Mobile Netw Appl (2014) 19:153–160
DOI 10.1007/s11036-014-0499-6

VCMIA: A Novel Architecture for Integrating Vehicular Cyber-Physical Systems and Mobile Cloud Computing

Jiafu Wan · Daqiang Zhang · Yantao Sun · Kai Lin · Caifeng Zou · Hu Cai

Published online: 27 February 2014

Abstract The advances in wireless communication technologies, vehicular networks and cloud computing boost a growing interest in the design, development and deployment of Vehicular Cyber-Physical Systems (VCPS) for some emerging applications, which leads to an increasing demand on connecting Mobile Cloud Computing (MCC) users to VCPS for accessing the richer applications and services. In this paper, we first identify the key requirements of designing an efficient and flexible architecture for integrating MCC and VCPS. Based on the requirements, we design a VCPS and MCC Integration Architecture (VCMIA), which provides mobile services for potential users such as drivers and passengers to access mobile traffic cloud. Then, we analyze two crucial cloud-supported components: GIS with traffic-aware capability and cloud-supported dynamic vehicle routing. Finally, we select Vehicle Maintenance Services (VMS) as an application scenario to carry out the validation. The proposed VCMIA can provide the flexibility for enabling diverse applications.

Keywords Vehicular cyber-physical systems · Mobile cloud computing · Architecture · Vehicle maintenance services

J. Wan
South China University of Technology, Guangzhou, China
e-mail: jiafuwan_76@163.com

D. Zhang (✉)
Tongji University, Shanghai, China
e-mail: daqiang.tongji@gmail.com

Y. Sun
Beijing Jiaotong University, Beijing, China
e-mail: ytsun@bjtu.edu.cn

K. Lin
Dalian University of Technology, Dalian, China
e-mail: link@dlut.edu.cn

C. Zou
Guangdong Jidian Polytechinc, Guangzhou, China
e-mail: caifengzhou@gmail.com

H. Cai
Jiangxi University of Science and Technology, Ganzhou, China
e-mail: hucai2013@163.com

1 Introduction

Cyber-Physical Systems (CPS) are increasingly composed of services and applications deployed across a range of communication topologies, computing platforms, and sensing and actuation devices [1–3]. Nowadays, vehicular networking serves as one of the most important enabling technologies, and is producing some novel telematics applications. In my view, vehicular networking with the capabilities of decision-making and autonomous control can be upgraded to Vehicular Cyber-Physical Systems (VCPS) [4, 5]. We believe that VCPS is an evolution of vehicular networking by the introduction of more intelligent and interactive operations. The services and applications in VCPS often form multiple end-to-end cyber-physical flows that operate in multi-layered environments. In such operating conditions, each service must process events belonging to other services or applications, while providing quality of service assurance (e.g., timeliness, reliability, and trustworthiness).

In recent years, Mobile Cloud Computing (MCC) can provide a flexible stack of massive computing, storage and software services in a scalable and low-cost manner, which has become an emerging hot research field [6–9]. With the support of MCC, VCPS platforms will have cost-effective, scalable and data driven features. The integration of VCPS and MCC, will promote the convenient and simple release and upgrade of the new mobile applications for VCPS. It is also important to guarantee safety and improve Quality of Service (QoS) for drivers or passengers. MCC technology is expected to highlight some innovative applications (e.g., historical traffic data and in-vehicle infotainment) for VCPS with richer traffic mobile video streaming, more supporting functionalities, and more reliable QoS.

VCPS and MCC still possess their own issues and challenges during the burgeoning integration [10–14]. Also, this seamless integration will introduce some new problems. To address this challenge, we focus on designing integration architecture and analyzing two crucial cloud-supported components in this paper. In my view, though other issues (e.g., reliable vehicle communication) are equally important for cloud-supported VCPS platform, we highlight the features and contributions as follows:

– The Integration Architecture of MCC and VCPS: By incorporating the dynamic interactions between MCC and VCPS, we propose a VCPS and MCC Integration Architecture (termed VCMIA) to provide more services and applications (e.g., driving assistances).
– The Analysis of Crucial Cloud-Supported Components in VCMIA: The cloud-supported VCPS has multi-layered features, each layer provides different service contents. We analyze the crucial service components including Geographic Information System (GIS) with traffic-aware capability and cloud-supported dynamic vehicle routing to determine the research directions and challenges.
– An Application Scenario of Cloud-Supported VCPS: In order to verify the proposed VCMIA, an application scenario, Vehicle Maintenance Services (VMS), is selected to conduct the validation.

The remainder of the paper is organized as follows. Section 2 analyzes the multi-layered VCPS and gives the conceptual architecture for cloud-supported VCPS. In Section 3, we propose a cloud-supported VCPS architecture including three layers. Section 4 outlines two crucial cloud-supported components in VCMIA. Section 5 gives an application scenario for cloud-supported VCPS in VCMIA, and Section 6 concludes this paper.

2 Developing Cloud-Supported VCPS

In this section, we in brief introduce the multi-layered VCPS, and then propose the conceptual architecture for cloud-supported VCPS.

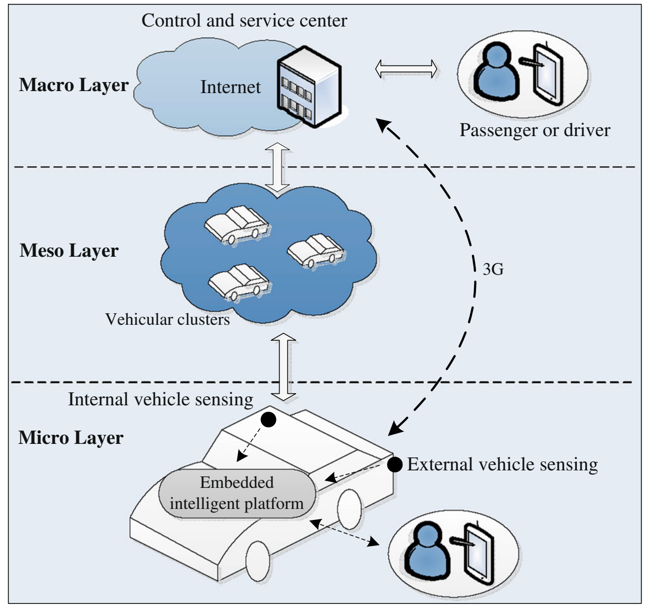


Fig. 1 Hierarchical VCPS

2.1 Hierarchical VCPS

The multi-layered VCPS is shown in Fig. 1. According to the different range of spatial regions, VCPS can be divided into three deferent layers: micro layer, meso layer and macro layer, described as follows:

– Micro Layer: In the vehicle range, the embedded intelligent platform of vehicle not only acquires both environment and vehicle body parameters but also integrates human factors for providing high-quality man-machine interaction by wired/short-range wireless technologies and advanced control algorithms [15]. In this layer, the basic design criterion for VCPS should ensure safety first and infotainment second.
– Meso Layer: The vehicular clusters usually formed by Vehicular Ad Hoc Networks (VANET) can provide more comfort and convenience (e.g., sharing of entertainment resources and safety information) to drivers or passengers. For the meso layer, the conspicuous challenges include computation offloading, network bandwidth limit, etc [16].
– Macro Layer: The control and service center provides all kinds of services (e.g., real-time traffic information and traffic contingency plans) to improve QoS. For example, the timely traffic information can help drivers conduct real-time path planning and avoid congestion. With the MCC support, the macro layer can also offer more services such as traffic mobile video streaming.

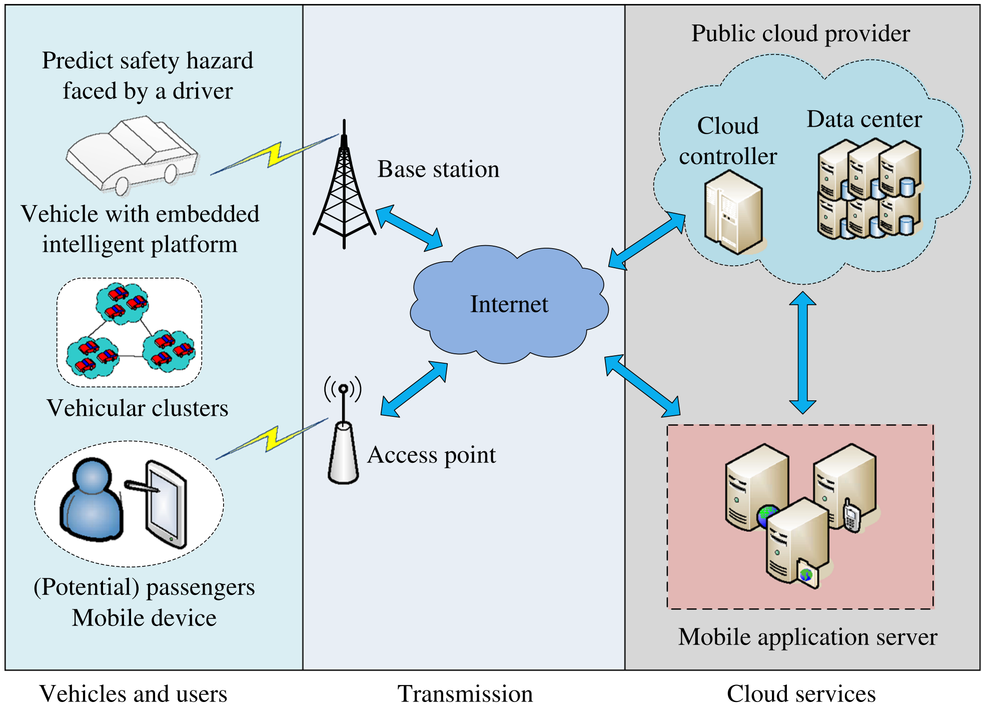


Fig. 2 Conceptual architecture for cloud-supported VCPS

2.2 Conceptual Architecture for Cloud-Supported VCPS

VCPS has emerged as an inevitable tendency for the higher development stage of intelligent transportation systems. In [5], the research focused on the micro layer to improve road safety and efficiency using the advanced wireless technologies and distributed real-time control theory. This research considers human factors and then integrates vehicle dynamics and communication with a field theory model to predict vehicle motion in the near future for identifying safety hazards and proactive collision warning. The reliability of this proposed method deeply depends on the real-time performance of embedded intelligent platform and the rationality of prediction model.

With the MCC support, the research contents of VCPS can extend from micro layer to multi-layers. The development of cloud-supported VCPS is based on two observations: 1) we can develop and deploy numerous mobile applications for VCPS platforms, which can access larger, and faster data storage services and processing power from the traffic cloud; and 2) some mobile applications have been designed for diverse MCC environments, and these examples can provide some useful references for incorporating MCC services into VCPS platform.

Figure 2 shows the conceptual architecture of cloud-supported VCPS. The mobile devices (e.g., embedded intelligent platform installed in the vehicle or smart phone) serve as gateways for VCPS, and access the Internet via Wi-Fi or cellular networks to coordinate with application servers. The mobile devices will then offload the tasks to the traffic cloud accordingly. Once the requests from drivers, passengers or embedded intelligent platform have been received, the cloud controllers will schedule the tasks on Virtual Machines (VM), which are rented by application service providers, and return the results. In some situations, the application servers can be also deployed in the traffic cloud.

3 Cloud-Supported VCPS Architecture

In this paper, we design the cloud-supported VCPS architecture to provide more service contents (e.g., historical traffic data and real-time traffic information) for drivers, passengers or traffic controllers. In this section, we propose a framework for an emerging vehicular networking system (i.e., VCPS) with MCC capability.

3.1 Integration Architecture

Figure 3 depicts the proposed framework for VCPS platform with MCC support. In sum, this platform is comprised of three layers (micro layer, meso layer and macro layer) as follows:

– In the micro layer, the key research topic is to focus on the following two aspects: 1) design and evaluate new applications for improved traffic safety and traffic operations by integrating human factors; and 2) develop an integrated traffic-aware mobile GIS.

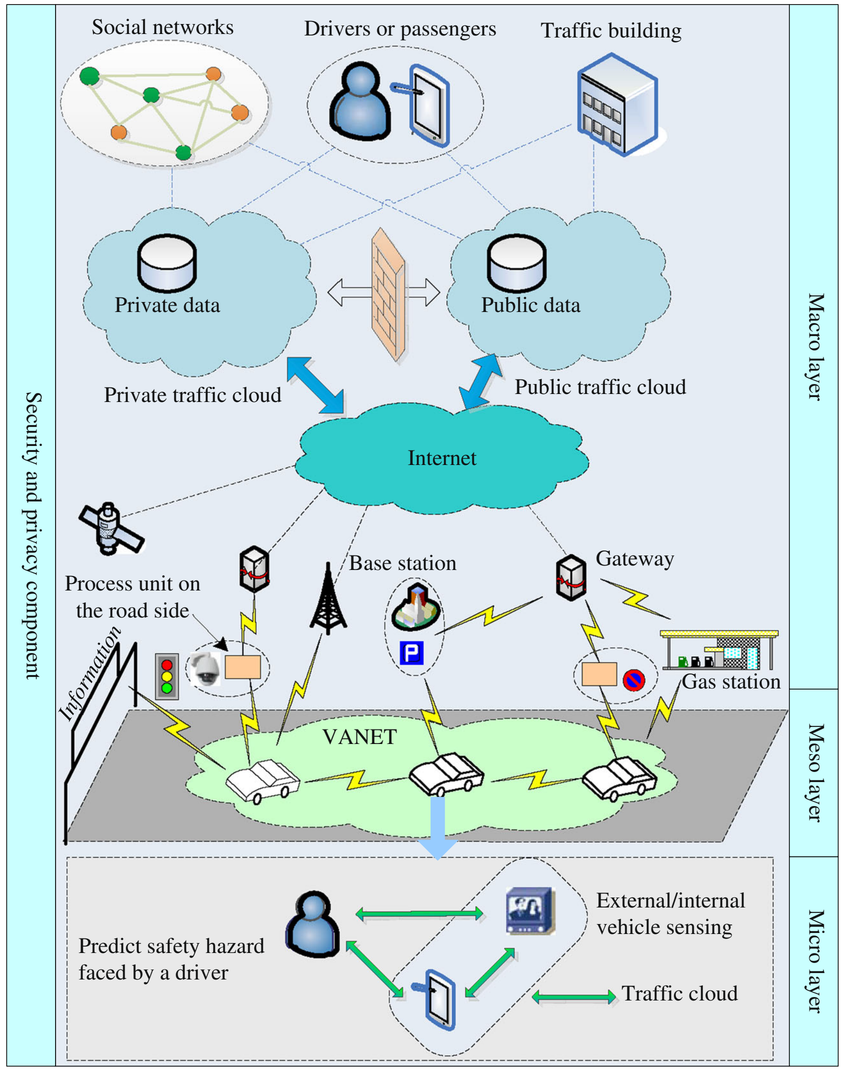


Fig. 3 VCMIA: VCPS and MCC integration architecture

- In the meso layer, the vehicular clusters formed by VANET usually share entertainment resources and safety information to drivers or passengers. For example, the traffic accident information can be forwarded to the near drivers for a timely reminder when a traffic accident happens.
- The macro layer includes wired/wireless transmission, cloud services, and users. The traffic video streaming from cameras are transmitted to the adjacent routing equipment via wired or wireless transmission, and then to the traffic cloud server via Internet. The traffic cloud servers possess powerful VM resources such as CPU, memory, and network bandwidth in order to provide all kinds of cloud services such as entertainment resources. The different users such as drivers, traffic controllers, researchers, or even passengers ubiquitously acquire multiple traffic cloud services by a variety of interfaces such as personal computers, TVs and smart phones.
- The novel solutions are needed to ensure the security and privacy of drivers and passengers in VCPS, especially in applications where the vehicles are tracked or driver behavior is monitored.

In the cloud-supported VCPS architecture, we further emphasize an important element: hybrid traffic cloud. In general, a hybrid cloud computing architecture can accelerate the migration from existing IT resources in transportation departments to cloud computing, make full use of resources, and reduce costs. The important traffic data and applications such as traffic contingency plans and traffic violation records can be deployed on a private traffic cloud to guarantee security, while operations related to system upgrade or testing can be carried out on a public traffic cloud. Moreover, when there are not enough resources on the private traffic cloud at the peak load time, some work can be switched to the public traffic cloud.

Fig. 4 Brief summarization of cloud-supported VCPS applications

Layer	Applications	Requirements/Features
Micro layer	• Safety hazard prediction	• Consider human factors and real-time performance
	• Entertainment	• Provide richer service contents
	• Traffic-aware mobile GIS	• Need traffic cloud support
Meso layer	• Safety information sharing	• Consider computation off loading
	• Entertainment resources sharing	• Consider network bandwidth limit
	• Gassaving	• Need the support of smart traffic light control system
	• Car-pool service	• Need mobile device (e.g., smart phone) support
Macro layer	• Vehicle maintenance services	• Need inter-cloud support
	• Emergency roadside services	• Intelligent location-based services
	• Real-time traffic information	• Traffic cloud support
	• Cloud-supported dynamic routing	• Automatically acquire real-time traffic information
	• Reservation service	• Inter-cloud supportand third-party services

3.2 Cloud-Supported VCPS Applications

Although the cloud-supported VCPS service contents are becoming more abundant, we still need breakthroughs in many aspects, such novel integration architecture, real-time message delivery, traffic-aware mobile GIS, and cloud-supported dynamic vehicle routing. From the macro layer, the emerging applications with the traffic cloud support provide more convenience (e.g., vehicle maintenance services) for drivers or passengers. The applications in the meso layer focus on information sharing by means of VANET. If the amount of information to be exchanged is overloaded, both network bandwidth and reliability are main problems. In the micro layer, some of applications such as traffic-aware mobile GIS still need the traffic cloud support. We briefly summarize the cloud-supported VCPS applications in Fig. 4.

4 Cloud-Supported Service Components in VCMIA

Though other issues such as security and privacy are equally important and to be addressed separately, we carefully select two crucial cloud-supported service components for QoS improvement of VCPS platforms, including GIS with traffic-aware capability and cloud-supported dynamic vehicle routing.

4.1 GIS with Traffic-Aware Capability

With the support of traffic cloud, mobile GIS functions can be enriched by integrating traffic dynamics with basemap management to provide driving assistances. The location-specific information of transportation data and the recent technological advances of GIS firmly convince that the integration of GIS and transportation models would be significant. For example, ESRI ArcGIS provides a conceptual transportation data models titled Unified Network for Transportation (termed UNETRANS) [17]. The UNETRANS model takes a geometric network as its underlying structure, and the revised model includes four object packages: inventory, network, events, and users (e.g., mobile objects). This model has been implemented by larger agencies as the basis for their transportation database.

Also, the recently published roads and highways data model provides the chances for integrating static transportation network data and time-varying traffic flow data from a variety of sources (e.g., traffic cloud). However, current ArcGIS lacks necessary computing tools for building a real-time traffic prediction model. In my view, the excellent transportation prediction model can be designed by depending on the existing ArcGIS and an extension traffic analyst using the geoprocessing framework. In addition, it is necessary to create the analysis tools that integrate them with ArcGIS. With the support of traffic cloud, traffic monitoring and analysis can be integrated with the mobile GIS functions in basemap management, traffic analysis, and route selection.

4.2 Cloud-Supported Dynamic Vehicle Routing

The Roadside Equipment (RSE) units deployed at strategic locations exchange information with On-Board Equipment (OBEs) installed on passing by vehicles. Both RSEs and neighboring OBEs are interconnected so that they can share traffic information and entertainment resources. By means of neighboring vehicles, the vehicles outside the range of

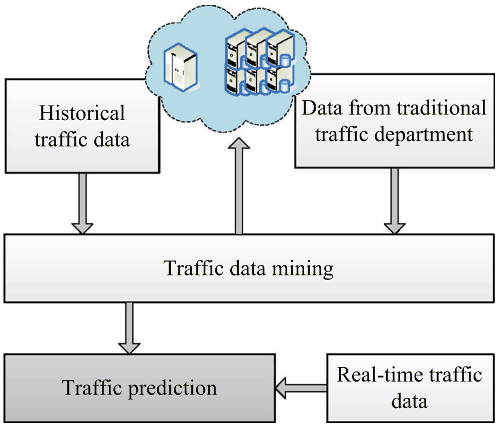


Fig. 5 A conceptual framework for cloud-supported dynamic vehicle routing

any RSE may still be connected to the rest of the vehicle and infrastructure network. This vehicle and infrastructure network can generate accurate real-time traffic information, based on which some fundamental traffic problems can be solved with high efficiency from a new perspective, including: 1) predict trend and future traffic conditions; and 2) utilize the predicted traffic information for improving traffic operations. Figure 5 shows a conceptual framework for cloud-supported dynamic vehicle routing.

In general, each driver will choose the best route in terms of minimum travel time, distance, cost or other criteria according to the given real-time and accurate traffic information. Intuitively, these decisions will jointly result in a state of Dynamic User Equilibrium (DUE). However, for a large-scale intelligent transportation system where drivers make their own decisions independently based on the same travel information, this may lead to a state similar to the result of Dynamic All-or-Nothing (DAN) assignment [18], since drivers with the same origin and destination will take the same routes. It is well known that the transportation network performance is optimal when the system is in a state of Dynamic System Optimal (DSO). In order to avoid the DAN scenario and account for the uncertainty in travel time prediction results, a stochastic route choice method based on discrete choice models may be used by each OBE to find the optimal route. This decentralized and proactive routing process can help the transportation network achieve a state of DSO.

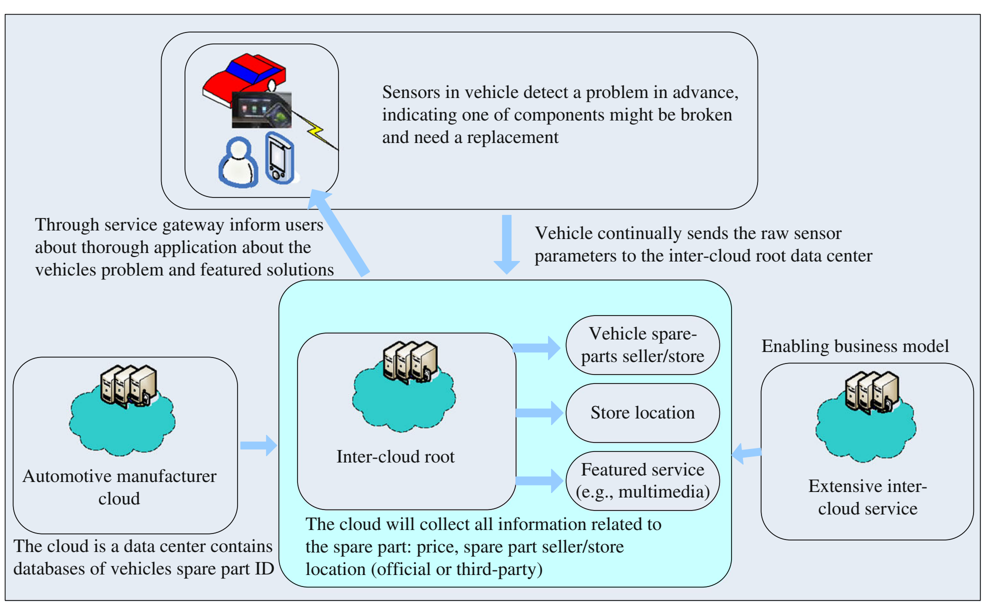
5 Application Scenario and QoS of Cloud-Supported VCPS

There are several application scenarios for VCMIA described in Fig. 3. We outline the cloud-supported VCPS applications from different layers in Section 3. For example, we need a telematics to process potential danger, such as unexpected problem occurring and routine maintenance.

5.1 Routine Maintenance and Unexpected Problem Occurring

In routine maintenance application of vehicles, all sensors in the vehicle collect the real-time parameter information which is saved into the vehicles storage daily. The same data is also uploaded to the vehicles manufacturer inter-cloud root data center. Then, the data is distributed to

Fig. 6 Framework for processing unexpected problem occurring



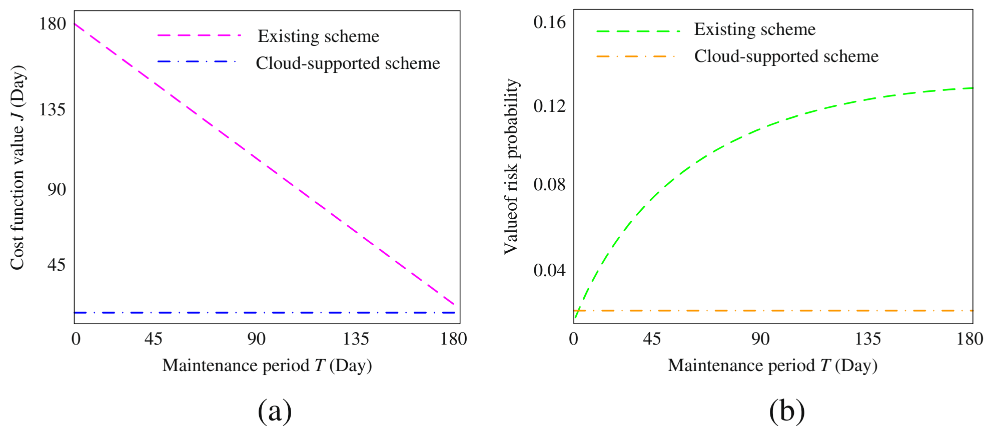


Fig. 7 QoS of cloud-supported VCPS. **a** Efficiency; **b** Risk factor

vehicle service center local agents. By means of the automotive manufacturer cloud, the official vehicle service center confirms historical data of vehicle. If users need to find alternatives to the maintenance schedule posted by official vehicle service center, they can query the other services from independent service center through the inter-cloud root service gateway.

In a particular case, when the sensors in the vehicle detect a danger in advance, indicating one of the components might be broken and need a replacement, the vehicle continually sends the raw sensor parameters to the inter-cloud root data center, as shown in Fig. 6. The cloud will collect all related information (e.g., spare part price, spare part seller, and store location). Then the users are informed about the vehicles danger and featured solutions through service gateway. In this way, an optimal cloud-supported scheme is provided for drivers to process the potential danger timely.

5.2 QoS of Cloud-Supported VCPS

The probabilistic method can be adopted to analyze the processing response time and risk factor of vehicle maintenance services. In order to achieve a quantitative analysis, the cost to be evaluated is calculated over the difference between time of start process and time of problem occurring. Therefore, we give the cost function as follows:

$$J = Min(T_p - T_s) \tag{1}$$

where T_p and T_s are the time of start process and time of problem occurring respectively.

For simplicity, we have made certain assumptions: 1) the maintenance period is known (e.g., half a year); 2) the probability of problem occurring approximately conforms to the exponential distribution; and 3) a suddenly occurred problem is not fatal, and vehicle can run under this status.

We adopt the following distribution function to evaluate the proposed scheme for specific applications:

$$F(x) = \begin{cases} 1 - e^{-\lambda x} & x > 0 \\ 0 & x \leq 0 \end{cases} \tag{2}$$

According to Eq. (2), the fault rate of problem occurring continually increases in a maintenance period. Meanwhile, the processing response time J gradually shortens as time goes on. Considering the above assumptions, we can see that an unexpected nonfatal problem can not affect the running of vehicle, but might result in less safety. Also, the fault rate of problem occurring roughly conforms to the exponential distribution in a maintenance period. We assume that the parameter of exponential distribution λ is $1/1440$. Also, the maintenance period T is usually a constant interval of values around 180 days.

Figure 7 shows the evaluation of efficiency and risk factor for an unexpected nonfatal problem using Eq. (2). The proposed scheme adopting VCPS technology and cloud computing can effectively and timely processes some abnormal problems. The users can receive a kindly warning and an alternative solution from vehicle service center. Therefore, the cost function value (processing response time) J is usually less than one day. However, for the existing scheme the processing response time J gradually shortens as time goes on, and the risk factor continually increases in a maintenance period. When the difference between T_p and T_s goes to 180, the value of risk probability runs to 0.12.

In the cloud-supported scheme, for routine maintenance the data concerning vehicle status is uploaded to the vehicle's manufacturer inter-cloud root data center daily. If some potential dangers happen, the official vehicle service center will immediately send a warning message to the user through VCMIA. Also, both efficiency and risk factor can satisfy the regularities as shown in Fig. 7.

6 Conclusions

The seamless integration of VCPS and MCC provides tremendous opportunities for intelligent transportation systems. In this article, we provided a brief review and outlook of this promising field and discussed a cloud-supported VCPS architecture (termed VCMIA). In particular, we outlined the cloud-supported VCPS applications. We also suggested two crucial cloud-supported service components to improve the QoS of cloud-supported VCPS. Finally, we give an application scenario (VMS) of cloud-supported VCPS to carry out the validation. We believe the cloud-supported VCPS will attract enormous attention and research efforts in near future.

Acknowledgments The authors would like to thank the National Natural Science Foundation of China (No. 61262013, 6136301, 61103185, 61300224), the Natural Science Foundation of Guangdong Province, China (No. S2011010001155), the High-level Talent Project for Universities, Guangdong Province, China (No. 431, YueCaiJiao 2011), the Opening Fund of Guangdong Province Key Laboratory of Precision Equipment and Manufacturing Technology (No. PEMT1303), the National 863 Project (No. 2012AA040909), the Natural Science Foundation of the Higher Education Institutions of Jiangsu Province, China (Grant No. 11KJB520009), and the 9th Six Talents Peak Project of Jiangsu Province (Grant No. DZXX-043) for their support in this research.

Statement This work is based in part on our previous paper titled "Vehicular cyber-physical systems with mobile cloud computing support", Presented at CloudComp 2013.

References

1. Chen M, Wan J, Li F (2012) Machine-to-machine communications: architectures, standards, and applications. KSII Trans Intern Inform Syst 6(2):480–497
2. Zou C, Wan J, Chen M, Li D (2012) Simulation modeling of cyber-physical systems exemplified by unmanned vehicles with WSNs navigation. In: Proceedings of the 7th International Conference on Embedded and Multimedia Computing Technology and Service. Gwangju, pp 269–275
3. Wan J, Chen M, Xia F, Li D, Zhou K (2013) From machine-to-machine communications towards cyber-physical systems. Comput Sci Inform Syst 10(3):1105–1128
4. Li X, Qiao C, Yu X, Wagh A, Sudhaakar R, Addepalli S (2012) Toward effective service scheduling for human drivers in vehicular cyber-physical systems. IEEE Trans Parallel Distrib Syst 23(9):1775–1789
5. Qiao C (2010) Cyber-transportation systems (CTS): safety first, infotainment second. Presentation Report
6. Suo H, Liu Z, Wan J, Zhou K (2013) Security and privacy in mobile cloud computing. In: Proceedings of the 9th IEEE International Wireless Communications and Mobile Computing Conference. Cagliari
7. Chen M (2012) AMVSC: a framework of adaptive mobile video streaming in the cloud. IEEE Globecom 2012. Anaheim, pp 3–7
8. Wang X, Chen M, Kwon T, Yang L, Leung V (2013) AMES-Cloud: a framework of adaptive mobile video streaming and efficient social video sharing in the clouds. IEEE Trans Multimedia 15(4):811–820
9. Lai C, Chao H, Lai Y, Wan J (2013) Cloud-assisted real-time transrating for HTTP live streaming. IEEE Wireless Commun 20(3):62–70
10. Wan J, Yan H, Liu Q, Zhou K, Lu R, Li D (2013) Enabling cyber-physical systems with machine-to-machine technologies. Int J Ad Hoc Ubiquitous Comput 13(3/4):187–196
11. Wan J, Yan H, Li D, Zhou K, Zeng L (2013) Cyber-physical systems for optimal energy management scheme of autonomous electric vehicle. Comput J 56(8):947–956
12. Chen M, Wen Y, Jin H, Leung V (2013) Enabling technologies for future data center networking: a primer. IEEE Netw 27(4):8–15
13. Zhang D, Huang H, Zhou J, Xia F, Chen Z (2013) Detecting hot road mobility of vehicular Ad hoc networks. Mobile Netw Appl 18(6):803–813
14. Kumar K, Lu Y (2010) Cloud computing for mobile users: can offloading computation save energy? Comput 43(4):51–56
15. Miloslavov A, Veeraraghavan M (2012) Sensor data fusion algorithms for vehicular cyber-physical systems. IEEE Trans Parallel Distrib Syst 23(9):1762–1774
16. Zhang D, Yang Z, Raychoudhury V, Chen Z, Lloret J (2013) An energy-efficient routing protocol using movement trends in vehicular ad hoc networks. Comput J 56(8):938–946
17. Azogu H (2011) Privacy-preserving license plate image processing. In: Proceedings of the 2nd IEEE Workshop on Multimedia Communications and Services, IEEE GlobeCom 2011. Houston, pp 5–9
18. Sheffi Y (1985) Urban transportation networks: equilibrium analysis with mathematical programming methods. Prentice-Hall, Englewood Cliffs