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Research Article

Physical Architecture Simulation Based on System Dynamics Modelling for an Autonomous Transportation System Scenario

Chen Liang, Zhenwu Chen, Liang Yang, Zihan Guo, Xianglong Feng, Zhijun Huang, Xiang Liu, Yuqing Qian, Yanqing Xu, Xiaochun Zhang, and Ji Zhang

Shenzhen Urban Transport Planning Center Co., Ltd., 10/F Tower B, Building No. 9, Shenzhen Bay Science and Technology Ecological Park, Nanshan District, Shenzhen 518057, Guangdong, China

Correspondence should be addressed to Xiaochun Zhang; lijunyuan@sutpc.com and Ji Zhang; zhangji@sutpc.com

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With the rapid growth of traffic demand and the development of intelligent technology, autonomous transportation system (ATS) has been considered as future transportation system. The evaluation of a designed physical architecture of ATS is necessary for understanding whether and how ATS operates and evolves automatically without manual works, and architecture simulation is a method for solving such research problem. Therefore, in this study, architecture simulation based on system dynamics modelling has been employed for physical architecture research. Under this methodology, a simulation case for scenario "Autonomous Vehicle on a Crossing in an Autonomous Transportation System" has been studied for understanding the information flow in ATS to evaluate and optimise its physical architecture of ATS. In conclusion, the system dynamic model could help researchers understand and evaluate the physical architecture's operation of ATS by scenario analysis.

1. Introduction

With further increase of traffic demand and the development of intelligent technology, it is obvious that intelligent transportation system (ITS) has been gradually taking place of the traditional transportation system in recent years. However, with further increase of traffic demand and the development of intelligent technology, autonomous transportation system (ATS) will take the lead. When automobiles were invented and ran alongside carriages, the traditional transportation system has already been established. However, this system was simple in comparison with ATS, and due to the backward computing technologies in 1850s, there were few studies in architecture designation by simulation or other designing theories.

In recent years, with the rapid development of ITS, technologies of transportation management (including information, computing, communication, and artificial intelligence) are increasingly used for improving the efficiency of transportation services. Compared to the traditional transportation system, there are less manual works in ITS; though manual work is still necessary in areas of transportation management, service, and so on. The following activities of ITS designation and optimisation reveal some development trends of transportation system: (1) results of traffic flow simulation demonstrate the information of traffic status, congestion prediction, vehicle guidance schemes, and so on; (2) the four-step model and activity-based model show the macroscopic traffic demand to assist administrators in designing traffic infrastructure, optimising public transportation schemes, and so on; and (3) the system dynamic model has been applied in public policy analysis, transportation resource supply-demand gaming analysis, and so on for the optimisation of system architecture and the allocation of resources. Furthermore, these tendencies would be upgraded in ATS, because the transportation system in ATS could operate and supply services automatically without manual work. This system will evolve automatically by the changing of transportation service demands. As a result, physical architecture of ATS would be more complex, but could still be studied for understanding the operation status, which makes it a starting point of research to understand this status and evaluate the ATS architecture researchers designed.

Research on ATS is currently in the initial stages of exploration and early studies largely concentrated on theoretic or qualitative analyses of ATS. For instance, Crayton and Meier [1] examined the public health impact of autonomous reform of transportation and suggested a corresponding research agenda. Hancock et al. [2] analysed the effects of the autonomy of the transportation system from technological and ethical standpoints, with a preference for the drawbacks. Other research studies focused on autonomous services that rely on carriers and infrastructures to support specific scenarios, including emergency health aid [3], Internet of Vehicle [4], and public transportation [5, 6]. In general, the development of ATS still requires a steady base in theory and technology in which a general and personalised architecture is very essential [7].

The construction of the ATS architecture involves two key processes, namely, design and simulation. However, the majority of current work on the ATS architecture mainly focuses on the theoretical level. For example, Xu et al. [8] utilised complex network theory to examine and evaluate the reliability of the logical architecture for ATS, as well as to identify the crucial nodes. With the help of fuzzy theory, Tang et al. [9] analysed architectural information and established mapping associations based on the traits of complex systems. Zhang et al. [10] constructed the evolution model and detailed the evolution process to reveal the evolution mechanism of ATS, showing the development law of the ATS architecture. Moreover, when referring to the ITS architecture, most existing design methodologies have scenario or scale restrictions [11–13].

Additionally, being one of the primary techniques for contemporary engineering verification, microsimulation is extensively used in the transportation industry to analyse and resolve dynamic issues. Despite the fact that it performs well in specific application scenarios and offers great support for related research, e.g., public transportation [14] and urban freight transport [15] it has not yet had a complete set of tools for simulation and evaluation in transportation architecture [12, 16, 17]. To put it simply, ATS architecture design, such as other system architectures, has various requirements for reliability, adaptability, and versatility [8, 18, 19], and it also needs to establish a relationship with simulation tools to better match the simulation possibilities and system requirements [20]. According to those reviews, few studies on physical architecture analysis and evaluation of ATS currently reveal a significant gap in the ATS physical architecture simulation modelling.

After a comprehensive investigation, it was determined that modelling and simulation based on system dynamics (SD) is a feasible comprehensive method because it provides a systematic approach that can illustrate the value of entity feedback and delayed response [21]. In SD simulation, a “stock and flow diagram” has been employed for modelling (see Figure 1). Stock is defined as containers of transmitters, while transmitters could be transited to another stock through a flow. Level variable describes the volume of transmitters a stock saved, and speed variable describes the volume of transmitter flow transfers per time unit (e.g., second, hour, year, and so on.). Figure 2 shows the mechanism of system dynamics simulation.

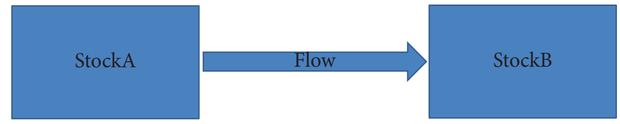


Figure 1: An example of stock and flow diagram.

Wen et al. [22] modelled the demand and supply of the designed public autonomous transportation system to analyse services. Sayyadi and Awasthi [23] integrated SD simulation and analytic network process to evaluate policies of the transportation system and to analyse their sustainability. Qu et al. [24] utilised SD to analyse logistics transportation systems for designing cost-effective IoT solutions. The transportation system is quite complicated since it is comprised of many different entities, which is particularly obvious in ATS. Additionally, there is currently no effective or appropriate way to design and simulate ATS architecture using SD, but it is highly promising for complicated and dynamic ATS architecture with customised demands.

In ATS architecture, information transfers through physical entities, which makes it critical to understand the status of this procedure for evaluating a designed architecture. SD modelling is a tool for simulating this procedure, and a methodology of utilising SD in ATS physical architecture has been established to solve such a problem. In this methodology, a simulation model based on SD has been introduced for understanding and evaluating an ATS physical architecture’s operation by a scenario “Autonomous Vehicle on a Crossing in an Autonomous Transportation System,” which shows that system dynamic model could be utilised in the designing of ATS physical architecture so that researchers and designers can test and evaluate the architecture they designed.

2. Architecture of ATS

According to previous studies, ATS includes components, function, service, physical entities, and sequential logics. For architecture research, those modules should be serviced to physical architecture, which contains a logic network established by physical entities composed by components and their functions, as well as sequential logics between physical entities composed by interoperability relationships.

2.1. Components. Components refer to the various parts that constitute the transportation system, which are the physical representations of the transportation system and serve as its foundation for both continued operation and maintenance. There are two types of components, one is transportation service demander, such as passengers and goods, which leads the formation of transportation system; the other one is supplier, such as transportation infrastructures (i.e., roads and traffic lights) and vehicles, which guarantees the

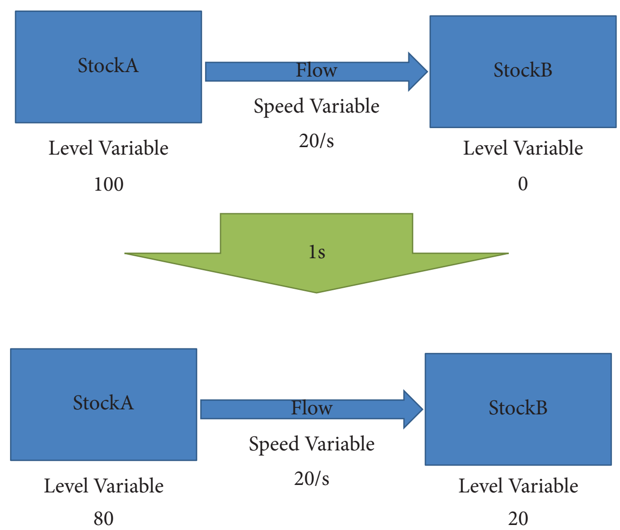


Figure 2: Mechanism of system dynamics simulation.

operation of the transportation system. Demanders and suppliers construct the transportation system, and they could not work standalone because according to the definitions, suppliers should work and adjust automatically for matching the demanders in ATS.

2.2. Function. Function is one of the basic elements in the architecture of ATS, which is driven by technology and utilised to implement numerous transportation-related services and guarantee the systematic and autonomous operation of the whole system, e.g., fetching the position of a vehicle, fetching the position of an obstacle, and recognising traffic signals.

2.3. Physical Entity. Physical entities are abstracted containers of real-world items made of components and functions with dynamic and measurable attribute information. By the rule of composing a physical entity, a component could only contribute to one entity, but one function can be realised by multiple entities. Physical entities should be categorised in accordance with the type of entity they transmit, including the type that develops the transportation system and the type that keeps it operating. From the theory of traffic flow, it should be separated into two categories, i.e., individuals and information. Level variables and capacity have distinct expressions as well. Although it is still feasible to divide up people and information, due to similar feature attributes, further subdivision is not possible from a procedural perspective.

The arrangement of physical entities follows principles of "sensing-learning-deciding-reacting" and "individual-module system." The information stream linking physical items generates the architecture. Physical entities can be divided into multiple hierarchies, while solitary physical entities should be avoided. The physical entity's structure is layered according to its level. The basic principle is that only one of the containment relationship and the sequential logical connection relationship can be selected. Meanwhile, rather than direct simulating, the operation result of the upper-layer physical entity depends on the lower-layer physical entity, which is the reaction of the lower-layer physical entity's simulation result. The simulation evaluation of the corresponding functional domains can be performed by simulating functions of various physical entities.

2.4. Service. Every function offers its service. To complete a service, the cooperation of different functions is necessary, and a structure of functions would be built. Function architecture is a base for constructing the physical architecture.

2.5. Sequential Logic. Corresponding to the flow component of the system dynamics model, the sequential logic is closely related to the data and the information required by certain specific functions, which is composed of information exchange pairs. An information exchange pair consists of a "source" physical entity, an information stream, and a "sink" physical entity. It indicates that a pair of physical entities completes an interaction through an information stream and forms process model through collaboration mechanism. The information stream corresponds to the interoperability relationship, which reflects the interaction relationship between physical entities, and consists of the two physical entities with information exchange in the architecture.

Sequential logic refers to the interconnection of the containers where the physical entities are located and forms the inherent logic of sequence. The information passing container parameters and the information receiving container parameters are the input and output of the sequential logic. There are several limitations to the sequential logic. For example, the sequential logic shall not directly connect physical entities of different levels with direct subordinate relationship, i.e., the lower-level physical entities shall not directly output data to the upper-level physical entities, while the upper-level physical entities shall not directly release data to the lower-level physical entities. Sequential logic, however, can be rationally explained even if there are no physical entities going in or coming out. Meanwhile, the process simulation simulates the sequential logic of the system dynamics architecture, and all simulation results are calculated from the bottom-level physical entities and sequential logic sets.

2.6. Physical Architecture. An essential component of the research on the system architecture of ATS is the connotation analysis and interaction mode of functional architecture, logical architecture, and physical architecture. The physical architecture primarily defines the numerous physical elements contained in the system and supports the realisation of logical architecture and functional architecture through these elements. For specific scenarios, physical architecture defines physical entities and information streams. It analyses the elements of ATS and builds system infrastructure based on physical entities and sequential relationships.

The process of establishing the physical architecture starts with a single subservice. It is necessary to first identify a number of subfunctions that correspond to the service, and then the physical entities that are provided and undertaken by the subfunctions are determined in accordance with the logical sequence of these subfunctions. The source physical entity and subservice determine the information stream and data between two physical entities. A physical architecture is then generated by connecting these physical entities and information streams. The major focus of the physical architecture analysis is the structure that the ATS should have from the standpoint of the physical system, including multiple key contents such as components, scenarios, information exchange pairs, and interoperability relationships. Figure 3 shows the relationship among those concepts.

3. Concept Model of Scenario

It is a typical scenario that an autonomous vehicle drives in a typical crossing of a transportation network that includes many physical entities such as "driver," "walker," and "roadside equipment." Those physical entities are linked by interoperability relationships for information transmission. Different from ITS and traditional transportation systems, information and signal services should be supplied automatically. Therefore, a physical structure should be built for services including right-of-way allocation, collision alert, and giving way to pedestrians, and would simulate the information flow among those functions. A model has been built for modelling this scenario: when an autonomous vehicle drives to a crossing, information from other vehicles should be received. This procedure includes the following steps:

(1) Data recording other vehicles' unusual behaviour is transferred from vehicles to roadside equipment

(2) Roadside equipment treats that information into transport status and transfers to operation centre and transport information centre

(3) Transport information centre publishes transport status as broadcast information through information publish department to the vehicle's On-Board Unit (OBU), while operation centre shows regulation information by analysing this transport information to OBU

(4) OBU receives broadcast and regulation information as driving scheme and connects to Body Control Module (BCM) for asking avoidance feedback

(5) OBU sends collision information to interaction module for sending collision alert to vehicle controller

(6) Vehicle controller operates the vehicle by consuming collision alert information

According to the scenario, there are in all 9 physical entities and 10 sequential logics (the other flow is for information consumption) (see Tables 1 and 2).

Figure 4 shows the stock and flow diagram of this empirical model.

In the previous research, the model has been constructed by empirical methods, and the flow has been built already. However, this research shows a new method for quantitative evaluation by system dynamics modelling. First, parameter sets have been employed for setting the volume of information of each physical entity and the flow speed of each sequential logic; second, those parameters have been put as the stocks' initial level variables and flows' speed variables. Then, this system dynamic model was run, and finally the level variables of all physical entities in each simulation step would be collected.

4. Results and Discussion

4.1. Simulation Results. According to Section 3, a system dynamics model has been built. The settings of level variables of physical entities and max flow speeds of sequential logics are shown in Tables 3–4. In this research, the level variable shows the volume of information, which is a relative volume (Info. Unit, IU), and time unit of speed variable is set as "step."

The results of this simulation model in different parameter sets are shown in the following diagrams.

4.2. Discussion. According to the results of five parameter sets shown in Section 4.1, there is a model for analysing the scenario of information transmission when autonomous vehicles are driving on a crossing in an ATS.

According to Figures 5(a) and 5(b) (parameter set 1), when there are no enough spaces to save information from operation centre and information publish department in OBU and BCM, information will be stuck in operation centre and information publish department as information is full in OBU, and information solved by BCM could not be transferred back to OBU and transferred to next step (i.e., interaction module). At the same time, information saving space in BCM is full and could not receive further under-solving information from OBU. As a result, information stayed in this area, and the whole system failed.

When the information space of BCM raised (Figures 6(a) and 6(b), parameter set 2), this system performs better. However, it costs many steps to response to the information of unusual behaviours from other vehicles. When information from other vehicles occurs, level variables of BCM, OBU, information publish department, and operation centre raise to a certain level (up to more than 900 IU). This is a result of the raising of space in BCM because BCM could save nearly all the "unusual behaviours" information and such information could be solved in a long period. Meanwhile, due to the large space in BCM, OBU could send much more information to BCM. However, this system may fail if more and more information is received by OBU, which will eventually fill BCM to the full.

Another way may be faster (parameter sets 3 and 4). In these two sets, maximum information saving space of OBU raises, and BCM is 1000 IU or 10000 IU. When OBU's space

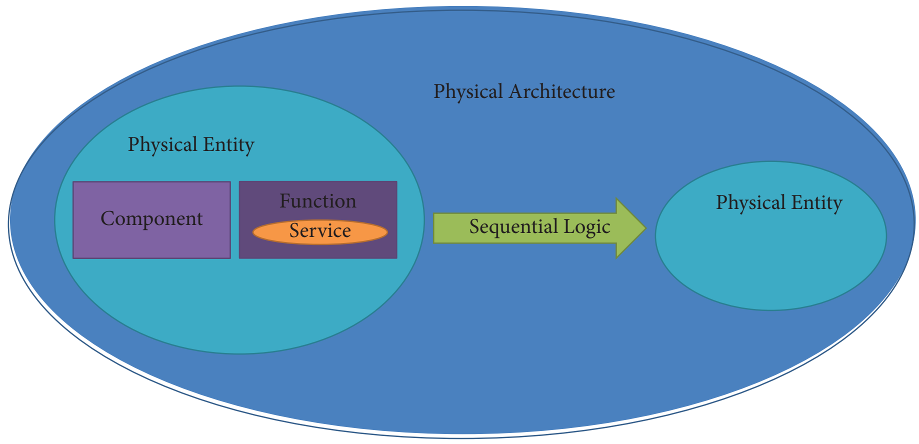


Figure 3: Relationship among concepts related to ATS.

Table 1: Physical entities of scenario.

#	Physical entity
1	Other vehicles
2	Roadside equipment
3	Operation centre
4	Transport info centre
5	Info publish department
6	OBU
7	BCM
8	Interaction module
9	Vehicle controller

Table 2: Sequential logics of scenario.

#	Sequential logic	From entity	To entity
1	Unusual behaviour	Other vehicles	Roadside equipment
2	Transport status a	Roadside equipment	Transport info centre
3	Transport status b	Roadside equipment	Operation centre
4	Broadcast info a	Transport info centre	Info publish department
5	Broadcast info b	Info publish department	OBU
6	Regulation info	Operation centre	OBU
7	Driving scheme	OBU	BCM
8	Avoidance feedback	BCM	OBU
9	Collision info	OBU	Interaction module
10	Collision alert	Interaction module	Vehicle controller

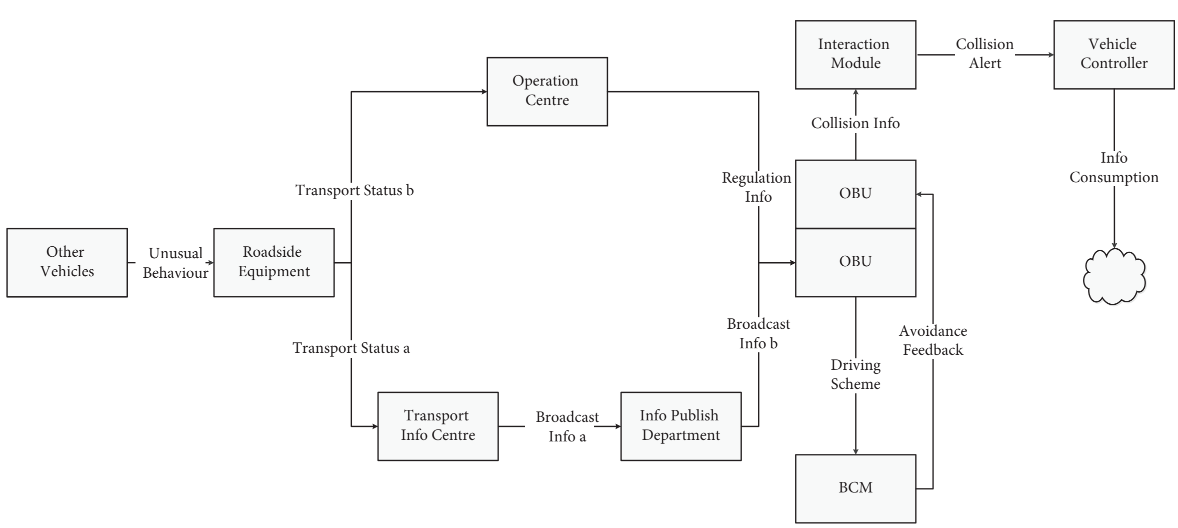


Figure 4: Stock and flow diagram of scenario "autonomous vehicle drives in a typical crossing of a transportation network."

Table 3: Minimum, maximum, and initial level variable (LV) of physical entities and maximum speed variable (SV) of sequential logics of scenario (parameter set 1).

Physical entity	Min. LV/IU	Max. LV/IU	Init. LV/IU	Sequential logic	Max. SV/(IU/s)
Other vehicles	0	Inf.	1000	Unusual behaviour	50 ± 5
Roadside equipment	0	10000	0	Transport status a	50 ± 5
Operation centre	0	100000	0	Transport status b	50 ± 5
Transport info centre	0	100000	0	Broadcast info a	50 ± 5
Info publish department	0	100000	0	Broadcast info b	50 ± 5
OBU	0	1000	0	Regulation info	50 ± 5
BCM	0	1000	0	Driving scheme	50 ± 5
Interaction module	0	10000	0	Avoidance feedback	50 ± 5
Vehicle controller	0	1000	0	Collision info	50 ± 5
				Collision alert	50 ± 5

Table 4: Parameter set 2 for research scenario.

Physical entity	Min. LV/IU	Max. LV/IU	Init. LV/IU	Sequential logic	Max. SV/(IU/s)
Other vehicles	0	Inf.	1000	Unusual behaviour	50 ± 5
Roadside equipment	0	10000	0	Transport status a	50 ± 5
Operation centre	0	100000	0	Transport status b	50 ± 5
Transport info centre	0	100000	0	Broadcast info a	50 ± 5
Info publish department	0	100000	0	Broadcast info b	50 ± 5
OBU	0	1000	0	Regulation info	50 ± 5
BCM	0	10000	0	Driving scheme	50 ± 5
Interaction module	0	10000	0	Avoidance feedback	50 ± 5
Vehicle controller	0	1000	0	Collision info	50 ± 5
				Collision alert	50 ± 5

Table 5: Parameter sets 3 and 4 for research scenario.

Physical entity	Min. LV/IU	Max. LV/IU	Init. LV/IU	Sequential logic	Max. SV/(IU/s)
Other vehicles	0	Inf.	1000	Unusual behaviour	50 ± 5
Roadside equipment	0	10000	0	Transport status a	50 ± 5
Operation centre	0	100000	0	Transport status b	50 ± 5
Transport info centre	0	100000	0	Broadcast info a	50 ± 5
Info publish department	0	100000	0	Broadcast info b	50 ± 5
OBU	0	10000	0	Regulation info	50 ± 5
BCM	0	1000/10000	0	Driving scheme	50 ± 5
Interaction module	0	10000	0	Avoidance feedback	50 ± 5
Vehicle controller	0	1000	0	Collision info	50 ± 5
				Collision alert	50 ± 5

Table 6: Level variables of other physical entities (parameter sets 3 and 4).

Physical entity	Max.	Min.	Average
Roadside equipment	0.45	0.00	0.13
Operation centre	0.16	0.00	0.02
Transport info centre	0.21	0.00	0.05
Info publish department	0.21	0.00	0.03
BCM	0.34	0.00	0.20
Interaction module	0.20	0.00	0.07
Vehicle controller	0.15	0.00	0.06

is high enough, there are no influences whether the BCM's space is large or not. The clearance time is shortened to 400 steps. These sets are better than those in set 2, but according to Figure 7 and Table 6, even though many physical entities are good running-condition, level variable in OBU is raised to the maximum information value (1000 IU). Therefore, these two sets could not solve the problem "more information" in parameter set 2.

According to Figure 8 and Table 8, the results of the final parameter set shows that during the running of simulation, information of "unusual behaviours" has been consumed, while all other physical entities run stably (level variable is between 0 IU and 1 IU). The last problem found in this scenario is caused by the information consumption speed. When raising the information consumption speed of sequential logics named "driving scheme," "avoidance feedback," "collision info," and "collision alert," which means when increasing the performance of autonomous vehicles, the system would run automatically and smoothly.

According to previous analysis, physical architecture can be only tested and verified by empirical analysis. However, in this research, as the quantitative analysis method "system dynamics simulation" has been utilised in the scenario "Autonomous Vehicle on a Crossing in an Autonomous

Table 7: Scenario parameter set 5.

Physical entity	Min. LV/IU	Max. LV/IU	Init. LV/IU	Sequential logic	Max. SV/(IU/s)
Other vehicles	0	Inf.	1000	Unusual behaviour	50 ± 5
Roadside equipment	0	10000	0	Transport status a	50 ± 5
Operation centre	0	100000	0	Transport status b	50 ± 5
Transport info centre	0	100000	0	Broadcast info a	50 ± 5
Info publish department	0	100000	0	Broadcast info b	50 ± 5
OBU	0	10000	0	Regulation info	50 ± 5
BCM	0	1000	0	Driving scheme	100 ± 5
Interaction module	0	10000	0	Avoidance feedback	100 ± 5
Vehicle controller	0	10000	0	Collision info	100 ± 5
				Collision alert	100 ± 5

Table 8: Level variables of physical entities except "other vehicles" (parameter set 5).

Physical entity	Max.	Min.	Average
Roadside equipment	0.52	0.00	0.31
Operation centre	0.09	0.00	0.03
Transport info centre	0.21	0.00	0.08
Info publish department	0.43	0.00	0.14
OBU	0.02	0.00	0.01
BCM	0.01	0.00	0.01
Interaction module	0.01	0.00	0.01
Vehicle controller	0.01	0.00	0.01

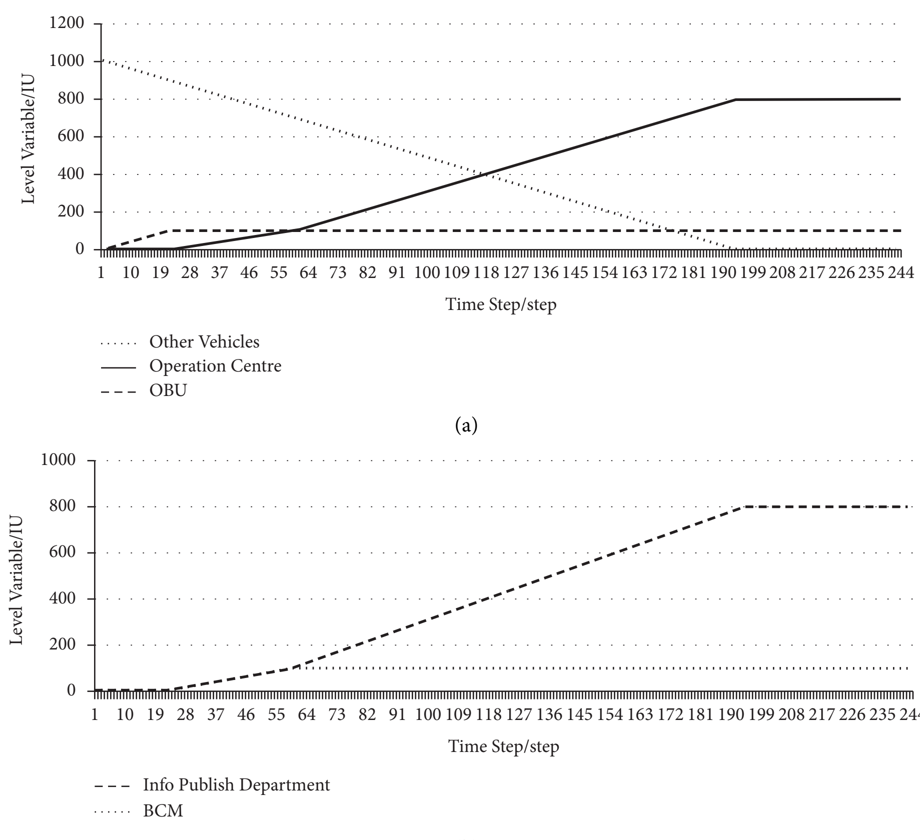
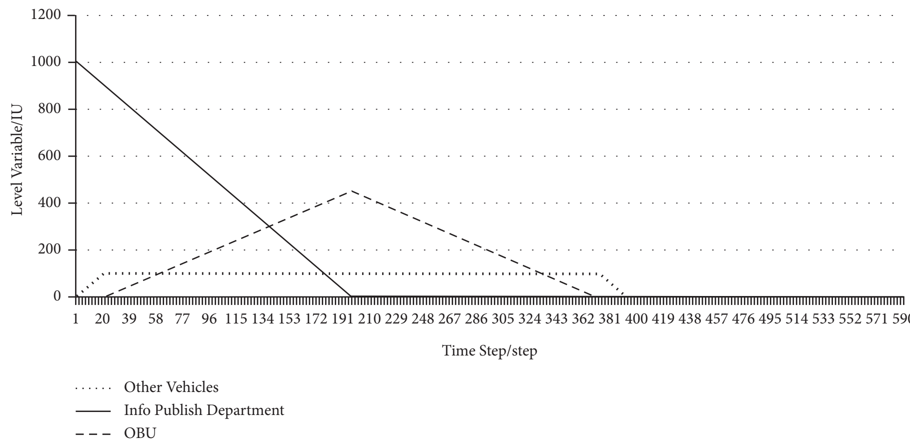
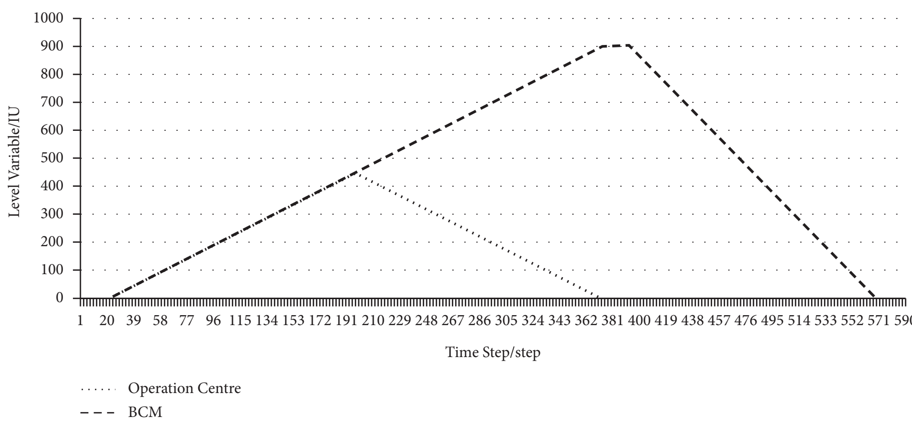


Figure 5: (a) Level Variables of Physical Entities (Parameter Set 1, OBU, etc.) and (b) Level Variables of Physical Entities (Parameter Set 1, BCM, etc.).



(a)



(b)

FIGURE 6: (a) Level Variables of Physical Entities (Parameter Set 2, OBU, etc.) and (b) Level Variables of Physical Entities (Parameter Set 2, BCM, etc.).

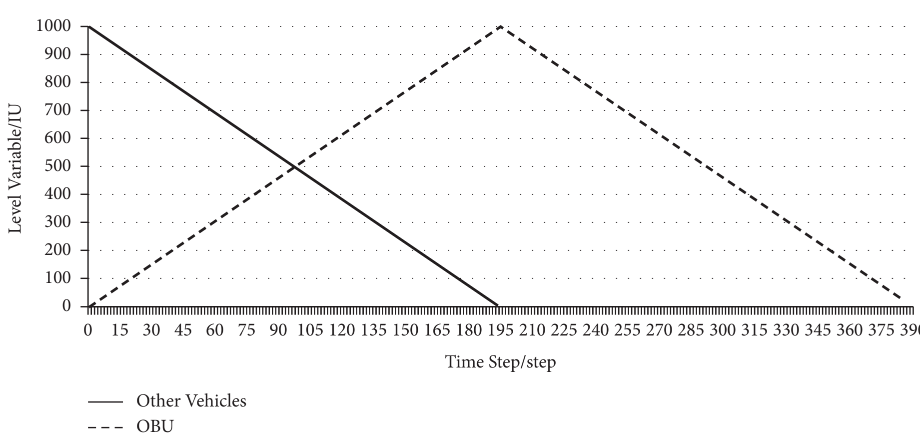


FIGURE 7: Level variables of “other vehicles” and “OBU” (parameter sets 3 and 4).

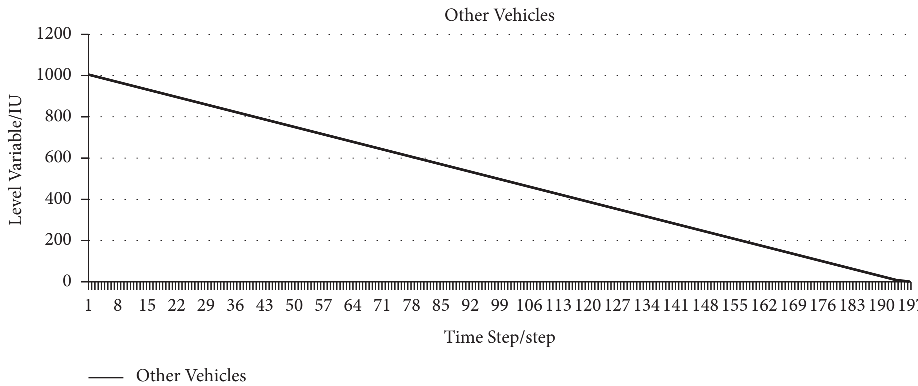


Figure 8: Level variables of physical entities (parameter set 5).

Transportation System," we could get the operation status of this physical architecture by the results of the SD model and also verify and optimise it conveniently.

5. Conclusion

In this research, system dynamics modelling has been utilised in the analysis of ATS' physical architecture. Estimating the necessary volume of information saving and the minimum speed of information transmitting are significant challenges in ATS designation. This research utilised system dynamics modelling and optimising a parameter set to evaluate this designed architecture. As a result, this research solved a problem of how physical architecture works in one generation of ATS. However, ATS has a character that it can evolve automatically, which includes several generations. In future research, there may be studies on the architecture simulation between generations of ATS.

Data Availability

The ATS physical architecture data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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