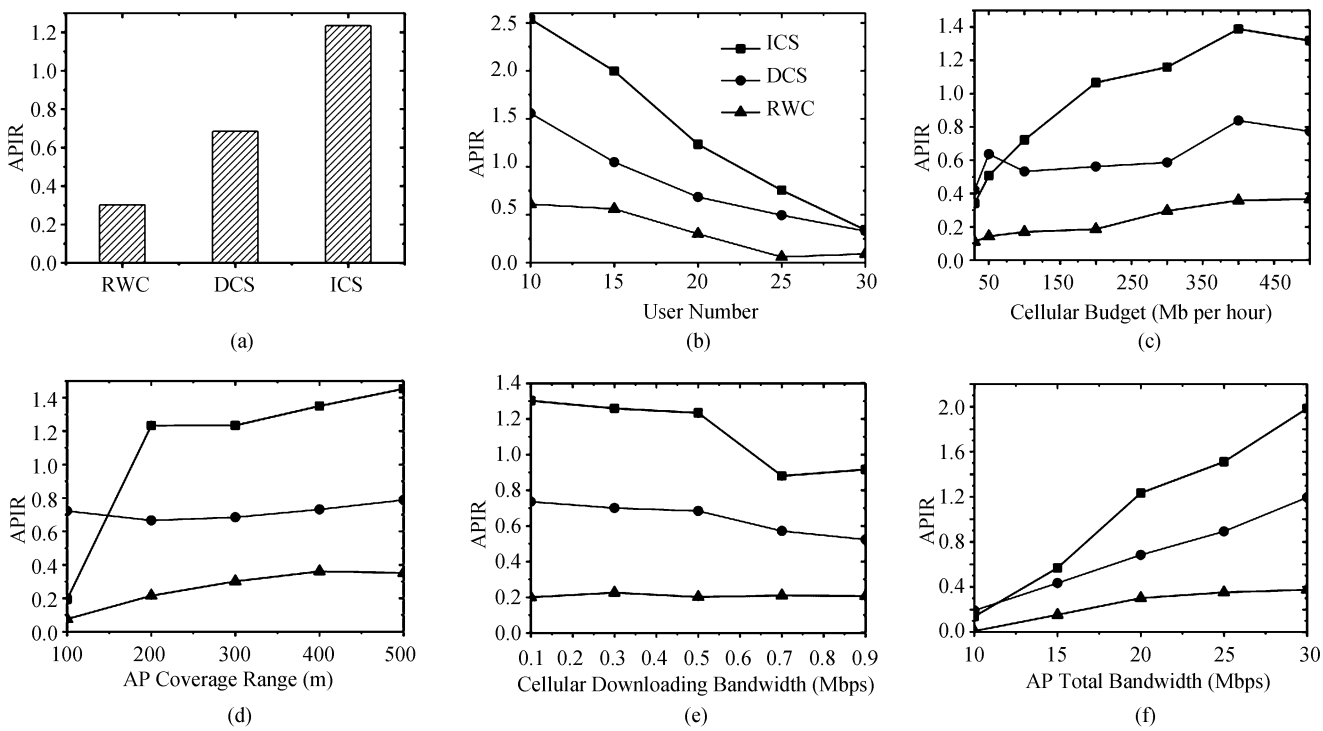

Fig.6. Testing results of OVD. (a) Performances under default setting. (b) Performances under different user numbers. (c) Performances under different cellular budgets. (d) Performances under different AP coverage ranges. (e) Performances under different cellular downloading bandwidths. (f) Performances under different AP total bandwidths.

4 On-Road Advertisement Scheduling and Delivery

Understanding the link between the customer's intent to buy a product and making the actual purchase is of vital importance to any business. Accordingly researchers have studied the correlation between such actions and how they relate to different parameters such as product descriptions and promotions[26-27]. Today, a number of merchants rely on e-display advertisements (Ads) to attract drivers and other vehicular occupants to their businesses. However, such advertisements are not personalized or catered to individuals and may miss out on a portion of the intended audience. Targeted online advertising, which has become quite popular in recent years, attempts to address this issue by using web searches, emails, and browsing habits to tailor advertisements to each individual. Goldfarb and Tucker[28] presented a study on how such online advertisement differs from the traditional approach. However, targeted advertisements are currently limited to online activities and do not reach out to road commuters. Additionally, not much is known about how such advertisements might affect the users' offline behavior and activities such as their traveling routes.

In this section, we will examine how to improve on-road advertisement by targeting the Ads to individual drivers by taking into account two important factors. Firstly, the human driver forms an essential component of the emerging vehicular network and accordingly his/her shopping decision needs to be modeled as part of the problem. Secondly, we need to also focus on the interaction between the human, cyber, and transportation elements in the scenario. Fig.7 shows the general idea of OAD and its model.

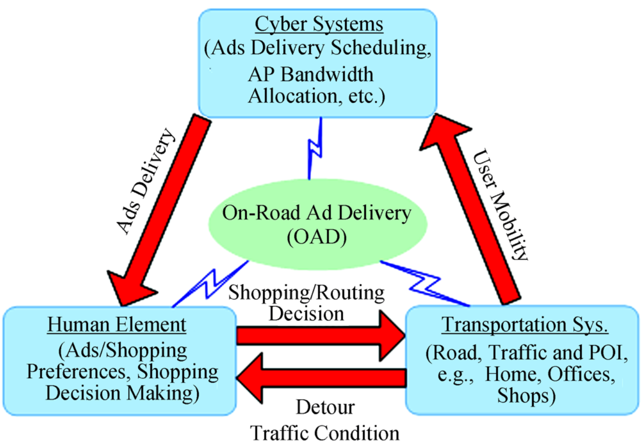

Fig.7. General concept of OAD.

4.1 On-Road Advertisement Delivery (OAD) Model

In order to model the problem, we start by analyzing the Ads from the perspectives of both the customer (or road commuter) and the advertiser. Accordingly, we design two role-specific parameters: a potential utility that is realized when a shop manages to attract a commuter to its location, and an attractiveness value that depends on the commuter, the Ad's content and the shop. Researchers have observed that our activities and routes demonstrate a high degree of regularity. [29-30] show that we frequently use fixed routes to travel to locations such as office and school. We can assume that based on the mobility profile, it is possible to figure out each user's starting and ending locations and his/her routes. Additionally, commuters frequently prefer to take routes with minimum detours when visiting a shop. We subsequently identify the intersections where such detours can occur with respect to the shops as their respective route change points, as shown in Fig.8. We also examine the overall detour experience of the commuters by comparing the average speeds of the route with and without the detour.

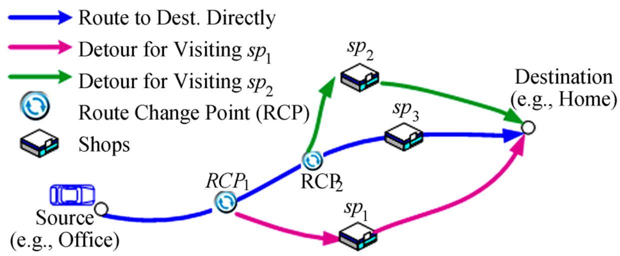

Fig.8. Example of OAD with three possible shopping detours.

Using prior research on marketing[26-27] as an indicator, we propose a shopping decision index that combines the Ad's attractiveness, the induced detour when visiting the corresponding shops, and the trip experience. We additionally define a resistance factor that corresponds to the difficulty in attracting a particular customer to a specific shop as another variable that affects his/her shopping choice. We consider both broadcast and unicast methods of Ad delivery that dictate whether an access point uses its entire bandwidth in each instant to deliver a single Ad, or shares the bandwidth between multiple Ads. The wireless delivery model also takes into account a probability of successful Ad delivery that is inversely proportional to the distance between the AP and the receiver. Finally, we define the total received utility (TRU) as the sum of all realized potential utilities across the system, and the objective of the on-road Ad delivery (OAD) problem is to maximize the value of this variable.

4.2 Solutions to Unicast and Broadcast Scenarios

We need to consider the pros and cons of the broadcast and unicast scenarios while designing our solutions. While the broadcast approach allows an AP to target all the receivers of a particular Ad with a single turn, it limits the flexibility with which we can cater our Ad schedule to each individual receiver. Unicast might waste some bandwidth repeating some content for different users, but its schedules are highly customized to each receiver. Accordingly, for the first type of scenario, we design a broadcast-based strategy (BRS) that schedules the Ads based on their effective cost-performance index. In the unicast case, we model OAD as a bi-partite graph and propose a number of solutions including a greedy strategy (GBS), a shopping chance dominant strategy (SCS) that focuses on the resistance factor and Ad attractiveness to attract customers as quickly as possible, and finally a comprehensive approach (USWS) that considers the shopping chance, utility profit, and wireless resource availability when scheduling the Ads.

In order to evaluate the effectiveness of our solutions, we define an average performance improvement ratio (APIR) over a benchmark strategy that chooses Ads at random. We can see from Figs. 9(a) and 9(b) that USWS does much better than the rest of the strategies under almost all conditions, which leads us to conclude that a well-designed unicast approach might be the best way to address Ad delivery. Fig.9(c) shows the performances of the algorithms as we increase the number of APs in the scenario, thereby increasing the amount of wireless resources at our disposal. Note that BRS still performs better than the other two naive unicast solutions (GBS and SCS). We additionally test the performance of USWS using real vehicular traces from Shanghai and integrating the commercial traffic simulator PARAMICS① with our network simulation, and find out that using such targeted Ad delivery also reduces traffic congestion during rush hour and improves driving conditions on the road.

In the next section, we will look at potential CTS applications that can help improve the efficiency of transit systems in large cities.

5 New Taxi Dispatch and Rideshare Services

The importance of building an efficient and sustainable transit system cannot be overstated. According to the Population Reference Bureau, 522 major cities in the world now have more than one million people as of 2013. 24 cities including Tokyo, Delhi, New York, and Shanghai have populations in excess of ten millions. The rapid growth of large cities creates significant challenges in their public transportation systems.

At the same time, we are witnessing a large-scale deployment of CTS infrastructure. The wide adoption of sensors, GPS, and communication devices in both vehicles and road infrastructure, makes massive amount of streaming data about people's daily commute available to government administrators. However, such information is currently only used to visualize traffic density on highways and the locations of taxis around the city. We believe that these real-time, multi-source data about urban transit systems are severely under-utilized and there is a great opportunity for further development. We propose the following applications to provide better taxi dispatch and carpooling services while also providing incentives for the government and private business to adopt and invest in CTS technology and infrastructure.

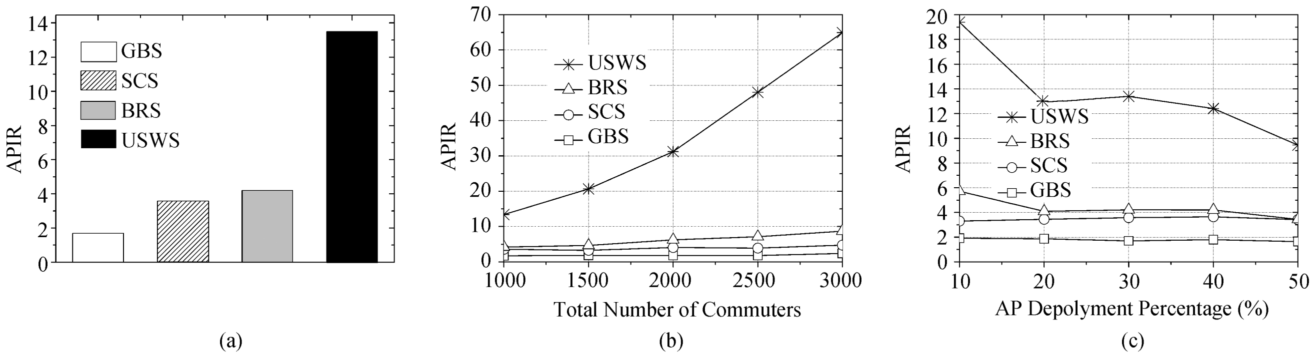

Fig.9. Testing results. (a) Performances under the default setting. (b) Performances under different commuter numbers. (c) Performances under different AP deployment percentages.

①Further information can be found in the PARAMICS Manual by Quadstone Paramics Ltd., 2009. http://www.paramics-online.com/, May 2014.

5.1 Taxi Dispatch with Cruising Guidance

A taxi service is an indispensable component of the urban transportation system, especially in large cities. A recent survey of New York City② reported that there were more than 13 000 taxis operating in the city with a stable delivery of 660 000 passengers every day. Taxi service in New York City transports 25% of all passengers, and accounts for 45% of all transit fares paid. Previous research on taxi dispatch systems has primarily focused on two aspects: 1) matching vacant taxis to passenger requests and 2) predicting potential passengers based on historical GPS data[31-32]. Researchers have applied techniques such as Integer Linear Programming techniques to address the former issue[33-34].

Despite the existence of such dispatch systems, which match taxis to passengers, in many large cities, most taxis still look for customers while cruising on the road without receiving any formal guidance (as shown in Fig.10(a)). Different from the conventional operation mode in existing taxi dispatch systems, we envision a new cyber-technology enabled taxi dispatch system that can efficiently provide vacant taxis with cruising route suggestions. These suggestions do not correspond to any specific pick-up requests but instead, help find prospective customers (and accordingly, this is complementary to the conventional operation mode). Accordingly, we propose a Taxi Cruising Guidance (TCG) problem with the aim of providing such route cruising suggestions to each vacant taxi during a time period. We further define global vacant rate (GVR), which is the ratio of the miles driving without a passenger onboard to the total miles driving during a given time period, to measure the performance of our solutions.

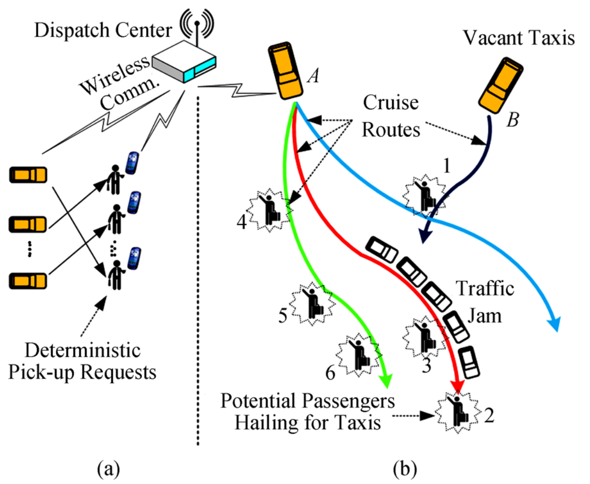

Fig.10. (a) Existing taxi dispatch operation mode. (b) Additional cruising route suggestion mode in new taxi dispatching systems.

Instead of dealing with the classic matching problem between the received pick-up requests from passengers and vacant taxis, TCG focuses on how to help cruising taxis identify passengers, by not only utilizing the knowledge about the appearance of possible passenger (by analyzing historical GPS trajectories of taxis) but also explicitly considering the current traffic conditions.

In [35], we proposed a busy-link dominant strategy (BDS) that considers issues related to both the traffic condition and competition among vacant taxis. We associated different road links with the number of prospective passengers that might appear on them and accordingly, placed more emphasis on those links with high probability of perspective passengers. We additionally modeled an uncoordinated cruising strategy (UCS) and traditional dispatch-based strategy (TDS) for comparison, and demonstrated that BDS provides significant improvement in terms of reducing the Global Vacant Rate (GVR).

A case study is presented by utilizing real traces collected from taxis in Shanghai. Figs. 11(a)∼(c) show the performance of different solutions during different time of the day, and with different numbers of taxis. In general, BDS yields better performance in terms of a lower GVR. As part of our research, we leverage a well-known microscopic traffic simulator TRANSIMS to demonstrate that the application of TCG is additionally beneficial to traffic management (i.e., minimize congestion as indicated by a higher average speed, refer to Fig.11(d)).

5.2 Rideshare System with Transfer-Allowed Carpooling

Carpooling has long held the promise of reducing travel cost and traffic congestion by accommodating more than one person in a car. The current transfer-incapable carpooling (TIC) scheme, however, cannot fully utilize the vehicles' available space because a carpooling passenger has to go from his/her origin to his/her destination by getting a ride from only one vehicle. To the best of our knowledge, all the existing work on carpooling is based on the TIC scheme[36-38]. This is akin to insisting on delivering some packets only using one-hop communications, which usually performs worse than allowing multi-hop communications.

Inspired by the "Store-and-Forward" strategy used in Delay-Tolerant Networks, we propose a new carpooling paradigm called transfer-allowed carpooling (TAC), in which each passenger can be served by more than one vehicle along their route thereby increasing the carpooling performance, as shown in Fig.12. In particular,

②Schaller Consulting. The New York City taxicab fact book. www.schallercon sult.com/taxi/taxifb.pdf, May 2014.

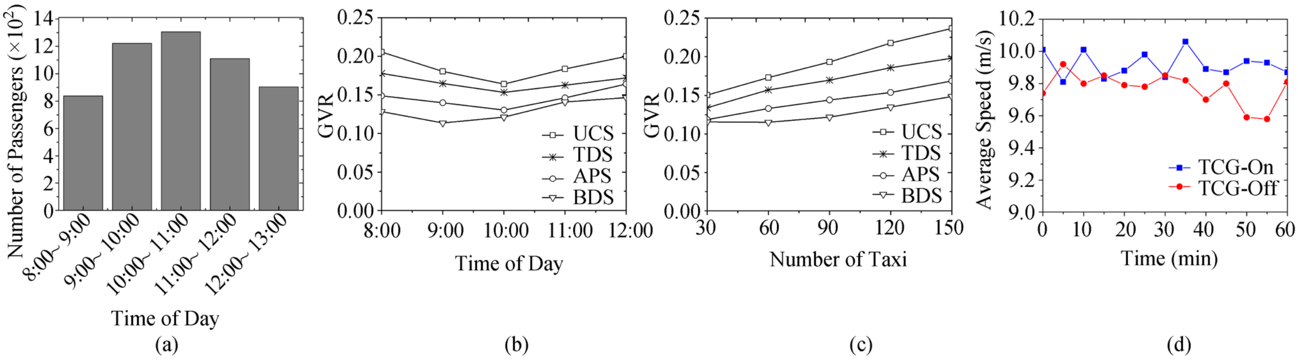

Fig.11. Testing results in the case study. (a) Number of passengers retrieved from real trace at different time durations of a day. (b) Performance with real trace at different time points of a day. (c) Performance with real traces under different numbers of taxi. (d) Testing with traffic simulator.

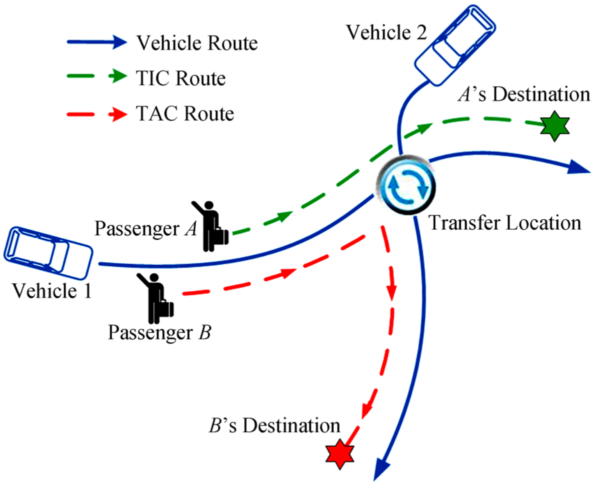

Fig.12. Example illustrating transfer-incapable carpooling (TIC) and transfer-allowed carpooling (TAC).

given 1) a number of carpooling requests (each with a maximum waiting-time and a maximum number of transfers per passenger), and 2) a list of participating vehicles (each specifying a maximum detour distance for a driver), we address a new optimization strategy called transfer-allowed carpooling (TAC) whose objective is to maximize the successful carpooling ratio (SCR). SCR is defined as the number of request served by carpooling to the total number of request.

In [39] we proposed two effective strategies, the driver experience-aware strategy (DES) and passenger experience-aware strategy (PES) from a driver's perspective. DES aims to reduce the overall travel distance, whereas, PES considers reductions in trip times for carpooling passengers. From Fig.13, we observe that 1) the proposed TAC approach can significantly improve the SCR by 30%∼70% as compared with the traditional TIC approach; 2) allowing only one transfer improves the efficiency of carpooling the most. We also find out that additional transfers do not result in further noticeable benefits; and 3) compared with TIC, TAC can further reduce the total travel distance, which is another benefit in terms of gas savings and emission reduction.

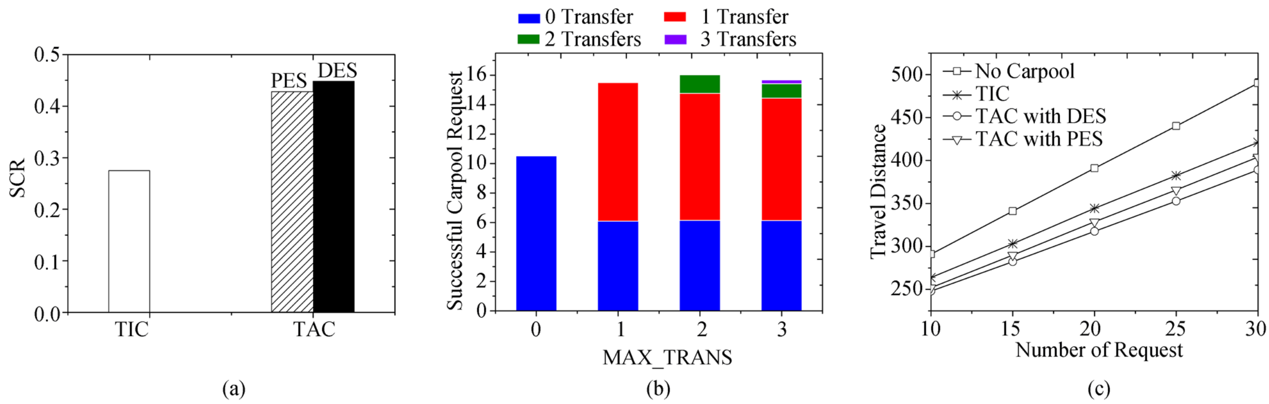

Fig.13. Testing result of TAC/TIC. (a) Performances with default setting. (b) TAC with DES result composition. (c) Total travel distance with different request numbers.

6 Conclusions

The emerging cyber transportation system (CTS) is ushering in a new era of ground transportation with continued advances in connected vehicles and autonomous driving. However, to be truly successfully, CTS must provide travelers, government transportation agencies, and private businesses with a multitude of useful applications to speed up its widespread adoption. In this paper, we have addressed some key issues for developing emerging applications of CTS by 1) examining the delivery of warning and safety services to the human driver, 2) discussing how a heterogeneous network could be utilized to serve streaming video to travelers, and 3) proposing targeted on-road advertisement, efficient taxi dispatch, and carpooling services to not only attract new customers and users to adopt CTS, but also give incentives for government agencies and private businesses to invest in CTS infrastructure and technology. We expect these applications to stimulate further work in their respective areas.

Ongoing and future work under consideration includes 1) safe transportation systems with mixed autonomous and human-driven vehicles, 2) improving sustainability with green routing, green signals, and the use of electrical vehicles for fuel-efficient and environmental friendly transportation operations, 3) cooperative control of infrastructure (communication and traffic signals) and vehicles (e.g., their routes, speeds) for efficiency and resilience, and 4) integrated driving, traffic, and network simulation for validation and evaluation of various CTS design and development[40].

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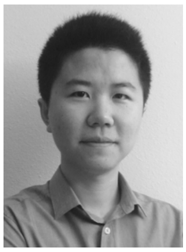

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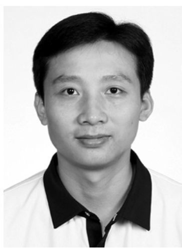

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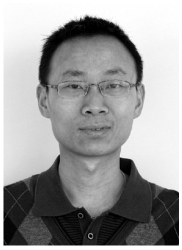

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