

Towards Characterizing and Classifying Communication-based Automotive Applications from a Wireless Networking Perspective

Fan Bai, Hariharan Krishnan, Varsha Sadekar
Electrical & Controls Integration Laboratory
General Motors Research Center
{fan.bai, hariharan.krishnan, varsha.k.sadekar}@gm.com

Gavin Holland, Tamer ElBatt
HRL Laboratories, LLC
{telbatt,gholland}@hrl.com

Abstract

Together, the Dedicated Short Range Communication (DSRC) and Vehicular Ad Hoc Network (VANET) technologies provide a unique opportunity to develop various types of communication-based automotive applications. To date, many applications have been identified by the automotive community. Given the large number and diverse nature of these applications, it is advantageous to develop a systematic classification methodology to facilitate future DSRC and VANET research. Toward this objective, we present a study that goes through two major steps: characterization and classification. First, we focus on a rich set of representative applications and characterize them with respect to plausible application- and networking-related attributes. The characterization process not only strengthens our understanding of the applications but also sets the stage for the classification step since it reveals numerous application commonalities. Thus, we have categorized the given applications into seven *generic* classes, with the consideration of balancing the trade-off between exploiting as many application similarities as possible while preserving their salient differences. This is of paramount importance to facilitate performance analysis for newly designed protocols. Finally, we have identified key performance metrics for each class of applications, which, we hope, could bridge the gap between the automotive and wireless networking communities. Accordingly, the proposed classes are envisioned to play a dual-role: to facilitate application simulation and performance evaluation, and to guide DSRC and VANET protocol research and development.

I. INTRODUCTION

Traffic accidents and highway congestion are a serious problem world-wide [1] [3]. To address this challenge, safety applications using expensive sensors, radars, cameras and other state-of-the-art technologies are currently integrated into vehicles to improve safety and convenience. Recently, however, communication-based safety applications have attracted more attention from industry and governments in the United States, Europe, and Japan because of their potential to lower manufacturing costs [2] [27] [32] [33] [34]. In addition to safety applications, wireless communication can also be shared by commercial and vehicular “infotainment” applications to, for instance, enhance the occupants’ driving experience. Thus, wireless communication can be used to not only enhance transportation safety [4] [5] [6] [7] and traffic efficiency [8], but also to create commercial opportunities to vehicle owners and automotive OEMs by providing infotainment applications [9] [10].

In the US, the federal government has recognized the importance of having a dedicated wireless spectrum for improving traffic safety and highway efficiency. The Federal Communications Commission (FCC) has allocated 75 MHz of licensed spectrum in the 5.9 GHz as the Dedicated Short Range Communication (DSRC) band for Intelligent Transportation Systems (ITS) [25], and its deployment is supported under major Department of Transportation (USDOT) initiatives [28] [29]. The medium access control (MAC) portion of the DSRC standard are currently being addressed by the IEEE 802.11p working group [31] [30], which is widely considered to be the leading technology for communication-based automotive applications. Major automotive OEMs, wireless device manufacturers, research institutions, public agencies, and private enterprises are conducting research

on various topics pertaining to vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications, such as, wireless channel modeling [11] [12], mobility modeling [13] [14], routing protocols [19] [20] [21] [22], security [15] [16], and market penetration mitigation strategy [17] [18].

A. Motivation of the Paper

This work is motivated by the fact that a systematic and thorough analysis of communication-based automotive applications from a networking point of view is still lacking. As a preliminary study, we attempt not only to raise awareness about the performance requirements of the automotive community, but also to attract sufficient attention from the networking research community.

The Vehicle Safety Communication Project [27] has identified a number of applications for potential deployment, including the perspective of user benefits [26]. These applications of interest vary significantly in terms of application characteristics, ranging from safety/warning applications to content download/streaming applications (for entertainment) to free-flow payment applications (for improving highway traffic efficiency and driver convenience). Analyzing and developing wireless networking solutions tailored to such large number of diverse applications, in an exhaustive manner, is a cumbersome and inefficient task. Obviously, there is a gap between developing communication-based automotive applications (the focus of the automotive community) and developing VANET protocols (the focus of the wireless networking community). To bridge this void, we aim at categorizing communication-based automotive applications, not only from application characteristics perspective, but also from a wireless networking perspective.

B. Contents of the Paper

To the best of our knowledge, this paper is the first study of classifying communication-based automotive applications from the perspective of network design. To do so, we are interested in answering the following questions throughout this study:

- 1) What are the key application characteristics and networking attributes in the design space of application development?
- 2) How should these applications be categorized into generic classes, from the viewpoint of network designers?
- 3) What are the relevant performance metrics that are needed to adequately evaluate the behavior of network protocols and applications, for each class of applications? What is the mapping, if any, between application-level metrics and network-level metrics?

Part of the challenge in our study is to create a rich set of application characteristics and network attributes which capture the major dimensions of the design space of V2V/V2I applications, in a systematic and thorough manner. With deep insight into the application design space, we have categorized a set of applications into several *generic* classes based on commonalities of individual applications. In addition, we have identified relevant performance metrics for each generic application class, at both the network-level and the application-level, to be used, among other things, for evaluating whether the performance of a given application meets the application class requirement. We have also developed two simple analytical models to bridge the discrepancy between network-level metrics and application-level metrics, for reliability and latency. In this paper, we focus

primarily on three major aspects: (1) investigating the application characteristics and network attributes, (2) classifying the applications into categories, and (3) defining relevant performance metrics for each class of applications.

C. Benefits of the Paper

Our aim for this study is to not only simplify the simulation effort for application evaluation, but also shed light on network protocol design and system integration for different applications. For instance, using our results, network designers may focus on just a few abstract classes of V2V/V2I applications, rather than a whole set of individual applications. Also, evaluating the performance trends of generic classes of applications with the same mechanisms/tools is more meaningful than focusing on individual applications. Moreover, this classification serves as a potential road-map for developing the VANET technology needed to support different applications. A generic class of applications is more likely to have a similar set of protocols and mechanisms in the network stack because similar application characteristics and performance requirements tend to implicitly mandate the same technical solution. Thus, network designers should be able to maximize the re-usability of common mechanistic “building blocks” (or modules) for a specific class of applications with similar application characteristics and performance requirements. In summary, the benefits of characterizing and classifying V2V/V2I applications include:

- 1) Development of a few types of application models to represent a large number of applications with similar properties belonging to the same class, for application simulation and validation.
- 2) Identification of key performance metrics relevant to each identified application class, as benchmarks for evaluating whether designed application mechanisms can meet common requirements mandated by application classes.
- 3) Creation of networking protocol stacks for each class of applications, with the consideration of improving re-usability of common mechanistic modules or networking protocols.

D. Organization of the Paper

This paper is organized as follows. In Section II, we introduce a set of representative V2V/V2I applications as background knowledge. Afterwards, we introduce the attributes used for characterizing those applications in Section III. In Section IV, we characterize each application according to the introduced attributes, which in turn constitutes a fundamental step towards identifying few *generic* application classes. Then, we introduce the application-level and network-layer performance metrics and QoS requirements for each application class in Section V. Finally, we conclude the paper and lay out our future research plan on related topics in Section VI.

II. BACKGROUND: A SET OF V2V/V2I APPLICATIONS FROM THE PERSPECTIVE OF USER BENEFITS

Research on Vehicular Ad Hoc Network (VANET) technology has mainly been driven by the demands of providing network support for application development. So far, DSRC research community has developed a large number of potential V2V/V2I applications for future deployment, ranging from safety/warning applications to highway traffic management applications to commercial applications. Since it is difficult to analyze a large number of applications, we chose 16 representative applications

based on criteria such as customer value, near-term feasibility of deployment, technical novelty, and diversity of enabling technologies. Throughout this paper, these 16 applications (shown in Table I) are the basis of our study.

From a value or customer benefit perspective, these applications can be roughly organized into three major classes: *safety-oriented*, *convenience-oriented*, and *commercial-oriented*.

- 1) **Safety applications** actively monitor the nearby environment (the state of other vehicles or of road conditions) via message exchanges between vehicles, so that applications are able to assist drivers in handling the upcoming events or potential danger. Some applications may automatically take appropriate actions (such as automatic braking) to avoid potential accidents, while other applications aim only to provide assistance to drivers as they chose. The latter applications are very similar to the former applications, even though the system requirements (such as reliability, latency, etc.) are less stringent. However, both types of applications aim to improve the level of vehicle safety.
- 2) **Convenience (Traffic Management) applications** share traffic information among roadway infrastructure, vehicles on the road, and centralized traffic control system, to enable more efficient traffic flow control and maximize vehicle throughput on the road. Ultimately, these applications not only enhance traffic efficiency, but also boost the degree of convenience for drivers.
- 3) **Commercial applications** provide drivers with various types of communication services to improve driver productivity, entertainment, and satisfaction, such as web access and streaming audio and video.

From the description of the applications in Table I, it is easy to see that SVA, EEBL, PCN, RHCN, RFN, CCW, and CVW can all be considered *safety-oriented* applications, whereas CRN, TP, TOLL, PAN, and PSL can be considered *convenience-oriented* applications. Likewise, RVP/D, SA, CMDD, and RTVR (and other Internet access applications) can be considered *commercial-oriented* applications. These groupings are derived from the characteristics and customer benefits of the applications. Note that, among those listed, safety-oriented applications are of special interest because they are expected to significantly reduce the fatalities and economic losses caused by traffic accidents.

III. CRITERIA OF CLASSIFICATION: APPLICATION CHARACTERISTICS AND NETWORK ATTRIBUTES

In this section, we define the application and networking criteria that we use in our classification. Careful selection of these criteria is critical to adequately capture the subtle but important differences between the various applications, and their various networking requirements. Thus, our approach was to first enumerate the characteristics of the applications in Table I in a systematic and thorough manner so we could gain important insight into the various application designs, and then use this insight to explore the demands these applications place on network design and enumerate their common network-related attributes. Thus, we grouped criteria into two major divisions, application-related characteristics and network-related attributes, which are shown in Table II and Table III, respectively. In the remainder of this section, we discuss the contents of these tables in more detail.

TABLE I
V2V/V2I APPLICATIONS OF INTEREST

Acro.	Name	Description	Benefits
SVA	Stopped or Slow Vehicle Advisor	A slow or stopped vehicle broadcasts slow/stopped vehicle warning messages to approaching vehicles in its neighborhood	Safety
EEBL	Emergency Electronic Brake Light	A vehicle braking hard broadcasts a warning message to approaching vehicles in its neighborhood for the duration of the event	Safety
PCN	V2V Post Crash Notification	A vehicle involved in an accident broadcasts a warning message to vehicles in its neighborhood until the accident site is cleared	Safety
RHCN	Road Hazard Condition Notification	A vehicle detecting a road hazard (e.g., fluid, ice) notifies vehicles within the potentially affected region	Safety
RFN	Road Feature Notification	A vehicle detecting a road feature (e.g., road curve, hill, road grade) notifies approaching vehicles in its neighborhood	Safety
CCW	Cooperative Collision Warning	A vehicle actively monitors kinematics status messages from vehicles in its neighborhood to warn of potential collisions	Safety
CVW	Cooperative Violation Warning	A road-site unit actively transmits signal phase, timing and related information to approaching vehicles. The vehicles use this information to warn drivers of potential violation of traffic signal	Safety
CRN	Congested Road Notification	A vehicle reports road congestion to vehicles or road-side units in other regions for the purposes of route and trip planning	Convenience
TP	Traffic Probe	Vehicles aggregate traffic probe information and transmit to road-side units for traffic management	Convenience
TOLL	Free Flow Tolling	Vehicle toll collection at highway toll booths (non-stop)	Convenience
PAN	Parking Availability Notification	A vehicle receives the availability of parking lots in a certain geographical region	Convenience
PSL	Parking Spot Locator	A vehicle receives a list of open parking spots upon entering a parking lot	Convenience
RVP/D	Remote Vehicle Personalization/ Diagnostics	Downloading of personalized vehicle settings or uploading of vehicle diagnostics from/to infrastructure	Commercial
SA	Service Announcements	Road-side businesses (e.g., MacDonalD's) announce services to vehicles as they pass by or come within range	Commercial
CMDD	Content, Map or Database Download	A vehicle downloads content (e.g., maps, multimedia, webpages) from home stations or from mobile "hot-spots"	Commercial
RTVR	Real-Time Video Relay	Transmission and relay of streaming real-time video from a vehicle to other vehicles or road-side units	Commercial

A. Application Characteristics

In this section, we introduce the application-related characteristics that we identified and used as the basis for our proposed classification. These characteristics, summarized in Table II, describe properties directly related to the applications themselves, such as user benefit and affected geographical region. As mentioned previously, the goal was to develop key characteristics that cover the various design aspects the set of applications that we explored. While we attempted to be as general and as thorough as possible, we acknowledge that future analysis of a broader set of applications may uncover other important characteristics. Indeed, it is our hope that the work presented here will inspire others to research and expand the list as future applications are explored and developed. However, as we will show, this list covers a sufficiently broad range of applications to be a useful reference tool for application and network designers. In the remainder of this section, we discuss these characteristics in more detail.

TABLE II
CANDIDATE CRITERIA TO CHARACTERIZE AND CLASSIFY APPLICATIONS (APPLICATION CHARACTERISTICS)

Application Characteristics	Description	Choices
User Benefit of Application	What benefit does the application bring to users?	Safety, Convenience, Commercial
Participants of Application	What entities participate in the application?	V2V, V2I
Application Region of Interest (ROI)	What is the size of the affected geographical region of the application?	Long, Medium, Short
Application Trigger Condition	When and how is the application triggered?	Periodic, Event-Driven, User-Initiated
Recipient Pattern of Application Message	What is the pattern of recipients for the application messages?	One-to-One, One-to-Many, One-to-a-Zone, Many-to-One
Event Lifetime	How long does the event last?	Long, Short
Event Correlation	What is the degree of event correlation in the ROI?	Strong, Weak, None
Event Detector	How many hosts can detect/generate the event?	Single Host, Multiple Hosts

- 1) **User Benefit of Application:** This describes the type of benefit or value the application provides to the end customer, as defined in a number of studies [26] (and discussed in Section II). Overall, there are three widely accepted application types: *safety-oriented* applications, *convenience-oriented* applications, and *commercial-oriented* applications.
- 2) **Participants of Application:** This specifies the entities that may be potentially involved in the application. Some applications only require communication among vehicles, while other applications require the coordination between vehicles and road-side infrastructure. Hence, communication-based automotive applications can be categorized as either *vehicle-to-vehicle (V2V)* applications or *vehicle-to-infrastructure (V2I)* applications.
- 3) **Application Region of Interest (ROI):** The ROI is the size of the geographical region covered by those entities participating in an application. Different kinds of applications have different ROI sizes. For example, in some safety applications, vehicles need to be aware of the kinematics status of other vehicles in their direct neighborhood (i.e., a few hundred meters), whereas in other safety applications vehicles need to know the hazard situation of a stretch of road that lies ahead (i.e., up to 1 kilometer). Likewise, for some convenience applications, vehicle occupants may want to know the status of road congestion far ahead (i.e., kilometers) for trip planning. Qualitatively, application ROI can be classified into three major types: *short-*, *medium-*, and *long-range*.
- 4) **Application Trigger Condition:** This specifies how applications are triggered, which is generally either *periodic*, *event-driven*, or *user-initiated*. Implicitly, it also specifies the kind of communication methods used by the application. For example, the vehicular kinematics status messages used for collision detection are normally broadcasted periodically, whereas warning messages for events such as panic braking are usually event-driven, and request messages for on-demand convenience services from vehicle occupants are generally user-initiated.
- 5) **Recipient Pattern of Application Message:** This specifies the pattern of potential message recipients for an event, which varies between applications. For instance, in safety applications like CCW and CVW, it is critical for all neighboring

vehicles to hear the broadcasted safety alert messages to avoid potential collisions (a *one-to-many* pattern), whereas for safety applications such as EEBL, SVA, and PCN, only vehicles in the region being affected (vehicles behind the event originator) need to hear the safety alert message (a *one-to-a-zone* pattern). Likewise, a *point-to-point* communication pattern is often used in many convenience and commercial applications, and a *many-to-one* pattern is also sometimes used. Thus, the pattern of event message recipients can be grouped into four categories: *one-to-many*, *one-to-a-zone*, *one-to-one*, and *many-to-one*.

- 6) **Event Lifetime:** This illustrates how long an application event (e.g., traffic accident or road congestion) persists in time. Among the criteria discussed so far, event duration is one application characteristic that may directly affect network system design. Among all applications, event lifetime may differ significantly. For example, some events have relatively short durations (e.g., EEBL events may last only a few seconds on average), while others may have relatively long durations (e.g. a PCN event may take hours before the crashed vehicles are cleared from the roadway). Among the applications we studied, most fell into one of two general categories: either a *short* event lifetime ($O(\text{seconds})$) or a *long* event lifetime ($O(\text{minutes or hours})$).
- 7) **Event Correlation:** This specifies the degree to which events generated by entities within a geographical region of interest are correlated with each other. For example, in an EEBL application, the occurrence of an EEBL event in a vehicle may be highly correlated with EEBL events generated by other vehicles in front of it. Another example is the RHCN application, where RHCN events in nearby vehicles may be highly correlated since they are caused by the same road hazard condition. Qualitatively, applications can be grouped into three categories: those with *strong* event correlation, *weak* event correlation, and *no* event correlation.
- 8) **Event Detector:** This specifies how many vehicles generate event messages in response to the same event. For instance, for applications such as SVA or PCN, where a vehicle reports its kinematics status, the vehicle is the sole event detector (i.e. of its kinematics state) and event message host (originator), whereas for applications such as RHCN and RFN, where a vehicle reports on road hazards, many vehicles may detect the same event (i.e. the same road hazard) and serve as event message hosts. Therefore, we classify application event detection as either *single* host or *multiple* hosts.

As mentioned previously, we believe these are the key defining characteristics, among the 16 applications that we studied, that are of most relevance to network design. However, we acknowledge that further application analysis may reveal other characteristics to add to the list, and we hope that it inspires others to do so. For the purposes of this study, however, these are the basis for the application characteristics portion of our classification effort. In the next section, we present our group of key network-related attributes and their relation to the application characteristics above.

B. Network Attributes

In this section, we introduce the key network-related attributes that we used in our classification to characterize the fundamental aspects of network design for communication-based automotive applications. These attributes, summarized in Table III, are more or less, are determined by the application characteristics discussed in the previous section, as we will

TABLE III
CANDIDATE CRITERIA TO CHARACTERIZE AND CLASSIFY APPLICATIONS (NETWORK ATTRIBUTES)

Network Attributes	Description	Choices
Channel Frequency	What channel does the application use?	DSRC-CCH, DSRC-SCH, WiFi
Infrastructure	Is infrastructure required?	Yes, No
Message Time-To-Live	How far do messages propagate?	Single-hop, Multi-hop
Packet Format	What type of packet is used?	WSMP, IP
Routing Protocol	How are messages distributed?	Unicast, Broadcast, Geocast, Aggregation
Network Protocol Initiation Mode	How is a network protocol initiated?	Beacon, Event-triggered, On-Demand
Transport Protocol	What form of end-to-end communication?	Connectionless, Connection-oriented
Security	What kind of security is needed?	V2V security, V2I security, Internet Security

show. In the remaining part of this section, we discuss these network attributes, and their relationship with the corresponding application characteristics, in detail.

- 1) **Channel Frequency:** This attribute specifies the type of physical-layer channels that may be used to support communication-based automotive applications. Following FCC regulations, safety-oriented applications are normally assumed to use a single DSRC control channel (CCH), whereas convenience-oriented applications use one of six DSRC service channels (SCH). On the other-hand, commercial-oriented applications can either occupy DSRC SCH channels, or any other channel frequency in the unlicensed Industrial, Scientific and Medical (ISM) bands (e.g. WiFi 2.4 and 5.8 GHz). In other words, the choice of channel is largely determined by the value of the *user benefit* characteristic of the application. While there are many other channels that can be used (such as cellular telephony or WiMAX), in practice the choice of channel is generally one of either *DSRC CCH*, *DSRC SCH*, or *WiFi*.
- 2) **Infrastructure:** This attribute specifies whether or not the application needs infrastructure (i.e. a road-side unit) for its operation. Obviously, infrastructure is needed if the *participants of the application* characteristic involves a road-side unit. Otherwise, infrastructure may not be required.
- 3) **Message Time-To-Live (TTL):** This attribute specifies how far a message is propagated by the network, and what type of packet forwarding/routing functionality is needed (i.e., single-hop or multi-hop) by the network layer. This attribute is partly determined by the *application region of interest* characteristic. Single-hop communication is sufficient for short-range applications, while medium- or long-range applications require multi-hop packet forwarding/routing functionality for extended reachability. Thus, design choices include either *single-hop* or *multi-hop* routing.
- 4) **Message Packet Format:** This attribute describes the format of the network packets that are used to encapsulate the application messages. This attribute is partly influenced by the *user benefit* characteristic of the application. In general, the automotive industry [26] and IEEE standard community [31] have promoted the idea that safety and convenience applications are more likely to use relatively constant and small-sized packets, whereas commercial applications are more likely to use variable and large-sized packets. In the DSRC standard, the Wave Short Message Protocol (WSMP) is proposed for safety and convenience use. It is essentially a simplified version of the IP protocol, with a smaller packet

header to reduce per-packet overhead for improved network efficiency. For commercial applications, it is assumed that the traditional IP packet format will be used. Thus, we classify packet formats into two types: either *WSMP* format or *IP* format.

- 5) **Routing Protocol:** This design choice illustrates what kind of network routing protocols are used for the various applications. Obviously, this network attribute is closely related to the *recipient pattern of application message* characteristic. For instance, most safety applications use *broadcast* routing (one-to-many) or *geocast* routing (one-to-a-zone), while convenience and commercial applications normally use *unicast* routing (one-to-one) or *aggregation* routing (many-to-one).
- 6) **Network Protocol Initiation Mode:** This attribute describes how the network protocol is triggered. Some safety applications mandate periodic broadcast “beaconing” of status messages, like CCW and CVW (i.e., *beacon mode*), whereas other safety applications, like EEBL and PCN, send messages only when a critical event is detected (i.e., *event-triggered mode*). For a portion of convenience and commercial applications, it is the vehicle occupants that initiate message announcements and service request (i.e., user-initiated *on-demand mode*).
- 7) **Transport Protocol:** This design choice indicates whether or not a reliable end-to-end connection is needed to support the application. As we discovered, safety and convenience applications generally follow the *connection-less* paradigm (e.g. WSMP, UDP), while commercial applications often use the traditional *connection-oriented* paradigm (e.g. TCP).
- 8) **Security:** This network attribute considers what kind of security solution is needed for the application. The choices include *V2V security*, *V2I security* and *Internet security*. Safety applications require high-level V2V security preventing vehicles from malicious attacks, convenience applications also mandate the stringent V2I security solution because financial transaction could be involved at road-side infrastructure, and most commercial application require the efficient collaboration between V2V/V2I security solutions and existing security solutions for Internet.

As we discussed, many of these network attributes are closely related to specific application characteristics. Intuitively, a given application characteristic or performance requirement normally requires a given networking mechanism or capability. In the next section, we show how sets of applications with similar characteristics and requirements lead to the same network solutions, resulting in a very useful general classification.

IV. APPLICATION CHARACTERIZATION AND CLASSIFICATION

In this section, we present the results of our application characterization and classification for the set of 16 applications shown in Table I. We then compare and contrast these applications first with respect to the application characteristics presented in Table II, and then with respect to the network attributes presented in Table III. We then show how, by combining the applications with similar characteristics and network functionalities, we are able to group these applications into 7 generic classes (from the perspective of network design).

TABLE IV
APPLICATION CHARACTERIZATION BASED ON APPLICATION CHARACTERISTICS

Acro.	User Benefit	Application Participants	Application ROI	Application Trigger Condition	Recipient Pattern	Event Lifetime	Event Correlation	Event Detector
SVA	Safety	V2V	Medium	Event	One-to-a-zone	Long	None	One
EEBL	Safety	V2V	Medium	Event	One-to-a-zone	Short	Weak	Many
PCN	Safety	V2V	Medium	Event	One-to-a-zone	Long	None	One
RHCN	Safety	V2V	Medium	Event	One-to-a-zone	Long	Strong	Many
RFN	Safety	V2V	Medium	Event	One-to-a-zone	Long	Strong	Many
CCW	Safety	V2V	Short	Periodic	One-to-Many	N.A.	N.A.	N.A.
CVW	Safety	V2I	Short	Periodic	One-to-Many	N.A.	N.A.	N.A.
CRN	Convenience	V2V	Long	Event	One-to-zone	Long	Strong	Many
TP	Convenience	V2I	Long	Event	One-to-one	Short	None	Many
TOLL	Convenience	V2I	Short	Event	One-to-one	Short	None	One
PAN	Convenience	V2I	Long	User-Initiated	One-to-one	N.A.	N.A.	N.A.
PSL	Convenience	V2I	Short	User-Initiated	One-to-one	N.A.	N.A.	N.A.
RVP/D	Commercial	V2I	Short	User-Initiated	One-to-one	N.A.	N.A.	N.A.
SA	Commercial	V2I	Long	User-Initiated	One-to-a-zone	N.A.	N.A.	N.A.
CMDD	Commercial	V2I	Long	User-Initiated	One-to-one	N.A.	N.A.	N.A.
RTVR	Commercial	V2I	Long	User-Initiated	One-to-one	N.A.	N.A.	N.A.

A. Application Characterization based on Application Characteristics

The process of application characterization is divided into two steps: *characterization of application attributes* and *characterization of network attributes* (i.e., network design), as shown in Table IV and Table V respectively. By first exploring all the relevant application characteristics for each application, we gain a more complete understanding towards the fundamental properties and functionality requirements of these applications. Later, we show how this effort gives rise to application characterization from the network design point of view.

Table IV lays out the main application characteristics of each application based on the selected application-related attributes summarized in Section III-A. Given the limited space, we are unable to discuss the characteristics for all 16 applications. Instead, we only highlight a few important application characteristics, illustrating how these criteria help to differentiate the often subtle difference between the various applications:

- 1) Notice that most of the safety applications have a medium-sized effective application range (i.e., a few hundred meters

to 1 kilometer), since safety messages, such as vehicular kinematics status or road conditions, are only relevant to other vehicles within a moderate geographical region. Exceptions are the CCW and CVW applications, which have a small application effective range because they require the closer monitoring of vehicles in their direct neighborhood (i.e., within 200 meters). Conversely, convenience applications generally require a medium or large effective range (i.e., up to a few kilometers), because it is vital for drivers to know the congestion situation or traffic condition at this range for effective detour or trip planning decision making. Similarly, commercial applications also tend to have a large effective range in order to access remote commercial service providers¹.

- 2) Most safety applications (e.g., EEBL, RHCN and SVA) and a few convenience applications (e.g., CRN, TP and TOLL) are initiated by the events happening on the road, such as vehicle collisions, detection of road hazards (e.g. ice, oil), sudden braking, or detection of traffic congestion. If no such events happen, these applications will not be called upon. Among safety applications, CCW and CVW are unusual because they rely on the periodical message updates to monitor the neighboring vehicles' driving status, regardless of safety events. On the other hand, most convenience applications and commercial applications are triggered on-demand by vehicle occupants, rather than by any safety event on the road or the vehicle itself.
- 3) The potential recipients of application messages, in most safety applications (e.g., SVA and EEBL), are vehicles within a specific zone (i.e., behind the vehicle which detects the event and originates the safety message). Thus, safety applications can be summarized as *one-to-a-zone* recipient patterns². At the same time, convenience and commercial applications vary from application to application: some convenience applications (e.g. TOLL) and commercial applications (e.g., RVP/D, CMDD, and RTVR) have point-to-point (*one-to-one*) modes, while other convenience applications (e.g., CRN) and commercial applications (e.g., SA) are fundamentally *one-to-a-zone* in nature.
- 4) "Event" is an important concept in safety applications, and a few convenience applications, because it is an event that initiates the application operations. In our study, we also characterize safety events via several properties of events, including event duration, event correlation, and event detectors. Consistent with our conjecture, we find that safety events drastically vary from application to application. For example, sudden braking (EEBL) is a one-shot event, while road hazard/feature events (RHCN or RFN) are persistent events. Also, different instances of RHCN or RFN events caused by the same road hazard/feature are more likely to be correlated with each other, in contrast to the totally independent PCN events. Even though the study of event characteristics is not directly used in the network design conducted in Section IV-B, we believe that such an analysis can help future network designers better capture the data traffic patterns induced by event-driven safety applications.

From an application benefits point of view, different applications have different functionalities, providing different usages for customers. Interestingly enough, we realize that many applications exhibit highly similar application characteristics, with the exception of a few minor differences. To validate whether such an observation is also valid from a network design perspective,

¹For example, fast food restaurant is willing to announce its service to vehicles in a long area (i.e., several kilometers) around its location.

²Again, CCW and CVW do not follow this general trend. In these two applications, all the vehicles in the neighborhood are supposed to receive the periodic update in order to avoid potential crash from any direction. So these two applications belong to one-to-many recipient patterns.

we also conduct an application characterization based on the relevant network attributes listed in Section IV-B.

B. Application Characterization based on Network Attributes

As mentioned in Section III-B, for each application we discovered that its characteristics tend to mandate a certain design in the network protocol stack. For example, applications with one-to-many recipient patterns are more likely to use broadcast routing protocols, while unicast routing protocols are suitable for applications with one-to-one recipient patterns. Similarly, a single-hop packet dissemination mechanism is adequate to support applications with small application Region Of Interests(ROI) (i.e. a few hundred meters). In contrast, multi-hop routing protocols are needed for applications with medium or large application ROI. This way, we are capable of determining the potential design choices for various components in the network stack by referring to their corresponding application characteristics and requirements³.

Table V lays out the main network attributes of each application based on the selected network attributes summarized in Section III-B, starting from the lower physical layer to the upper transportation layer. These network attributes cover design issues such as the physical layer channel frequency, the usage of infrastructure, message TTL(Time-To-Live), routing protocol and network protocol triggers at the network layer, transportation layer design, and security solutions. Again, we only emphasize a few important network attributes, discussing the potential impact of application characteristics on these network design issues.

- 1) The message packet format is determined by the type of application (from the perspective of user benefit). Normally, safety and convenience applications use light-weight short messages in the WSMP format, to improve network resource efficiency. Commercial applications, on the other-hand, generally prefer the traditional heavy-weighted IP format to be compatible with existing Internet commercial services.
- 2) The network-layer routing protocol is one essential component in a network stack, differentiating the reachability and recipient patterns of various applications. Most safety applications utilize multi-hop geocast routing protocols⁴, because of the one-to-many communication nature in safety applications. CCW and CVW applications, instead, use the single-hop broadcast scheme to announce the periodic update in their direct neighborhood. Convenience and commercial applications either use geocast/broadcast protocols to announce messages in a region (for advertisement service like SA, or traffic congestion notification like CRN), or exploit unicast protocols to forward packets to a given destination (for financial transactions like TOLL, or data download from infrastructure like CMDD).
- 3) How the network routing protocol is triggered is another interesting design choice to be examined in our study. Event-driven safety applications (e.g., SVA, EEBL and CRN) require the event-triggered mechanism in network protocols, periodic-based safety applications (e.g., CCW and CVW) mandate the periodic beacon (or hello message) mechanism, and user-initiated convenience and commercial applications (e.g., SA, RVP/D and PSL) are triggered in an on-demand fashion.

³At the same time, we also notice that some of the network attributes are purely the choices of network designers, since different technical approaches are able to achieve the same objective.

⁴Geocast routing distributes packets within a given zone or region. Thus, a geocast routing protocol can be viewed as a special case of broadcast routing.

TABLE V
APPLICATION CHARACTERIZATION BASED ON NETWORK ATTRIBUTES

Acro.	Channel Frequency	Infra-structure	Message TTL	Packet Format	Routing Protocol	Network Trigger	Transport Protocol	Security Solution
SVA	DSRC CCH	No	Multi-hop	WSMP	Geocast	Event-triggered	Connection-less	V2V security
EEBL	DSRC CCH	No	Multi-hop	WSMP	Geocast	Event-triggered	Connection-less	V2V security
PCN	DSRC CCH	No	Multi-hop	WSMP	Geocast	Event-triggered	Connection-less	V2V security
RHCN	DSRC CCH	No	Multi-hop	WSMP	Geocast	Event-triggered	Connection-less	V2V security
RFN	DSRC CCH	No	Multi-hop	WSMP	Geocast	Event-triggered	Connection-less	V2V security
CCW	DSRC CCH	No	Single-hop	WSMP	Broadcast	Beacon	Connection-less	V2V security
CVW	DSRC CCH	Yes	Single-hop	WSMP	Broadcast	Beacon	Connection-less	V2I security
CRN	DSRC SCH	No	Multi-hop	WSMP	Geocast	Event-triggered	Connection-less	V2V security
TP	DSRC SCH	Yes	Multi-hop	WSMP	Unicast	Event-triggered	Connection-oriented	V2I security
TOLL	DSRC SCH	Yes	Single-hop	WSMP	Unicast	Event-triggered	Connection-oriented	Internet security
PAN	DSRC SCH	Yes	Multi-hop	WSMP	Unicast	On-demand	Connection-oriented	V2I security
PSL	DSRC SCH	Yes	Single-hop	WSMP	Unicast	On-demand	Connection-oriented	V2I security
RVP/D	DSRC SCH WiFi	Yes	Single-hop	IP	Unicast	On-demand	Connection-oriented	V2I security
SA	DSRC SCH WiFi	Yes	Multi-hop	IP	Geocast	On-demand	Connection-less	Internet security
CMDD	DSRC SCH WiFi	Yes	Single-hop	IP	Unicast	On-demand	Connection-oriented	Internet security
RTVR	DSRC SCH WiFi	Yes	Multi-hop	IP	Unicast	On-demand	Connection-oriented	Internet security

- 4) The involvement of infrastructure in network design and application development is another key issue for consideration⁵. Both infrastructure-oriented approaches and non-infrastructure approaches (or, even a combination of both approaches) are used to achieve the objective of supporting the applications or services discussed above. Deployment of infrastructure-oriented services depends on considerations such as availability of infrastructure, costs and technology deployment. Infrastructure can facilitate the design of convenience applications as well as enable commercial applications by providing the gateway to the existing Internet infrastructure. As a side note, the involvement of infrastructure also complicates the design of security solution. We believe that security solutions for V2V applications are different from that for V2I applications. Also, the gateway to the Internet requires the compatibility of V2V/V2I security solutions with the existing

⁵Please note the infrastructure in this paper only refers to road-side units along the roads, rather than base stations in cellular systems. Two minor differences exist between infrastructure and vehicles: (1) Infrastructure is stationary while vehicles are mobile; (2) infrastructure may have the direct connection to Internet, but vehicles do not.

Internet security solutions.

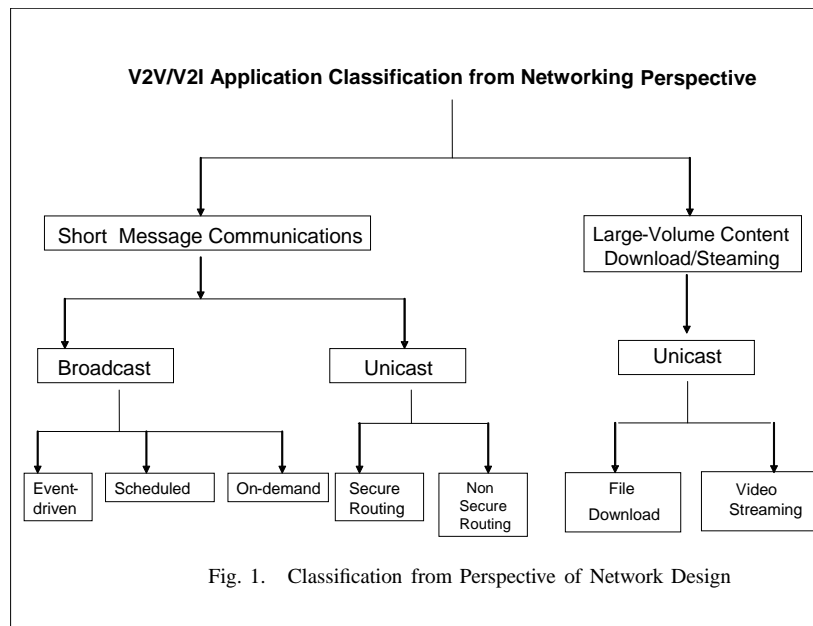
Throughout our study, we found that Table IV and Table V reveal a number of interesting observations. Generally speaking, many applications exhibit highly similar application characteristics, resulting in similar protocol designs in the network stack. For instance, (1) RHCN and RFN are nearly the same, except that the type of safety warning messages are different: RHCH is about road hazards, while RFN is about road features. (2) PCN and RHCN are also similar except for the number of event originators: PCN has a sole message host, while RHCN has multiple message hosts. Even though this difference gives rise to different levels of data traffic burstiness from event generation, the network protocol stacks for these two applications are still similar to each other. (3) Also, CCW and CVW applications can be categorized into the same type, although the former is a V2V application whereas the latter is a V2I application.

In summary, the first 7 safety applications (SVA, EEBL, PCN, RHCN, RFN, CCW, and CVW) all utilize broadcast/geocast routing protocols to distribute safety/warning messages in the WSMP format. On the other hand, some convenience applications mostly rely on user-initiated unicast routing protocols to deliver non-safety messages in the WSMP format, while commercial applications may exploit IP protocols to enable enhanced functionality such as QoS routing. This, in turn, suggests that the studied applications naturally lead themselves to fewer numbers of *generic* and *abstract* classes, which is the subject matter of the next section.

C. Application Classification

With a deep understandings of application characteristics and network attributes towards all these 16 applications, we are able to classify them into a number of *generic* categories. Notice that application classification can be conducted at different levels, depending on the requirements of design granularities. For example, a simple classification effort and a few abstract categories are adequate for high-level concept design of automotive communication applications. On the contrary, empirical design of prototype systems normally mandates an exhaustive effort, resulting in a sophisticated multi-level of application categories. With looking into more system details, an application categorization at level of concept design can be enriched and further classified, morphing into its counterpart at level of empirical system design.

At the initial stage of this emergent research field, we believe that a high-level classification is sufficient to serve the purpose of clarifying the concepts and identifying the synergy among various applications, without unnecessarily complicating the problem formation. Later on, the empirical prototype system can be designed and implemented based on the refined and enriched version of this study. Here, we present such a way to classify the aforementioned applications from the perspective of network design (as shown in Fig. 1), among other alternatives. Generally speaking, V2V/V2I applications can be classified into two broad generic classes, namely **Short Message Communications** and **Large-Volume Content Download/Streaming**. Most safety and convenience applications belong to the first class, since the messages in these applications are light-weight WSMP messages. Considering that the IP message format is appropriate for large-volume data (such as Internet web access or video/audio streaming), most commercial applications fall under the second category.



1) *Short Message Communication Type*: First, we discuss the class of Short Message Communication which uses light-weight WSMP packets. This class can be classified, depending on the recipient pattern and routing protocol, as either Broadcast/Geocast or Unicast applications. Clearly, most safety applications require message announcements be sent to a large number of nodes (one-to-many or one-to-a-zone), hence, they would fall under the Broadcast/Geocast-oriented type. On the other hand, many convenience applications (including payment-type applications) would fall under the Unicast-oriented type.

According to the network protocol triggering condition, **Broadcast/Geocast**-oriented applications can be further classified as event-driven, scheduled (periodic) and on-demand approaches. The event-driven approach is used for safety applications focusing on life-threatening events, and the scheduled approach is suitable for safety applications requiring periodic message updates, whereas the on-demand approach is appropriate for convenience applications such as parking spot locator. As a side note, high-level V2V security solutions are required to protect safety applications from malicious hackers. These three sub-classes of Broadcast/Geocast-oriented applications are:

- *Event-driven Broadcast/Geocast Approach*: SVA, EEBL, PCN, RHCN and RFN applications, as well as CRN application, belong to this category. (class 1)
- *Scheduled (periodic) Broadcast/Geocast Approach*: CCW and CVW applications fall into this category. (class 2)
- *On-demand Broadcast/Geocast Approach*: Some convenience or commercial applications, like SA, belong to this category. (class 3)

The secure routing of financial transactions in convenience applications also plays an important role in **Unicast**-oriented applications. Thus, these Unicast-oriented applications can be classified as either involving stringent secure routing for financial transactions, or those which do not involve secure routing. Thus, we list these two sub-classes of Unicast-oriented applications are:

- *Secure Unicast Approach*: One example of this approach are TOLL applications (e.g., Drive-thru payment, Free-flow

TABLE VI
NETWORK DESIGN CONSIDERATIONS FOR 7 TYPES OF APPLICATIONS

Application Type	Channel Frequency	Packet Format	Routing Protocol	Connection to Internet	Transportation Protocol	Security
Event-driven Broadcast/Geocast	DSRC CCH	WSMP	Event-driven multi-hop broadcast/geocast	No	Connection-less	V2V Security
Scheduled Broadcast/Geocast	DSRC CCH	WSMP	Scheduled multi-hop broadcast/geocast	No	Connection-less	V2V/V2I Security
On-demand Broadcast/Geocast	DSRC SCH, or WiFi	WSMP, or IP	User-initiated on-demand multi-hop broadcast/geocast	No	Connection-less	V2V/V2I Security
Secure Unicast	DSRC SCH	WSMP	multi-hop unicast with secure routing	No	Connection-oriented	Stringent V2V/V2I Security
Normal Unicast	DSRC SCH	WSMP	multi-hop unicast	No	Connection-oriented	V2V/V2I Security
File Download	DSRC SCH, or WiFi	IP	multi-hop unicast	Yes	Connection-oriented	V2V/V2I /Internet Security
Media Streaming	DSRC SCH, or WiFi	IP	single-hop unicast with QoS routing	Yes	Connection-oriented	V2V/V2I /Internet Security

Tolling). RVP/D also falls into this category since it is potentially related with the control components of vehicles. (class 4)

- *Normal Unicast Approach*: TP, PAN and PSL applications fall into this category. Also, some of commercial applications (e.g., vehicle-to-vehicle online chatting or social networking application) belong to this category. (class 5)

2) *Large-Volume Content Download/Streaming*: Next, we focus on the second major class of applications, namely Large-Volume Content Download/Streaming, which is normally implemented in the IP format for compatibility. These applications often utilize unicast protocol because of their one-to-one communication nature. This class is further classified depending on the content type: either file download or media streaming. The former type allows short-term disruption in network service, so it is inherently latency-tolerant. The latter type requires a relatively smooth streaming transfer, so it is fundamentally latency-sensitive. It is straightforward to notice the following memberships in large-volume content download/streaming applications:

- *File Download*: CMDD application (e.g., map database download or web access/browsing) is one example of this approach. (class 6)
- *Video Continuous Streaming*: RTVR application (e.g., video/MP3 streaming among vehicles or from road-side infrastructure for entertainment) falls into this category. (class 7)

These seven types of V2V/V2I applications and their key considerations in network design are summarized in Table VI. From the above discussion, we conclude that the given set of applications can be classified into 7 generic classes. Since these applications are carefully chosen to represent many other applications, we believe that our classification methodology and classification results can also apply to a large number of V2V/V2I applications.

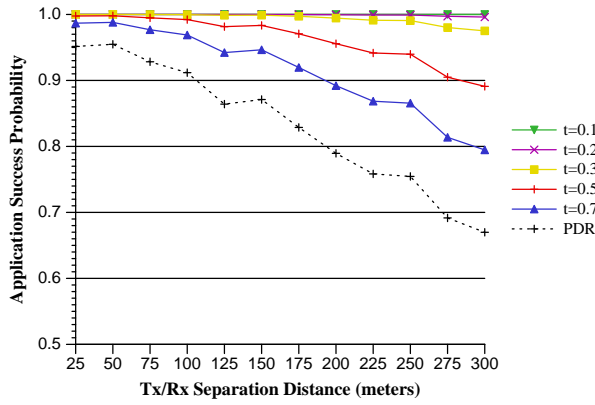
The potential benefits of application classification include:

- 1) Such a classification effort not only contributes to capturing the common features and technical requirements of applications, but also helps to develop common network stacks for the identified generic classes. In the near future, with the deeper understanding of these *generic* and *abstract* classes, we are able to increase the module re-usability of wireless networking solutions for the given set of applications with similar characteristics.
- 2) At the same time, such a classification effort helps to identify common requirements and performance metrics relevant to each application class. It also eases application modeling in simulation studies targeted at the performance evaluation of a large number of applications. By appropriately isolating generic network design from different application instantiations, we argue that it is much more efficient to model these 7 generic classes than it is to model all 16 applications in an exhaustive manner without exploiting their noticeable commonality. Thus, a generic model should suffice for gathering statistics for the performance metrics defined for a specific class. Gathering performance results for a particular application, for the purposes of detailed analysis, could be achieved by deriving the application of interest as a simple extension from its generic model.

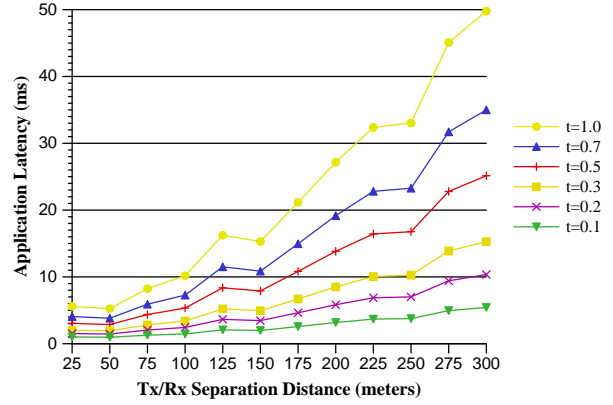
V. PERFORMANCE METRICS AND QOS REQUIREMENTS

Defining and gathering the “right” performance metric is crucial to efficiently guiding the development of networking algorithms and protocols, towards guaranteeing satisfactory performance of the applications, under a wide variety of realistic operating environments. Performance metrics can be generally classified to **network-level** (or packet-level) metrics and **application-level** metrics. In traditional Internet and Mobile Ad hoc Networking (MANET) communities, the network-level metrics have received wide interest. This is primarily because of the strong need to analyze and understand, at a microscopic packet-level, how protocols/algorithms behave under different environments and user dynamics. Examples of these packet-level metrics include: packet delivery ratio (PDR) and average per-packet latency, etc. On the other hand, the application-level metrics also constitute the driving force for protocol development, when applications play an important role in pushing the development of technical solutions. For example, QoS performance requirements are clearly defined for voice over IP (VoIP) and video streaming applications in the traditional telephony industry and on-line video rendering business (e.g., VoIP E2E latency is about 50-100 msec). Notice that the mapping between packet-level metrics and application-level metrics is generally non-trivial.

Based on the classification proposed in Section IV-C, our objective is to introduce performance metrics for these classes of application, which quantitatively capture their key characteristics. Referring to the 7 generic classes, it can be easily noticed that the first 2 classes (event-driven and scheduled broadcast/geocast approaches used to accommodate safety applications) significantly differ from traditional applications, because of their safety nature. One of our major challenges is to define the application-level metrics relevant to safety applications. For safety-oriented applications, we introduce both network-level metrics and application-level metrics as well as discuss their relation to each other through simple mappings, which are our focus of this section. We believe that such an understanding helps the networking research society and the automotive society to bridge the gaps between them. For the remaining types of applications, we are able to borrow the well-defined metrics from



(a) Application reliability P_{app} for varying broadcast intervals t (sec) and tolerance interval $T = 1$ (sec).



(b) Application-perceived mean packet latency ΔT for varying broadcast intervals t (sec) and per-packet latency $\Delta\tau = 5$ (ms).

Fig. 2. Analytical results for the application-level reliability (a) and time-to-successful reception (b) metrics for broadcast-based applications, where the baseline packet delivery ratio P_{net} (shown in (a) as PDR) is empirically measured from real-world experiments

existing literature. Accordingly, we begin with performance metrics for broadcast-oriented safety applications, and follow with unicast-oriented applications. Finally, we discuss the QoS performance metrics for content download/streaming applications.

A. Performance Metrics for Broadcast-based Safety and Non-safety Applications (class 1, 2 and 3)

For broadcast(geocast)-based safety applications, network-level and application-level metrics are important to capture the performance of network protocols and performance of applications, respectively.

1) *Network-level Metrics*: Two major network-level metrics are defined to capture the performance of network protocols: (a) **Packet Delivery Ratio (PDR)** $P_{net}(d)$ and (b) **Average Per-packet Latency (APL)** $\Delta\tau$. Packet Delivery Ratio $P_{net}(d)$ is defined as the probability of successfully receiving packets at distance d from broadcasting vehicle, illustrating the reliability of packet transmission over wireless medium. Average Per-packet Latency $\Delta\tau$ is defined as the duration between the time of generating a packet at sender vehicle and the time of successfully receiving that packet at receiver vehicle. Only successfully received packets are counted to calculate average per-packet latency.

These two network-level metrics serve an important role for network designers in verifying and debugging protocols and answering fundamental questions of the form: What dominates the performance of average per-packet latency $\Delta\tau$? What is the maximum back-off time experienced by the MAC for a given network density? How does $P_{net}(d)$ vary with distance under extreme network densities? However, these metrics are of limited utility from an application perspective, because performance requirements are typically given in terms of application-level metrics as opposed to packet-level metrics. For example, application reliability of SVA could be required to be above 99% for warning messages to be received within 1 second. An effort of examining the application performance, from application point of view, is lack in the current VANET community. Accordingly, the mapping function between safety application requirements and packet-level metrics is also lack in previous studies. This, in turn, suggests the need for a set of application-level metrics that can bridge the gap between network performance and application performance, directly relating to the aforementioned application requirements from automotive

safety engineers' perspective. Next, we define two candidates of application-level metrics.

2) *Application-level Reliability Metric*: In event-driven safety applications, same safety messages are broadcasted several times when the safety event occurs; Similarly, different safety messages in the scheduled safety applications (containing the GPS and kinematics information of vehicles) are more likely to be correlated with each other. Thus, the safety applications are claimed as "reliable" as long as more than one of several safety messages are successfully received in a given duration. To capture this comprehension, we also introduce the concept of application-level reliability. **Application-level T-Window Reliability** (TWR) $P_{app}(d)$ is defined as the probability of successfully receiving at least one packet out of multiple packets from a broadcasting vehicle at distance d , within a given time interval T (we call this time interval T as application tolerance window) [24]. This metric describes the application-level reliability for safety application, rather than reliability of wireless communication at packet level.

Using scheduled broadcast protocols as an example, we propose a simple model relating the application-level reliability with packet-level reliability. According to definition, application reliability $P_{app}(d)$ is the probability of successfully receiving at least one packet during tolerance time window T , at distance d . Since safety application periodically broadcasts its information with given fixed broadcast interval t , we know that application reliability $P_{app}(d)$ is the probability of successfully receiving at least one packet among M (here, $M = \frac{T}{t}$) consecutive packets. This, in turn, is equal to $1 - Pr(\text{receiving no packet among } M \text{ consecutive packet})$. Given the assumption that packet drops are independent, we know that $Pr(\text{receiving no packet among } M \text{ consecutive packets})$ follows a binomial distribution with probability $P_{net}(d)$ and $n = 0$. Therefore, $Pr(\text{receiving no packet among } M \text{ consecutive packets}) = (1 - P_{net}(d))^M$. By putting all the steps together, we obtain an analytical model linking application-level reliability to network-level reliability, as follow

$$P_{app}(d) = 1 - (1 - P_{net}(d))^M \quad (1)$$

$$= 1 - (1 - P_{net}(d))^{\frac{T}{t}} \quad (2)$$

Based on Eqn.2, safety application reliability $P_{app}(d)$ at distance d is a function of both wireless communication reliability $P_{net}(d)$ at distance d and the safety application re-broadcast interval t . Eqn.2 can be readily used to map packet-level reliability to application-level reliability, providing us the freedom to use either metric in the application performance specification. As an intuitive example, both the network-level reliability⁶ and the resultant application-level reliability, are presented in Fig. 2(a) as a function of distance d between the transmitter and receiver. Shown are the results for varying broadcast interval t (seconds) for a constant application tolerance interval of $T = 1$ (seconds). Notice that the application reliability can be high even if the PDR is low as long as t is small compared to T . In this instance, $T/t \approx 3$ results in an application reliability of 97% for a 67% PDR. Also notice that network-level reliability, which is typically used by wireless networking designers, says nothing about whether the application performance is met or not. The simple mapping we have enables network research community to accurately account for application requirements, and also allows automotive research community to evaluate the impact that wireless network reliability has on communication-based automotive applications.

⁶The network-level reliability metric, Packet Delivery Ratio (PDR), was collected via several empirical measurement campaigns conducted by the authors [24].

3) *Application-level Latency Metric: Time-to-Successful Reception* (TSR) ΔT is defined as the duration between the time when a broadcast packet is generated at application layer of transmitting vehicle and the time at which the first successful packet is received by the application layer of receiving vehicle [23]. Notice that this measure is equal to the average per-packet latency $\Delta\tau$ discussed earlier if and only if there are no packet losses. In case of packet losses, this measure becomes larger due to the direct impact of successive packet collisions on this measure. This measure is directly related to safety application requirements through the following constraint

$$P(\Delta T \geq t_0) \leq \epsilon, \quad (3)$$

where t_0 is the maximal allowed value of time-to-successful reception for the given application and ϵ is arbitrarily small value (e.g., at the order of 10^{-3}).

Again, using scheduled broadcast protocols as an example, we are able to relate the network-level average per-packet latency $\Delta\tau$ and the application-level latency ΔT . For a given sequence of packet broadcasts P_i ($i = 1, 2, 3, \dots$), with assumptions of independent packet losses, packet transmissions can be modeled as independent Bernoulli trials with probability of success P_{net} and probability of failure as $(1 - P_{net})$. Thus, the probability mass function (PMF) of Time-to-Successful Reception ΔT would be given as

$$f_{TSR}(\Delta T)$$

$$= \begin{cases} \Delta\tau(P_1) & \text{w/ } p = P_{net} \\ t + \Delta\tau(P_2) & \text{w/ } p = P_{net}(1 - P_{net}) \\ 2t + \Delta\tau(P_3) & \text{w/ } p = P_{net}(1 - P_{net})^2 \\ 3t + \Delta\tau(P_2) & \text{w/ } p = P_{net}(1 - P_{net})^3 \\ \vdots & \vdots \\ \vdots & \vdots \\ (n-1)t + \Delta\tau(P_n) & \text{w/ } p = P_{net}(1 - P_{net})^{(n-1)} \\ \vdots & \vdots \\ \vdots & \vdots \end{cases}$$

Assuming per-packet latency for different packets is the same (i.e., $\Delta\tau(P_1) = \Delta\tau(P_2) = \dots = \Delta\tau$), the above equation can be simplified as

$$f_{TSR}(\Delta T)$$

$$= \begin{cases} \Delta\tau & \text{w/ } p = P_{net} \\ t + \Delta\tau & \text{w/ } p = P_{net}(1 - P_{net}) \\ 2t + \Delta\tau & \text{w/ } p = P_{net}(1 - P_{net})^2 \\ 3t + \Delta\tau & \text{w/ } p = P_{net}(1 - P_{net})^3 \\ \vdots & \vdots \\ \vdots & \vdots \\ (n-1)t + \Delta\tau & \text{w/ } p = P_{net}(1 - P_{net})^{(n-1)} \\ \vdots & \vdots \\ \vdots & \vdots \end{cases}$$

Thus, the expected value of Time-to-Successful Reception can be calculated based on its PMF, as follow

$$E[\Delta T] = \sum_{i=1}^{\infty} (\Delta T(P_i) \times p(P_i)) \quad (4)$$

$$= \Delta\tau + t \left(\frac{1}{P_{net}} - 1 \right) \quad (5)$$

Eqn.5 reveals that application-level latency ΔT is a function of per-packet latency $\Delta\tau$, re-broadcast interval t and wireless communication reliability P_{net} . This way, we are also able to map the packet-level latency to the application-level latency, so that we can specify the latency requirement in either of them.

As another intuitive example, the application-perceived latency for varying broadcast intervals t (seconds) is presented in Fig. 2(b) as a function of distance d between the transmitter and receiver. Here, $\Delta\tau = 5ms$. Again, we observed that application-level latency experienced by users is not solely determined by the network-level latency.

Interestingly, from Eqn.2 and Eqn.5, we find that both application-level reliability and application-level latency are not only affected by wireless communication behavior (e.g., network-level reliability P_{net} and network-level latency $\Delta\tau$), but also significantly affected by the communication-based automotive application parameter (i.e., broadcast interval t). Thus, by appropriately adjusting the automotive communication system parameters (such as broadcast interval t), we are still able to achieve the required application performance even under the scenarios where the wireless communication behavior is not satisfactory.

In summary, we find out that reliability and latency (at both network-level and application-level) are the major metrics to capture the performance trends of broadcast-oriented safety applications (class 1 and 2). At the same time, we also realize that only packet-level reliability and latency metrics are relevant to user-initiated on-demand applications (class 3).

B. Performance Metrics for On-demand Message Unicast-based Applications (class 4 and 5)

Different than safety applications where broadcasted messages are somehow correlated with each other, messages in convenience applications normally bear important pieces of information which are independent from each other. This is similar to many traditional Internet applications. Therefore, we believe that network-level metrics, such as packet delivery ratio and per-packet latency, are the most relevant metrics to capture the performance for these applications.

1) *Network-level Reliability Metric*: In most convenience applications, messages are uncorrelated with each other. Given this consideration, the packet-level reliability metric **Packet Delivery Ratio** (PDR) not only captures the network-level reliability, but also accurately describes the application-level reliability. Hence, the network design should strive to deliver all transmitted packets successfully. Thus, we expect that the network-level reliability requirements of convenience applications are roughly at the same level as those of safety applications.

2) *Network-level Per-Packet Latency*: With the same argument, we believe that network-level **Average Per-packet Latency** (APL) is the relevant metric for convenience applications, as compared to the application-level latency metric. For applications requiring secure routing (class 4) such as free-flow TOLL collection, the challenging part is that the entire process of the financial transaction (including handshaking, authentication and transaction) has to be completed over a short time period

when the OBU, moving at, say, 70 mph, lies within the communication range of the RSU. This situation implicitly requires a very small network-level latency (e.g., a few hundred millisecond) to successfully complete the financial transaction. Such a latency requirement is even more stringent than broadcast-based safety applications. Unsecured routing applications (class 5) do not enforce such strict latency requirements because the cumbersome handshaking mechanism for security is unnecessary.

From the above discussion, we realize that the packet-level latency and the network-level packet delivery ratio seem to capture the most important characteristics of convenience applications (class 4 and class 5).

C. Performance Metrics for Content Download and Streaming Applications (class 6 and 7)

Unlike the first 5 classes of applications, which rely highly on short message communication, content downloading and streaming applications provide efficient downloading and streaming of large data files. As a result, performance measures of these applications are focused on network-level metrics (such as packet-level packet delivery ratio and end-to-end latency) and application-level QoS metrics (such as end-to-end throughput and jitter).

1) *Packet-level Metric*: Performance measures of Internet web-access applications also apply to file download applications (class 6, e.g. FTP or map database download). Generally speaking, this type of applications is delay-tolerant since it does not involve real-time communications. Hence, latency requirements are not considered for these applications. On the other hand, these applications are typically loss-sensitive, since packet loss may hinder the successful data transfer and thus damage the reconstructed data file. Therefore, we argue that packet-level metric such as **Packet Delivery Ratio (PDR)** is the most important performance metric for file download applications.

On the contrary, media (video or VoIP) streaming applications are normally latency-sensitive but loss-tolerant. Thus, we argue that **End-to-End Latency** metric is the most important packet-level metric for such type of applications. End-to-end delay, in the traditional Internet literatures, captures the latency that VoIP or video streaming applications experience. Many factors, such as wireless propagation/transmission delay, encryption delay, filtering and other processing delay, contribute to application-level end-to-end delay. In fact, this metric is the Average Per-packet Latency (APL) metric defined in Section V-A.

2) *Application-level QoS Metrics*: Besides packet-level metrics like packet delivery ratio and end-to-end latency, application-level QoS metrics also play an important role in defining application performance trends for streaming applications (class 7). For example, media streaming applications use similar application-level performance measures developed for real-time media streaming over the Internet, including end-to-end throughput and end-to-end jitter. **End-to-End Jitter (E2EJ)** refers to the variance of delays for several consecutive packets arriving at the destination. For example, successive packets might suffer different delays, resulting in a choppy voice quality directly affecting quality of service. **End-to-End Throughput (E2ET)** illustrates the bandwidth that streaming applications enjoy, which also directly determines the quality of service for end users.

To summarize, packet delivery ratio (PDR) is the most important performance metric to capture the performance trend of delay-tolerant loss-sensitive content downloading applications (class 6). However, for delay-sensitive loss-tolerant streaming applications (class 7), end-to-end delay, jitter and end-to-end throughput are the major three performance metrics to illustrate quality of service, among other metrics.

TABLE VII
SUMMARY OF PERFORMANCE METRICS AND QoS REQUIREMENTS

Metric Level	Metric Name	Definition	Applied Classes
Network	Packet Delivery Ratio (PDR)	The probability of successfully receiving packets at a given distance from broadcasting vehicle.	1, 2, 3, 4, 5, 6
Network	Average Per-packet Latency (APL)	The duration between the time of sending a packet at sender vehicle and the time of receiving that packet at receiver vehicle, if that packet is successfully received.	1, 2, 3, 4, 5, 7
Application	T-Window Reliability (TWR)	The probability of successfully receiving at least one packet out of multiple packets from a broadcasting vehicle at a given distance, within a given time interval T (T is tolerance window).	1, 2, 3
Application	Time-to-Successful Reception (TSR)	The duration between the time when a packet is generated at transmitting vehicle and the time when the first successful packet is received at receiving vehicle.	1, 2, 3
Application QoS	End-to-End Jitter (E2EJ)	The variance of per-packet latency for several consecutive packets arriving at the destination from the same source.	7
Application QoS	End-to-End Throughput (E2ET)	The maximal bandwidth of streaming applications can occupy over wireless channel.	7

D. Summary

Based on the above discussion, we summarize the key performance metrics of our interests in Table VII. Clearly, both network- and application-level performance metrics play important roles in accurately capturing the performance of automotive communication applications: *Network-level metrics help to evaluate the performance of the wireless network. Application-level metrics, on the other hand, are used to evaluate the performance of the targeted applications which the end users would directly experience in their daily usage.*

Safety-oriented applications (class 1, 2 and 3) is of our special interests, because they have a great potential to provide real-time safety alerts and benefit the drivers. Here, we find that the network-level metrics include Packet Delivery Ratio (PDR) and Average Per-packet Latency (APL), while other metrics like T-window Reliability (TWR) and Time-to-Successful Reception (TSR) fall into the category of application-level metrics. In addition, we also establish the relationship between network-level metrics and application-level metrics for safety-oriented applications. Via such a linkage, we are able to translate the needs of the specific applications into the application-independent wireless networking performance measures.

VI. CONCLUSION AND FUTURE WORK

In this paper, we analyze the characteristics of various communication-based automotive applications in a systematic manner and classify them into several major *generic* and *abstract* categories. Such an application characterization and classification effort facilitates the design and implementation of network protocol stack for these applications. In this study, we first propose a rich set of attributes of the applications, including both application characteristics and networking attributes, to better capture the properties of various applications. We then carefully investigate and analyze the attributes of 16 vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) applications. We realize that these applications can be categorized into three major classes:

Short Message Broadcast type (for safety applications), On-demand Short Message Unicast type (for convenience applications) and Large-Volume Content Download/Streaming (for commercial applications). Finally, we present a list of performance metrics and QoS requirements for each type of applications, which are used to evaluate the performance trend of applications and network protocols.

The analysis of application characteristics and networking attributes, the classification of various vehicular communication applications, and the identification of key performance metrics for each category of applications presented in this paper, shed some light on our future task of developing network protocol stack for various communication-based automotive applications. As the next step, we aim to continue our current effort of investigating the potential network solutions for these 7 generic types of vehicle-related communication applications, with the consideration of re-usability of network protocol modules (or building blocks). To be specific, we would like to decompose the network protocol stack into a set of mechanistic building blocks for different types of applications, so that we are able to maximize the re-usability of common building blocks for various applications.

VII. ACKNOWLEDGEMENT

The authors would like to thank our colleagues, Carrol C. Kellum, Donald K. Grimm, Priyantha Mudalige, Chaminda Basnayake, Jijun Yin, and Siddhartha Goel, for their insightful discussion in the brainstorm phase of this piece of research.

REFERENCES

- [1] W. Chen and S. Cai, "Ad Hoc Peer-to-Peer Network Architecture for Vehicle Safety Communications", IEEE Communications Magazine, April 2005.
- [2] J. Misener, R. Sengupta, and H. Krishnan, Cooperative Collision Warning: Enabling Crash Avoidance with Wireless Technology Proc. 12th World Congress on ITS, Nov. 2005.
- [3] H.-J. Reumerman, M. Roggero, M. Ruffini, "The Application-based Clustering Concept and Requirements for Intervehicle Networks", IEEE communication Magazine, April 2005.
- [4] Jijun Yin, Tamer A. ElBatt, Gavin Yeung, Bo Ryu, Stephen Habermas, Hariharan Krishnan, Timothy Talty, "Performance evaluation of safety applications over DSRC vehicular ad hoc networks", Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks, Philadelphia, PA, USA, September 2004.
- [5] Marc Torrent-Moreno, Daniel Jiang, Hannes Hartenstein. "Broadcast reception rates and effects of priority access in 802.11-based vehicular ad-hoc network", Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks, Philadelphia, PA, USA, September 2004.
- [6] Q. Xu, T. Mak, J. Ko and R. Sengupta, Vehicle-to-Vehicle Safety Messaging in DSRC Proc. 1st ACM Workshop on Vehicular Ad hoc Networks (VANET), Oct. 2004.
- [7] Tamer ElBatt, Siddhartha Goel, Gavin Holland, Hariharan Krishnan, Jayendra Parikh, "Cooperative Collision Warning Using Dedicated Short Range Wireless Communications", The Third ACM International Workshop on Vehicular Ad Hoc Networks (VANET 2006), Los Angeles, California, September 29, 2006.
- [8] J. Anda, J. LeBrun, D. Ghosal, C.-N. Chuah and M. Zhang, "VGrid: Vehicular AdHoc Networking and Computing Grid for Intelligent Traffic Control", IEEE 61st Vehicular Technology Conference VTC 2005 Spring, 29th May - 1st June, Stockholm, Sweden.
- [9] Shirshanka Das, Alok Nandan, Giovanni Pau, M.Y. Sanadidi, Mario Gerla, "SPAWN: A Swarming Protocol for Vehicular Ad Hoc Networks", in Proceedings of the 1st ACM VANET, Philadelphia, PA, October, 2004.
- [10] Alok Nandan, Shirshanka Das, Giovanni Pau, M.Y. Sanadidi, and Mario Gerla, "Cooperative downloading in Vehicular Ad Hoc Networks", In Proceedings of the 2nd Wireless On-Demand Network Systems and Services (WONS 2005), St Moritz, Switzerland, 2005.
- [11] Vikas Taliwal, Daniel Jiang, Heiko Mangold, Chi Chen, Raja Sengupta, "Empirical determination of channel characteristics for DSRC vehicle-to-vehicle communication". Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks, Philadelphia, PA, USA, September 2004.
- [12] Jijun Yin, Gavin Holland, Tamer Elbatt, Fan Bai, Hariharan Krishnan, "DSRC channel fading analysis from empirical measurement," in Proceedings of the 1st IEEE International Workshop on Vehicle Communications and Applications (Vehiclecomm), Beijing, China, October 2006. (to appear)
- [13] Guolong Lin, Guevara Noubir, Rajmohan Rajaraman, "Mobility Models for Ad hoc Network Simulation". INFOCOM 2004
- [14] F. Bai, N. Sadagopan, A. Helmy, "The IMPORTANT Framework for Analyzing the Impact of Mobility on Performance of Routing for Ad Hoc Networks", AdHoc Networks Journal - Elsevier, Vol. 1, Issue 4, pp. 383-403, November 2003.
- [15] Fabio Picconi, Nishkam Ravi, Marco Gruteser, and Liviu Iftode, "Probabilistic Validation of Aggregated Data for V2V Traffic Information Systems". In Proceedings of Third ACM Intern. Workshop on Vehicular Ad Hoc Networks (VANET, held with Mobicom), Los Angeles, 2006.
- [16] Maxim Raya, Panos Papadimitratos, and Jean-Pierre Hubaux, "Securing Vehicular Communications", Accepted for publication in IEEE Wireless Communications Magazine, 2006
- [17] Timo Kosch, "Phase-Transition Phenomena with Respect to the Penetration Rate of DSRC Enabled Vehicles", 12th World Congress on Intelligent Transportation Systems (ITS) San Francisco, USA, November 2005
- [18] Steven E. Shladover, Swe-Kuang Tan, "Analysis of Vehicle Positioning Accuracy Requirements for Communication Based Cooperative Collision Warning", accepted to Journal of Intelligent Transportation Systems, Vol. 10, No. 3.
- [19] Christian Lochert, Martin Mauve, Holger Fler, Hannes Hartenstein, "Geographic routing in city scenarios". Mobile Computing and Communications Review 9(1): 69-72 (2005)

- [20] Gokhan Korkmaz, Eylem Ekici, Fusun ozguner, Umit Ozguner, "Urban multi-hop broadcast protocol for inter-vehicle communication systems". Vehicular Ad Hoc Networks 2004: 76-85
- [21] J. LeBrun, C.-N. Chuah, D. Ghosal, and H. M. Zhang, "Knowledge-Based Opportunistic Forwarding in Vehicular Wireless Ad Hoc Networks", IEEE 61st Vehicular Technology Conference VTC 2005 Spring, 29th May - 1st June, Stockholm, Sweden.
- [22] Jasmine Chennikara-Varghese, Wai Chen, Onur Altintas and Shengwei Cai, "Survey of Routing Protocols for Inter-Vehicle Communications", The Second International Workshop on Vehicle-to-Vehicle Communications 2006 (V2VCOM 2006).
- [23] T. ElBatt, S. Goel, G. Holland, H. Krishnan, J. Parikh, "Cooperative Collision Warning using Dedicated Short Range Wireless Communications," Proceeding of ACM VANET workshop 2006.
- [24] F. Bai, H. Krishnan, "Reliability Analysis of DSRC Wireless Communication for Vehicle Safety Applications," Proceeding of the 9th International Conference of Intelligent Transportation System, 2006.
- [25] Notice of Proposed Rulemaking and Order FCC 03-324, Federal Communications Commission, Feb. 2003.
- [26] Vehicle Safety Communications Project, Task 3 Report, Identify Intelligent Vehicle Safety Applications Enabled by DSRC, <http://www.itsdocs.fhwa.dot.gov/JPODOCS/REPTSTE/14136.htm>
- [27] Vehicle Safety Communications Project Final Report, CAMP IVI Light Vehicle Enabling Research Program, DOT HS 810 591, April 2006.
- [28] Vehicle Infrastructure Integration (VII), USDOT Major Initiative, <http://www.its.dot.gov/vii/>
- [29] Cooperative Intersection Collision Avoidance Systems (CICAS), USDOT Major Initiative, <http://www.its.dot.gov/cicas/index.htm>
- [30] Standard Specification for Telecommunications and Information Exchange Between roadside and Vehicle Systems - 5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications ASTM E2213-03, Sept. 2003.
- [31] IEEE 802.11 WG, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications IEEE, Aug. 1999.
- [32] Press Release, "Cars Are Talking; Safety Is the Topic", By Jeremy W. Peters, 2 January 2006, The New York Times.
- [33] Press Release, "GM Develops Vehicles With a Sixth Sense: Technology helps drivers 'watch out' for the other guy", General Motors News Release, October 24, 2005, GM Communications.
- [34] Press Release, "From GM, a car that won't crash", Business Week, by David Welch, January 9, 2006