2012 15th International IEEE Conference on Intelligent Transportation Systems
Anchorage, Alaska, USA, September 16-19, 2012

# A Scaled-Down Traffic System based on Autonomous Vehicles: A New Experimental System for ITS Research

Wen He, Guisheng Chen, Shuming Tang, Deyi Li, Mu Guo, Tianlei Zhang, Peng Jia, Feng Jin

*Abstract*— **In this paper, we present our recent efforts on developing a physical environment for performing traffic experiments. The two main characteristics of this environment are: (1) the whole environment is scaled down from the real traffic, (2) the traffic behaviors are performed by numbers of miniature autonomous vehicles. Performing traffic experiments in an actual environment has long been a hard problem. Moreover, modeling traffic phenomena is also a tough task, due to the complexity of the natural traffic system. However, with the rapid development of autonomous vehicle technology, we have an opportunity to improve these problems from a new perspective. That is using autonomous vehicles to perform traffic experiments. But with the limitations in cost and land availability, directly using full size autonomous vehicles also seemed unrealistic. Thus, we built a 1/10 scaled-down traffic system (SDTS) with more than 50 miniature autonomous vehicles. The environmental design, autonomous vehicles developing, agent modeling, traffic control, and real-time monitoring is considered systematically during system design. The SDTS can be used as a repeatable, appraisable, and verifiable experimental platform for traffic researches, such as testing traffic solutions, verifying key technologies in intelligent vehicles, and performing experiments about ITS. By now, the SDTS has supported a series of workshops, exchange activities and competitions in China.**

## I. Introduction

Traffic congestion has become a worldwide problem especially in metropolitan areas. The boring traffic jams not only reduce people's quality of life, but also impact economic, environment and energy system. According to 2011 Urban Mobility Report released by Texas Transportation Institute [1], in 2010, traffic congestion has made U.S. drivers pay an extra $101 billion in total cost. In China, the traffic condition is also unfavorable. An investigation showed that, because of slow moving traffic, the average commuter in Beijing had to pay an extra RMB 335.6 per month in 2009 [2].

In order to improve the traffic situation, numerous researchers and projects have attempted to address the problem since the 1930s. At that time, scientists tried to use probability theory to model vehicles arrival patterns and find out the mechanics of the basic traffic flow [3-5]. However, with the tremendous increase in the number of automobiles, the relationship between vehicles becomes more and more inter-dependent. The statistical methods to some extent could not suit the new situation well. From then on, scientists began to study the problem from the kinematic characteristics of vehicles in the micro-level [6-8] and fluid characteristics of traffic in the macro-level [9, 10]. After 1980s, with the rapid development in computer technology, simulation methods had got a wide application and Cellular Automaton Model (CAM) was introduced to model the traffic flow [11, 12]. In the CAM, vehicle positions are evolved based on a set of moving rules and the states of their neighboring cells. After a number of discrete time steps, various traffic conditions can be deduced. In the following internet era, agent-based computing [13] and cloud computing [14] are used to handle the traffic problems. Based on these latest technologies, a new method of Artificial Transportation Systems (ATS) [15, 16] is proposed and has become a new hotspot in transportation domain. The ATS do not simply simulate the traffic system, but try to deal with the traffic problems from the perspective of complex systems. Traffic phenomena can be grown and cultivated in the ATS with methods of artificial systems, computational experiments, and parallel execution.

Although significant efforts have been made with the methods above, multiple challenges still exist in traffic researches. Firstly, under the legal and moral obligation, and also due to cost and safety concerns, we could hardly perform traffic experiments or test proposed strategies in an actual traffic environment. Although the ATS are proposed as an experimental field for performing computing experiments, they are still based on computer but not the physical environment. Secondly, traffic system is a typical complex system [16]. Each vehicle is influenced not only by the current traffic situation, but also by the belief, desire, and intention of the driver. Thus, the modeling of the traffic phenomena has long been a difficult problem. Thirdly, the traditional simulation methods are generally used to model the behavior of an existing system, and are often focused around some specific areas under certain conditions. It is hardly to predict the traffic situation in the future, such as what the world will be when the autonomous vehicles come to our life.

In recent years, besides the progress in ITS, another remarkable advancement in transportation field is the maturity of autonomous vehicle technology. In 2010, Google announced their project on building self-driving car, and had covered 140,000 miles on the road. July in the same year, intelligent vehicle from Parma finished an epic driverless trip from Parma, Italy to Shanghai, China, along a 13000 km and 3 months journey. Indeed, just about every traditional

W. He is with the Department of Computer Science and Technology, Tsinghua University, Beijing 100084, China. She is also with the Xi'an Communication Institute, Xi'an 710106, China (e-mail: he-w09@mails.tsinghua.edu.cn).

G. Chen and D. Li are with the Chinese Institute of Electronic System Engineering, Beijing 100141, China.

S. Tang is with the Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China.

M. Guo and T. Zhang are with the Department of Computer Science and Technology, Tsinghua University, Beijing 100084, China.

P.jia is with the Department of Automotive Engineering, Military Transportation Institute, Tianjin 300161, China.

F. Jin is with the Xi'an Communication Institute, Xi'an 710106, China

automaker is developing its own intelligent vehicles, no matter BMW, Audi, Volkswagen or Toyota. In China, The Future Challenge----Intelligent Vehicles Competition has successfully held for three years. The autonomous vehicle Red Flag HQ3 developed by the National University of Defense Technology has successfully completed a 286 Km journey over an expressway.

The great progress in autonomous vehicles has shown us an exciting future. Although the studies on autonomous vehicles are still in the experimental stage, technologies in autonomous driving have brought huge changes to the traditional automobile industry, from simplifying driving tasks to enhancing vehicle safety and reducing car accidents.

And from another aspect, the intelligent characteristics presented by autonomous vehicles also show that, autonomous vehicles have already got the ability to simulate or partly as an alternative to human driving. That means, autonomous vehicles could do something more than intelligent driving. Based on this understanding, we proposed a new idea in researching traffic problems. That is using autonomous vehicles instead of common vehicles to perform traffic experiments.

However, directly using the full size autonomous vehicles to perform traffic experiments may still meet the problems in space and cost. Thus, we further proposed to scale down the traffic environment, and build a scaled-down traffic system (SDTS) with miniature autonomous vehicles.

With the thought mentioned above, a 1/10 scale traffic environment with more than 50 autonomous vehicles has been built since 2009. And several workshops and exchange activities have been held on the SDTS. This research also has attracted more than 11 research institutions in China. In Sep 2011, on the first China Intelligent Industries Expo, more than 70 miniature autonomous vehicles from these research institutions displayed their intelligent driving behaviors on the SDTS together.

Fig.1. Workshops and exchange activities held on the SDTS

This paper introduces the basic thought and the implementing schemes of the SDTS. The rest of the paper is organized as follows. Section II presents some considerations in designing the SDTS. Section III introduces the system architecture of the SDTS. And the detail of each model is described in section IV. Finally, some conclusions with future works are made in Section V.

## II. Some Considerations of the SDTS

The general purpose of designing this SDTS is to provide a repeatable, appraisable and verifiable physical environment for traffic researches, such as testing traffic solutions, verifying key technologies of intelligent vehicles, and performing experiments about ITS. The main characteristics of the SDTS are: (1) the whole environment is scaled down from the real traffic, (2) the traffic behaviors are performed by numbers of miniature autonomous vehicles.

In a usual way, autonomous vehicles are designed for excellent performance including dynamic, security, and intelligence. But as an experimental system, another performance of diversity is important in forming a natural traffic flow. Besides this, a systematical consideration of the purpose, principles and functions of the SDTS is made.

### A. What Could We Do Under the SDTS

When studying traffic problems under the SDTS, what we miniature is just the size in physics and cost in economy, but could keep the vehicles' characteristics in driving behaviors and traffic attributes. Thus, with the SDTS based on miniature autonomous vehicles, we may: (1) visually simulate and evolve traffic problems in a physical environment. The various proposed strategies could be tested and observed in the real traffic environments with a low cost and without the constraints in morality or law; (2) naturally build the driving behavior in a human-like way. We need not to give exact kinematic functions or find out an optimal accelerate model for vehicles, but only to control the brake and throttle pedals according to the states of vehicles like a human driver; (3) research new phenomena in traffic flows with the participant of autonomous vehicles, so as able to provide references for future traffic rules; (4) also test and verify various technologies related to intelligent vehicles, robot control, sensors network, connected car, and so on.

### B. Basic Principles of the SDTS

To better fulfill the purposes proposed above, two principles are considered seriously in designing the SDTS. That are modularity and design-distributed.

*Modularity:* Each module has its own function, and provides service through a well-defined public interface. Modularity design allows us to perform different experiments on the SDTS easily. For example, traffic researchers do not need to concern the details about vehicles control and communication, but focus more on the traffic problems themselves. And for the other researchers, they also do not need to know much about the traffic theory, but could conduct experiments on intelligent control, sensors network, or computer vision on the SDTS.

*Design-distributed:* Since traffic system is naturally a geographical distributed system, each object in it has its own decision and control system and interacts with other objects autonomously. In the SDTS, we also employed the distributed design pattern for supporting a flexible, adaptable architecture. We built each vehicle, traffic signal and traffic control center as an autonomous agent. Each agent has its own intelligence to integrate the real-time traffic situation and make a smart decision based on knowledge bases.

### C. Basic Functions of the SDTS

Besides modeling the basic traffic flow based on autonomous vehicles, the SDTS should also at least have following functions to satisfy various research requirements: (1) Real-time traffic data acquisition; (2) Wireless communications between vehicles and roadside infrastructure; (3) Interface for responding the real-time traffic control strategies; (4) Interface for changing vehicles' driving behaviors; (5) Interface for comparing and estimating the experimental results; (6) Historical data storage and retrieval.

## III. SYSTEM ARCHITECTURE

According to the research aim and purposes proposed above, the overall system architecture of the SDTS is depicted in Fig.2. It consists of six components: (1) Scaled-down Traffic (SDT); (2) Experimental Design System (EDS); (3) Driving Agents Modeling System (DAMS); (4) Traffic Control System (TCS); (5) Simulated Traffic (ST); and (6) Real-time Monitoring System (RMS).

The SDTS is an experimental system running under the guidance of the EDS, which defines attributes of vehicles and roads, designs rule sets according to the experimental targets, and sends these results to the TCS and the DAMS in a well-defined format.

The component of DAMS is built to generate different social and behavioral attributes for autonomous vehicles, and integrate these attributes to specific driving behaviors such as car-following, lane-changing, path-planning, and so on.

The TCS is used to set management strategies for traffic. Besides the traffic signals and signs in common, different rules like right of way, priority, and restrictions can also be established.

The SDT is a physical entity of the SDTS, which is consisted of scaled-down traffic environmental and autonomous vehicles.

The ST is a parallel transportation system to the SDT, which used to realize the parallel control and management with the idea from Artificial Transportation System [14], and also compare the experimental result with the SDT.

The component of the RMS is built to monitor, estimate and predict the real-time traffic conditions. In one aspect, the real-time data collected by the RMS can be saved as history data and published as the real-time traffic condition. In another aspect, the results from the traffic estimation and prediction module can be used to guide control and management strategies in experiments. Besides, the vehicles positioning and navigation are also fulfilled in the RMS.

## IV. SYSTEM REALIZATION

### A. *The Determination of the Scale*

From the perspectives of economic cost and land availability, the scale of the SDTS is expected to be as small as possible. But from another aspect, autonomous vehicle is an integrated smart system of environmental perception, decision making, and action taking. The minimal size of the autonomous vehicle should satisfy the installation requirements of various sensors, computing devices, communication units, power supplies, and so on.

Through a series of experiment, we found that, the minimal scale satisfied the requirements proposed above is about 1/13. Considering extra space for new sensors in the future, we finally choose 1/10 as the scale factor of the SDTS. Moreover, the scale of 1/10 can have a better compatible. Since 1/13 chassis can also be used as a kind of smaller cars in this environment.

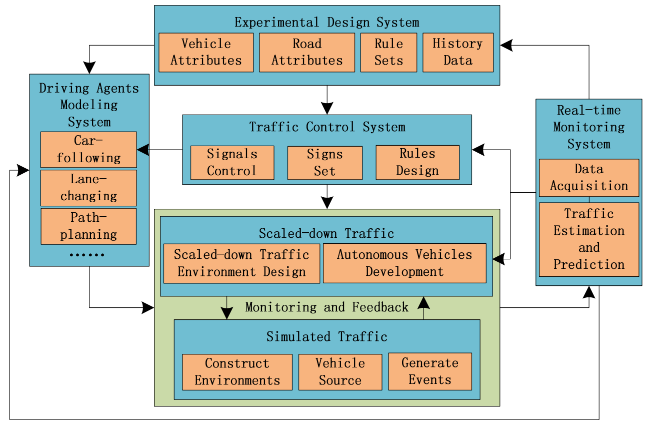


Fig.2. System architecture for the SDTS

### B. *Scaled-down Traffic*

The Scaled-down traffic is the physical environment of the SDTS. It consists of Scaled-down traffic environment and autonomous vehicles.

*Scaled-down Traffic Environment Design*

To ensure the reality of the SDTS, a good consistence between the scaled-down and the actual traffic system should be satisfied. Besides this, more flexibility and controllability are also important. Therefore, the design of the scaled-down traffic environment should meet the requirements as follows:

- *Similarity in environment*

Similarity in environment means that, the scaled-down traffic environment should have similar geometric shapes and traffic elements to the actual traffic environment. The size of their corresponding parts satisfies a linear scale, so that the scaled-down environment could keep the characteristics of the actual roads. But notice that similarity doesn't mean to reproduce, but under the experimental requirements to build a typical traffic scene, which consisted of various traffic components from the actual traffic.

- *Configurability in scene*

Due to limited space in laboratory, the scaled-down traffic environment could not contain all the desired traffic components in one time. To better support multiple experiments, the environment is designed as configurable blocks. Thus, we can easily combine these blocks into desired scenes, and flexibly meet the multiple requirements of experiments.

- *Controllability in remote*

As an experimental platform, most of the elements in the environment are hoped to be controlled remotely, such as the traffic signals and signs. And it would be better, if we could watch, control and record the real-time conditions of experiments remotely. Thus, monitoring devices are installed around the environment, network and power interface are reserved for the future use.

According to the requirements proposed above, a scaled-down traffic environment 10 meters long and 8 meters wide has been built under the 1/10 scale factor. The lane width in the environment is 30cm. And the total length of all roads is 176 meters, corresponding to 1.76 Km in actuality according to the scale factor. The basic traffic components contain: single-track road, 2-lane road, 4-lane road, left-turn lane, viaduct, intersection, T-junction, crosswalk, traffic light, road sign, and parking lot. Fig.3. shows one of the appearances of this environment.

Fig.3. One appearance of the scaled-down traffic environment

*Autonomous Vehicles Development*

Autonomous vehicles are the main bodies in the SDTS. According to the scale factor defined above, the autonomous vehicle is based on a 1/10 scaled model chassis. The sensors equipped on the vehicle include 4 monocular cameras, a rotary encoder, an infrared sensor and a RFID reader. The computational unit of the vehicle is an industry control computer. The overall system architecture is given in Fig. 4. And the details in realization can be seen in [17].

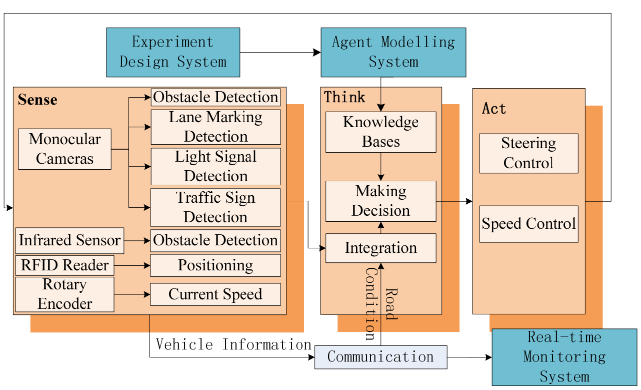


Fig.4. System architecture of autonomous vehicle

It is noted that, the SDTS is a real traffic environment. Thus, any vehicles obey traffic rules could run on it, just like there are various kinds of vehicles as well as different personality styles of drivers in the actual roads. Considered from this point, we could try to develop autonomous vehicles in various methods, and run them together in the same experiments. May be this is another way to reflect the diversity in traffic.

### C. Driving Agent Modeling System

Through the Autonomous Vehicles Development (AVD), vehicles have got the ability in perception, recognition, and making decision. But at this time, all the vehicles have similar driver characteristics because of their same knowledge bases and decision functions. As an experimental system, we definitely hope that vehicles could show the diversity in daily traffic just as mentioned. Thus, agent modeling is used to meet this requirement.

A little difference to the common agent building is that, what we built here is not just a complete driver agent, but a series of agent modules in different driving stages. And these modules can be combined into different types of vehicles under the requirements of experimental design. Finally, those agents' models are delivered to autonomous vehicles via wireless communication networks.

In our work, we divided the factors that influence the driver behaviors into social and behavioral attributes. The behavioral attributes are linked to the personal preference in driving such as manners in car-following, lane-changing, gap-acceptance and desired velocity. And according to the personality presented in these behaviors, we divide drivers into cautions, common and aggressive drivers. Meanwhile, the social attributes are mainly connected with the role in a journey, such as the purpose is for working, shopping, or business, the vehicle type is household, commercial or commuted. Each of these attributes may have different influence on final behaviors: the extent of flexibility may differ from limited to high, the scope of time requirement may vary from plenty to tight. Finally, both the social and behavioral attributes will be integrated into specific driving behaviors such as car-following, lane-changing, path-planning, and so on.

*Car-following module*

The function of the car-following module is to maintain a safety space and time gap between the current vehicle and its front vehicle. The process of car-following is divided into three phases: free, alert, and urgent. The parameters used to divide them contain: alert distance $d_a$, safety distance $d_s$. Definitely, the two parameters are time varying according to the velocity difference between the current vehicle and its front vehicle.

$$\textit{Free phase : if } d \geq d_s\text{ , } v_d = \min(v_{\max}, v_{\lim})$$

$$\textit{Alert phase : if } d < d_s \;\&\; d \geq d_a\text{ , }\textit{keep } v_d \leq v_{front} \,\|\, \textit{Chang Lane}$$

$$\textit{Urgent phase : if } \; d < d_a\text{ , }\textit{decelerate, till } d > d_a$$

here $d$ is distance between the current vehicle and its front vehicle, $v_d$ is the desired velocity of the current vehicle, $v_{front}$ is the velocity of the front vehicle, $v_{max}$ is the max velocity that the current vehicle can get, and $v_{lim}$ is the limited velocity in current road.

*Lane-changing module*

Generally, lane changes can be classified as either mandatory or discretionary. Mandatory lane changes are performed to follow a specific path, such as vehicle need to get off a lane. Discretionary lane changes are performed to keep a desired speed. This can be triggered by an alert phase in car-following module. The related parameters including (1) current speed $v$; (2) the gap to the front vehicle $d_f$; (3) the gap to the front vehicle in the target lane $d_{tf}$; (4) the gap to the following vehicle in the target lane $d_{tl}$; (5) the velocity of the following vehicle in the target lane $v_{tl}$.

*Path-planning module*

Path-planning module is optional for human drivers, but obviously is crucial for intelligent vehicles. When deciding the driving routes, the origin and destination of each vehicle will firstly be determined by the trip purpose, which is generated by the EDS. And then according to whether reference the dynamic traffic information, exact routes of vehicles are decided in three ways: (1) Static mode: routes are pre-determined according to the geographical topology or the historical data. Vehicles will not react to any real-time changes in traffic conditions the entire way; (2) Dynamic mode: vehicles will incorporate the real-time traffic information, published by the RMS, into their path planning. Routes are calculated frequently in time according to current conditions of roadway, position, and destination; (3) Predictive mode: in this mode, routes are also calculated in real-time, however the referenced information is not current traffic conditions, but the short-term future traffic conditions generated by Traffic Prediction and Estimation module in the RMS.

## D. *Experimental Design System*

In an experiment, experimental design is the top-level work to decide the intention, purpose, and methods in advance. In a general experimental design, we need to identify the objectives, and then design the steps of performing research processes include: selecting the process factors, setting values for controlled variables, specifying methods for independent variables, and collecting and analyzing the responses of output variables.

To our traffic experiments, one example flow chart is given in Fig.5. This experiment is aimed at observing the variation in fundamental stream characteristics of traffic flow. The Experimental unit is definitely the scaled-down traffic, and the dependent variables are speed, flow, and density of the traffic flow. The controlled variables including road attributes, building attributes, and traffic signs which need to be decided in advance. Well, the independent variables may contain traffic rules, signal control methods for the TCS, and attributes of vehicles, rule bases of vehicles for the AMS.

Fig. 6 shows the experimental result of flow-density diagram. In this experiment, environment was set to be a two-lane highway and the data were collected in a 6-meter straight road. At the beginning of the experiment, vehicles were arrived at an average rate of 0.2 per second according to a Poisson process. And the arrival rate of vehicles grew steadily over time. At the end of the experiment, the arrival rate reached 1.6 per second. There were three kinds of vehicles ran in the road, which were cautions, common and aggressive vehicles. The ratio of these vehicles was set to be 2:6:2. The road flow was recorded in the middle of the road by RFID readers. From the result diagram, we could see the classical reversed λ-shape which is agree with the theory and is very representative for traffic phenomenon. And from this simple experimental result, we can also see a good consistency between the scaled-down and the actual traffic environments.

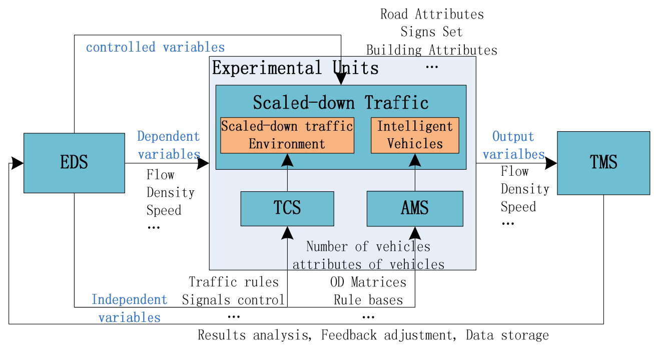


Fig.5. The flowchart of one experimental design

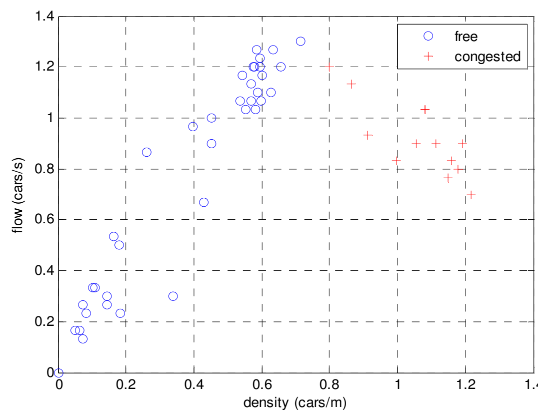


Fig.6. The flow-density diagram of one experiment

## E. *Simulated Traffic*

The ST is built as a parallel transportation system of the SDT, which function is to realize a parallel control and management with the idea from Artificial Transportation System [13].

The term "parallel" here is not parallelism in the sense of parallel computing, where tasks or calculations are divided into smaller ones and carried out simultaneously, but implies the parallel interaction between an actual transportation system and its corresponding artificial or virtual counterparts. In the SDTS, we considered the scaled-down traffic as the actual traffic system, and the simulated traffic as its corresponding artificial counterparts.

In ATS, parallel systems are used to seek adaptive dynamic and effective solutions of the actual traffic system with the method of computational experiments and adaptive control methods. But in the SDTS, both the two systems are experimental system, and can perform experiments directly. Thus, another function of the parallel system is to help us compare and contrast the differences between the two experimental methods. And evolve and perform larger scale experiments on the ST based on the data generated by the SDT.

## F. Real-time Monitoring System

Real-time traffic data is the fundamental of traffic management, estimation and prediction. In the SDTS, we use RFID equipments to record the traffic flow. The RFID tags are applied on the start and end points of a road, as well as some important road segments. Each vehicle is equipped with a RFID reader. When a vehicle drives into or leaves a road segment, the number of the RFID tag together with the current time, speed and destination of the vehicle will be sent to the data center via a WIFI network. Then data center can integrate all these data into the real-time traffic situation.

Besides data monitoring, another function of these RFID tags in the SDTS is to realize vehicle localization and navigation. Due to the scaled-down size in environment, the requirement of positioning accuracy is high. And the current precision of the GPS system cannot achieve this centimeter-accuracy. To simplify the problem, we use RFID tags as markers to report the approximate locations of vehicles. And realize the route guidance in the scaled-down traffic environment, with the map of the field.

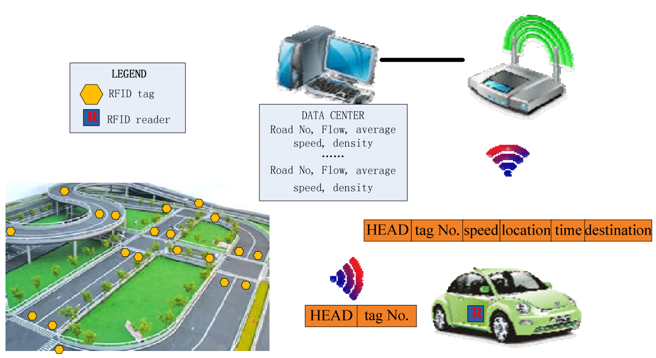


Fig.7. The real-time monitoring system in the SDTS

## V. Conclusion

In this paper, we presented the design rationale of the scaled-down traffic system, which is an experimental environment for researching, testing and evolving traffic problems based on miniature autonomous vehicles.

Due to the complexity of traffic system, and also the restriction in moral and law, performing traffic experiments in actual environment is always difficult. To study traffic problems based on autonomous vehicles, we could not only effectively avoid the complexity and uncertainty in modeling traffic problems, but also create a new method for performing real traffic experiments. However, with the limitations in cost and land availability, directly using full size autonomous vehicles also seems unrealistic. Thus, we built a 1/10 scaled-down traffic experimental system with more than 50 miniature autonomous vehicles. The system has systematically considered the problems in environmental design, intelligent vehicles developing, agent modeling, traffic control, and real-time monitoring. By now, the SDTS has got the ability to conduct traffic experiments preliminarily, and has supported a series of workshops, exchange activities and also competition in China. We hope that, the building of the SDTS could provide a repeatable, appraisable and verifiable experiment platform for researching traffic problems, testing traffic solutions, verifying key technology in intelligent vehicles and performing experiments about ITS.

Although the SDTS has performed some effect on ITS research, the SDTS is still at a preliminary stage. Much work need to be done to improve the robustness, usability and applicability: (1) To improve the robustness of the intelligent vehicles in different environment especially under different lighting conditions; (2) To improve and enrich agent models to adapt wider situations; (3) To enrich experimental design databases for many more cases; (4) To optimize man-machine interface for a more friendly operation.

## Acknowledgement

This work was supported in part by National Natural Science Foundation of China under Grants 60974095, 90920305, and 91120008.

## References

[1] Shrank, David, Tim Lomax, “TII’s 2011 Urban Mobility Report,” *Texas Transportation Institute*, September 2011.
[2] Beiqi Foton Company, Horizon Research Group, Inc, “2009 Foton Chinese Index for Mobility,” January 2010.
[3] Kinzer, J.P. , “Application of the theory of probability to problem of highway traffic,” *Proc. Inst. Traffic Eng.,* pp. 118-124, *May.* 1934.
[4] Adams, W. F. , “Road Traffic Considered as a Random Series,” *J. Inst. Civil Engineers*, 4, pp. 121-130, U.K., 1936
[5] Greenshields, B. D, “A study of traffic capacity,” *Highway Res. Board Proc. Annu. Meet.*, vol.14, pp. 448-477, 1935.
[6] Chandler, R.E., R. Herman, and E.W.Montroll, “Traffic Dynamics: Studies in Car Following,” *Oper. Res.*, vol. 2, pp. 165-184, Jun.1958.
[7] R. Jiang, Q. S. Wu, and Z. J. Zhu, “A new continuum model for traffic flow and numerical tests,” *Trans. Res. B.* vol.36, pp. 405-419, 2002.
[8] Saskia Ossen, Serge P. Hoogendoorn,“ Heterogeneity in car-following behavior: Theory and empirics,” *Transp. Research Part C: Emerging Technologies,* vol. 19, pp.182-195, 2011.
[9] Lighthill, M.J., G.B. Whitham, “On Kinematic Waves. II. A Theory of Traffic Flow on Long Crowded Roads,” *Proc. of the Royal Society of London. Series A. Mathematical and Physical Sciences*, vol.229, pp. 317-345, 1955.
[10] B.G. Heydecker, J.D. Addison, “Analysis and modelling of traffic flow under variable speed limits,” *Transportation Research Part C: Emerging Technologies*, vol. 19, pp. 206-217, 2011.
[11] Nagel, K., M. Schreckenberg, “ A cellular automaton model for freeway traffic,” *Journal de Physique I*, vol. 2, pp. 2221-2229, 1992.
[12] Minjie, C., et al, “A study of step calculations in traffic cellular automaton models,” *in Intell. Transp. Syst. (ITSC) 2010* 13th International IEEE Conf., pp.747-752, 2010.
[13] Bo, C., H. H. Cheng, “A Review of the Applications of Agent Technology in Traffic and Transportation Systems,” *IEEE trans. On intell. Transp. Sys.*, vol. 11, pp. 485-497, June 2010.
[14] ZhenJiang, L., C. Cheng, et al., “Cloud Computing for Agent-Based Urban Transportation Systems,” *Intelligent Systems, IEEE*, vol. 26, pp. 73-79, Jan. 2011.
[15] Wang F-Y, “Parallel Control and Management for Intelligent Transportation Systems: Concepts,Architectures, and Applications,” *IEEE Trans. on Intell. Transpt. Syst.*, vol. 11, pp. 630-638, sept. 2010.
[16] Fei-Yue, W. and Shuming, T., “A framework for artificial transportation systems: from computer simulations to computational experiments. in Intelligent Transportation Systems,” *in Proc. of the 8th IEEE Intel. Transp. Syst.* pp. 1130-1134, Sept. 2005.
[17] Wen, H., et al., “Monocular based lane-change on scaled-down autonomous vehicles,” in *IEEE Intell. Veh. Symp.(IV), 2011*, pp.144-149, June 2011.