Building The System Dynamic Models for Disaster Emergency Response System in The Long Highway Tunnel – A Fire Case

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ABSTRACT:

There are many kinds of public transportation systems are developed in Taiwan recently, for example the Hsueh_Shan Tunnel that is a 12.9 km long tunnel. In accordance with the world's fire events, the fire risk hidden in the space of long road tunnel could cause serious life loses and structural damage. First of all, a systematic modeling method is conducted to construct the causal relationships during emergent rescue procedures of a disaster based on the standard operation procedures of emergency response and domain knowledge in this paper. Then the stock-flow diagrams are given with the corresponding Arche-type models in the System Dynamic. Finally, the parameters and empirical formula in the models are imported to simulate the emergency response scenario when a fire happened. The results indicate that the models can be used to establish properly rescue and evacuation strategies. It was believed that a crisis assessment model for the tunnel's disaster management can be built in the future.

1. INTRODUCTION

1.1 Research Purposes

Highway tunnels are specially designed spaces that meet traffic requirements and landforms. It is enclosed and underground, which sets them apart from open spaces in highway traffic management. In addition, disaster relief operations are different from the response and rescue for buildings. Its spatial features may contribute to severe casualties and transportation interruptions when an accident occurs, especially in long tunnels or tunnel groups, such as overheated vehicles, collisions, and dangerous goods transportation may cause accidents. Once a fire breaks out, the onsite high temperature would exceed 1200℃, and part of tunnel structures could collapse, thus, obstructing preliminary disaster relief operations, and possibly leading to severe disaster and casualties.

This study acquires tunnel facility knowledge through ontology, uses system dynamics to construct a system diagram, explains the cumulant and flow rate when a fire breaks out in a tunnel, and drafts a causal feedback loop diagram. Based on the precedence order and the causal feedback relationship between the situations in fire hazards and standard emergency response operations, this study drafts a system dynamic flow diagram by combining the system diagram with the causal feedback loop diagram in order to digitize the cumulant, flow rate, and variables in the system, and displays the fire size and the disaster situation by scenario simulation through variable designs. The results can be used to estimate the effects of different ratios of rescue resources in situations of disaster and provide information and suggestions to decision makers for handling fire disasters and reducing disaster damage.

1.2 Research Scope

In recent years, the long tunnel works of Hsuehshan Tunnel National Freeway No. 5 and Pakuashan Tunnel were completed and open to traffic in Taiwan. Hsuehshan Tunnel is 12.9 km long, the fifth longest tunnel in the world, and the driving environment inside the tunnel is a confined space. Thus, relevant safety management, facilities maintenance, and emergency response must be provided in immediately. However, Taiwan does not have prior experience in the management of long tunnels. Once a disaster or accident occurs in the tunnel, it would spread faster within the confined space, making the disaster relief very difficult. The severity of the disaster may increase without proper prior planning and management, and make reconstruction more difficult. Although no severe tunnel fire accident has occurred in Taiwan, and the statistical data of the freeways and national highways accident rate indicates that the traffic accident rate in tunnels is far lower than that in open spaces, according to foreign tunnel accident surveys, and damages resulted from tunnel accidents are more severe than in open space accidents. Focusing on long tunnel disaster response, this study discusses the impact of various ratios of resources and time inputted during disaster relief on the degrees of disaster scopes, through a scenario simulation of emergency response operations and system dynamics. This study takes the Hsuehshan Tunnel as the research target, applies

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ontology as a reference for disaster relief, and uses system dynamics as the research method.

2. METHODOLOGY

2.1 System dynamics theory and its modeling procedures

System Dynamics was developed by Prof. Jay W. Forrester, of the U.S. M.I.T Sloan School of Management (Forrester, 1961); it mainly discusses relevant issues in engineering and management, and leads the concept of causal feedback in the system of social science research. The system dynamics and name are the same as the existing scientific name in the domain of engineering. The system dynamics in the domain of engineering describes the changes in motions of objects by using the principle of conservation of momentum (Yang, 2007). The system refers to the whole, the elements in the system integrate with each other, will continuously affect each other in the long-term, and move toward the same purpose. The so-called system analysis considers problems based on the viewpoint of the whole, thus, all parts are considered in problem solving, and seek solutions in the best interest of the whole. A new method, a new tool, and a new concept of management combines control, system theory, information theory, decision theory, and computer simulation. The system dynamics is a precise research method for describing, exploring, and analyzing the flow, information, organizational boundaries, and strategies in a complex system, it can design the system structure and behaviors through quantitative system simulation and analysis. The system dynamics is a methodology for processing dynamic behaviors of the information feedback system, it provides an experimental and quantitative analysis method, and thus, can provide an overall, long-term, and distributive solution for very complicated dynamics, and provides feedback for time delay problems. (Chang, 2008)
The major steps of the modeling and analysis processes of system dynamics are the "definition of the problem", "description of the system", "drawing of a causal feedback loop diagram", the "creation of a system dynamic flow diagram", and "model construction and scenario simulation", the function orientations of all steps, and their relations, are shown in Figure 3-1. This flow can be preliminarily classified into two major classes: problem concept analysis and model simulation analysis. The purpose of problem concept analysis is to learn the cause and influences of system problems through "definition of the problem", "description of the system", and the "drawing of a causal feedback loop diagram", and to propose the thoughts or logic for solving the problems. The purpose of model simulation analysis is to model the thought or logic for solving problems through the "creation of a system dynamic flow diagram" and a "model construction and scenario simulation", and determine feasible problem solving strategies based on the simulation results of the models of different situation designs. The overall flow is described as follows: (Yang, 2007)

A. Definition of the problem
The primary variables composing the problems in the system are regarded and discussed using nouns, such as goal, existing circumstance, and gap, and then a graph of primary variables, which vary with time, is created to judge what type of problems the time-varying trends would result in. Once the type and meaning of a problem are properly defined, a "description of the system" and "a drawing of a causal feedback loop diagram" can be constructed synchronously. (Han, 2002)

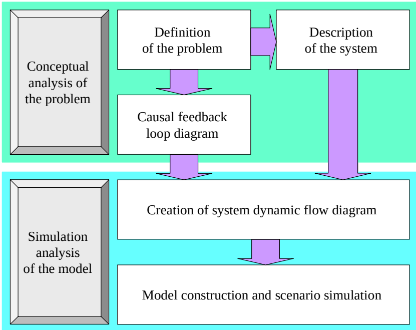

Figure 1. A modelling workflow for the System Dynamics

B. Description of the system
In order to describe the relevance between the main components (or elements) and components (or elements) and the flow type, as formed by the components (or elements) in the system resulted from the problem trend, often the system diagram, drawn in system analysis, can be regarded as the specific expression of this step.

C. Causal feedback loop diagram
Different variables mentioned in the "definition of the problem" are connected in series to form a "causal feedback loop", accomplished by using the concepts of causal relations and feedback, the characteristics of causal relations, application directions, and system structure of all variables are clearly known by drawing this feedback loop diagram. These information are helpful in determining the thought and logic for solving problems. The trend of problem variations with time can be regarded as the combined influence of the flow of system components (system diagram) and the flow of information transfer between the variables (causal feedback loop diagram) at each time of interaction effect.
The relationship between the causal and the causal feedback must be known before making the causal feedback loop diagram.
The causal relation defines the relation between the two variables as a positive direction or a negative direction. The positive direction means when the quantity of one-side increases, the quantity of the other side will also increase; or when one side decreases, the other side will also decrease. The negative direction means when one side increases, the other side will decrease at the same time; or when one side decreases, the other side will increase at the same time. Variables are connected by cause and effect, and indicated by Arrows, the arrowhead origin represents the influencing variable, and the arrowhead terminal represents the influential variable. If they are in a relation of positive variation, it is indicated by "+"; if they are in a relation of negative variation, it is indicated by "-".
When the influence relation between the variables forms a closed loop, namely a variable is an influencing variable, as well as an influenced variable, and a feedback loop is formed. The property of the feedback loop should be determined by the sum of "+" and "-" in the loop, when the loop contains only "+" or "-" and the sum is an even number, it is a "positive feedback loop", as shown in Figure 2. When the sum of "-" in the loop is an odd number, it is a "negative feedback loop", as shown in Figure 3.

A characteristic of the positive feedback loop is that the system state of the loop presents a sustainable growth or sustainable decline with time, namely the so-called "divergence" in mathematics.

A characteristic of the negative feedback loop is that the system state of the loop presents an asymptotic growth or decline with time, and finally, approaches to the goal, namely the so-called "convergence" in mathematics.

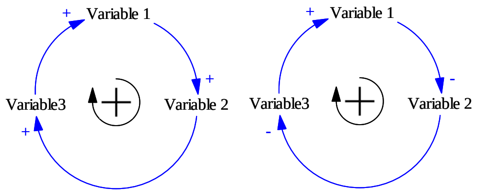

Figure 2. positive feedback loop

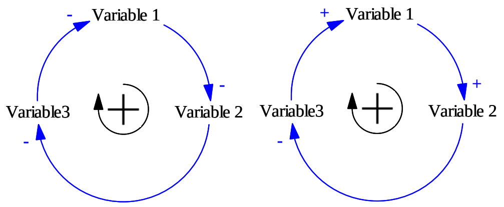

Figure 3. negative feedback loop

D. System dynamic flow diagram

In the step of "creation of the system dynamic flow diagram", we can regard the system diagram and the causal feedback loop diagram as the blueprints of a dynamic system model, and then use a set of specific objects (symbols), as designed by the system dynamics, to describe the dynamic system model in the aforesaid blueprint concept. The diagram describing models using objects (symbols) is called the system dynamic flow diagram.

The system dynamic flow diagram has four basic objects: Stock, Flow, Connector, and Auxiliary. The "stock" represents the state of a system variable at a specific time, the numerical value is the accumulation of the net balance between inflow and outflow, namely the accumulation of past activity results of the system, much like the state variables in general computing equations; the "flow" represents the speed of change of some storage variables, meaning an instantaneous behavior, the numerical value is mostly determined by the mutual relations between stock variables and auxiliary variables, much like the control variables in general computing equations; the auxiliary represents the design of parameters or variables; the connector represents a transfer of relevant information among auxiliary, flow, and stock. The stock and flow can be used for deductions of causal feedback loop diagrams, namely the presentation of variable information flows (see Figure 4).

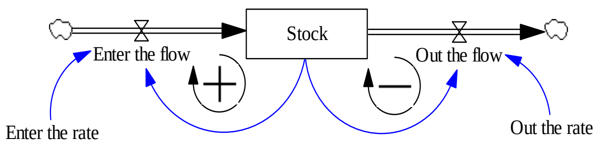

Figure 4. A system dynamic flow diagram

E. Model construction and scenario simulation

Relevant data and mathematical expressions are input into the objects of the system dynamic flow diagram to form a system dynamic model, which can make different scenario simulations (system dynamic simulation software Vensim is used in this study for demonstration). After this step is finished, a feasible problem solving strategy can be concluded and analyzed through the simulation results of the model, under different situation designs.

2.2 Introduction of system archetype

The system archetype was developed by the Innovation Consulting Company in the mid 1980's, it was constructed by continuously reinforcing positive feedback loops, and repeatedly regulated negative feedback loops, in conjunction with the effects of time delay. The system archetype represents a simplified system model, under different types of problems in daily life, in order that we can begin with the knowledge of the fundamental characteristics of a dynamic system, and gradually become accustomed to further and more careful observations and analyses of complex problems, using a system archetype as a template to deduce practical work problems. The archetype used in this study will be introduced as follows (Yang, 2007).

A. System archetype: sustainable growth

A sustainable growth system is composed of the "current state of a system" and the "element of sustainable growth". When the element of growth is strengthened, the current state of the system will be promoted, and the promotion of state will become the driving force for reinforcing the elements in the next stage, thus, the positive feedback loop will allow the system state to grow continuously with time.

B. System archetype: limits to growth

This is an archetype developed from a sustainable growth archetype (composed of the "current state of the system" and the "element of sustainable growth"). When the growth reaches a certain limit, a negative feedback loop will be started (when the current state of the system reaches the tolerance of the limiting conditions, and then, the element of sustainable growth weakens or disappears). This limit may be a limit to resources or an intervention of external environmental tolerance.

C. System archetype: growth and decline competition

The core structure of the growth and decline competition archetype is mainly composed of three terms (current system state, element of growth, and element of decline); where "current system state" and "element of growth" construct a continuously growing positive feedback loop. When the element of growth is reinforced, the current system state will be promoted, and the promotion of the state will become the driving force for enhancing the element in the next stage, thus, the positive feedback loop will allow the system state to continue growing over time; where "current system state" and "element of decline" construct a continuously declining negative feedback loop. When the element of decline is strengthened, the current system state will be reduced, the decline of state will slow down decline, and thus, the negative feedback loop will cause the system state to approach to a fixed value over time. Due to the effects of the two loops continuously occurring, the final state of system is the result of competition.

3. RESEARCH RESULTS AND ANALYSIS

This study constructs the influences of the variations of resource inputs of rescue units on evacuations and situations of disaster for vehicles on fire in tunnels, according to the standard operational procedure of the Hsuehshan Tunnel emergency response, and employ simulation and discussion based on the research analysis of the system dynamics, definition the of problems, description of the system, construction a of causal feedback loop diagram, construction of a system dynamic flow diagram, and situation analysis.

3.1 Definition of problem

Problem discussion of the ideal state in a tunnel, which is the normal state without fire, the real state is with vehicles on fire, as the fire becomes more severe (the gap between ideal state and actual state), and the threat (pressure) to the tunnel and persons in tunnel will become larger. Thus, the tunnel fire problem occurs, as shown in Figure 5.

Figure 5. A problem definition for the tunnel's fire

Determine the problem for discussion, begin with a definition of the problem, and then analyze the objects of interest to this problem, the subject description, and problem types (archetype), are shown in Table 1.

Table 1. Problem definition analysis sheet

Emergency response operational procedures	Interested objects	Subject description	Problem type (archetype)
Accident occurred and is detected	Vehicle V.S. fire	Vehicle on fire	Limits to growth
Accept and confirm	Vehicle V.S. fire V.S ventilation	Initiate ventilation system when a vehicle is on fire	Limits to growth + Negative feedback loop
Report and dispatch Evacuation conduct and Traffic control Preliminary response of rescue units	Vehicle V.S. fire V.S ventilation V.S. self-defense fire-marchal	Initiate ventilation system when a vehicle is on fire, self-defense fire-marchal carries out emergency response and evacuates people from the accident area	Limits to growth + Negative feedback loop + Negative feedback control + Negative feedback loop
Handling of accident and rescue of persons in need or wounded	Vehicle V.S. fire V.S. ventilation V.S. self-defense fire-marchal V.S. sanitary unit	Initiate ventilation system when a vehicle is on fire, self-defense fire-marchal carries out emergency response and evacuates people from the accident area, sanitary unit awaits orders to rescue wounded persons	Limits to growth + Negative feedback loop + Negative feedback control + Negative feedback loop + Negative feedback control
Restoration	Vehicle V.S. fire V.S ventilation V.S. self-defense fire-marchal V.S. sanitary unit V.S. fire-fighting unit	Initiate ventilation system when a vehicle is on fire, self-defense fire-marchal carries out emergency response and evacuates people from the accident area, sanitary unit awaits orders to rescue wounded persons, self-defense fire-marchal and fire-fighting unit carry out fire fighting operations	Limits to growth + Negative feedback loop + Negative feedback control + Negative feedback loop + Negative feedback control +

			Growth and decline competition

3.2 Description of system

The description of the system indicates the primary components, and the relevance between components and the flow type is formed by the components of the system resulted from the interested objects and subject description in the definition of the problem. According to the problem definition in Table 4-1, five sub-systems can be described, which are:

A. Quantity of vehicles on fire

Increase, decrease, and accumulation of vehicles on fire in the tunnel are the most important in system problem definition. (see Figure 6)

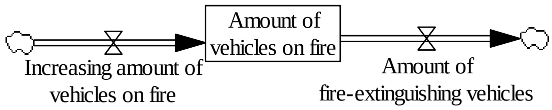

Figure 6. A subsystem for the vehicles on fire

B. Inputted resources of self-defense fire-marchal:

The self-defense fire-marchal conducts evacuation, traffic control, and preliminary response operations when a vehicle is on fire in the tunnel, the resource input state is described in Figure 7.

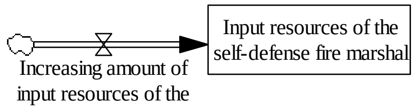

Figure 7. A subsystem for the input resources of self-defense fire-marchal

C. Masses in the traffic accident area:

People in the accident area of a vehicle fire in the tunnel are evacuated through evacuation conduct; the evacuation state is described in Figure 8.

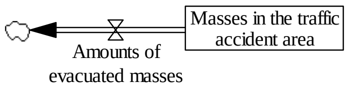

Figure 8. A subsystem for the people in the accident area

D. Inputted resources of sanitary unit:

It enters rescue resources through the reports of the Control Center, and awaits orders to rescue wounded persons; the resource input state is described in Figure 9.

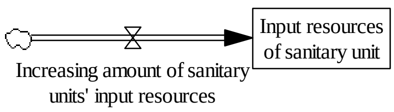

Figure 9. A subsystem for the input resources of sanitary unit

E. Inputted resources of fire-fighting unit:

It starts rescue resources through the reports of the Control Center, and extinguishes any vehicle fires in the tunnel; the resource input state is described in Figure 10.

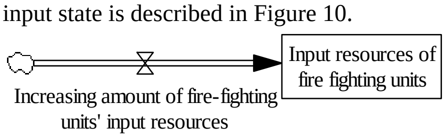

Figure 10. A subsystem for the input resources of fire-fighting unit

3.3 Construction of causal feedback loop diagram

The variables mentioned in the problem definition are indicated by causal relations to judge the positive-negative relevance between variables, and then, connect them in a series to form a feedback loop, in order to know the causal relations among the various variables and the application orientations, and the characteristics of the system structure are based on this feedback loop. The variables are determined according to the problem definition in Table 1, and the causal feedback loop diagram of handling vehicle fires in a tunnel is drawn using the concepts of causal relations and feedback. According to the problem definition sequence, the construction process of the causal feedback loop diagram is as follows:

A. Vehicles on fire:
The discussed problem type is "limits to growth"; it indicates the quantity of vehicles on fire would increase, as limited to the limiting conditions of "vehicles in accident area", the maximum number of vehicles on fire ends at "vehicles in accident area".

B. Start up ventilation system when a vehicle is on fire:
The discussed problem type is "limits to growth + negative feedback loop"; it indicates an increase of vehicles on fire worsens the tunnel fire, the Control Center starts up the fan to reduce the increment rate of vehicles on fire.

C. Emergency response of self-defense fire marshal and evacuation of people in accident area:
The discussed problem type is "limits to growth + negative feedback loop + negative feedback control + negative feedback loop"; it indicates an increase of vehicles on fire worsens tunnel fire, and the Control Center starts the fan to reduce the increment rate of vehicles on fire. The self-defense fire-marchal inputs rescue resources, carries out emergency response, and evacuates people from the accident area.

D. Sanitary unit awaits orders to rescue wounded persons:
The discussed problem type is "limits to growth + negative feedback loop + negative feedback control + negative feedback loop + negative feedback control"; it indicates an increase in vehicles on fire worsens tunnel fire, and the Control Center starts the fan to reduce the increment rate of vehicles on fire. The self-defense fire-marchal inputs rescue resources, carries out emergency response, and evacuates people from the accident area, the Control Center notifies the sanitary unit to input rescue resources and await orders to rescue wounded persons.

E. Self-defense fire marshal and fire-fighting unit carry out fire fighting operations:
The discussed problem type is "limits to growth + negative feedback loop + negative feedback control + negative feedback loop + negative feedback control + negative feedback control + growth and decline competition"; it indicates an increase in vehicles on fire worsens tunnel fire, the Control Center starts the fan to reduce the increment rate of vehicles on fire. The self-defense fire-marchal inputs rescue resources, carries out emergency response, and evacuates people from the accident area, the Control Center notifies the sanitary unit to input rescue resources and await orders to rescue wounded persons. The self-defense fire-marchal and fire-fighting unit start fire-fighting operations. After this complete process, the causal feedback loop diagram of handling of vehicle fire in tunnel is drawn (see Figure 11).

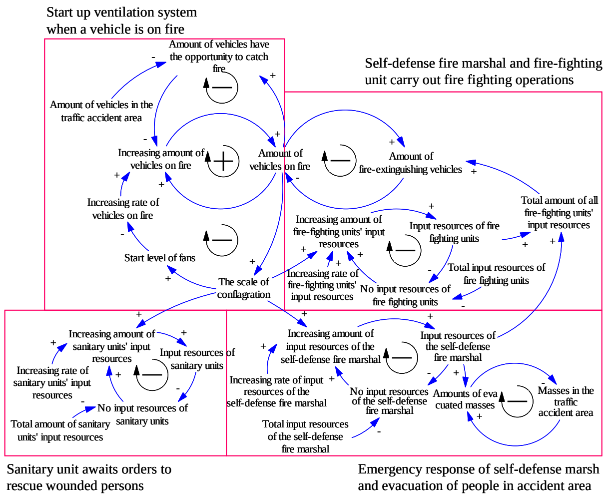

Figure11. A whole causal feedback loop diagram for the DERS in the long highway tunnel

The causal feedback loop diagram mainly describes the causal relations among variables and the presented feedback state. By the construction of a causal feedback loop diagram of vehicle fires in a tunnel, we can know what variables influence vehicle fires, and thus, the required resource input of rescue units when vehicle fires occur in a tunnel, and know the variation relations between cause and effect.

3.4 Construction of system dynamic flow diagram

The system dynamic flow diagram, flow type of the components in the system diagram, and various variables discussed in the causal feedback loop diagram are formed into a system dynamic model by using the objects (symbols) of system dynamics, the cumulant, inflow, outflow, variables, and control variables are defined. The problem types are presented in the system dynamic flow diagram, according to the system diagram and causal feedback constructed in 3.2 and 3.3, the content of construction is shown in Figure 12, and the parameter values are defined as follows:

Cumulant: the quantity of vehicles on fire, inputted resources of self-defense fire-marchal, people in the accident area, inputted resources of sanitary unit, and inputted resources of fire-fighting unit.

Inflow: the increment of vehicles on fire, increment of inputted resources of self-defense fire-marchal, increment of inputted resources of sanitary unit, and increment of inputted resources of fire-fighting unit.

Outflow: the decrement of evacuated people and vehicles on fire.

Variables: the increment rate of vehicles on fire, number of possible vehicles on fire, fire size, start-up degree of fan, not yet inputted resources of self-defense fire-marchal, not yet inputted resources of sanitary unit, not yet inputted resources of fire-fighting unit, total inputted resources of fire-fighting unit, and total number of possible vehicles on fire.

Control variables: the number of vehicles in the accident area, increment rate of inputted resources of self-defense fire-marchal, total inputted resources of self-defense fire-marchal, rescue rate of self-defense fire-marchal, increment rate of inputted resources of sanitary unit, total inputted resources of sanitary unit, increment rate of inputted resources of fire-fighting unit, total inputted resources of fire-fighting unit, and fire extinguishing rate.

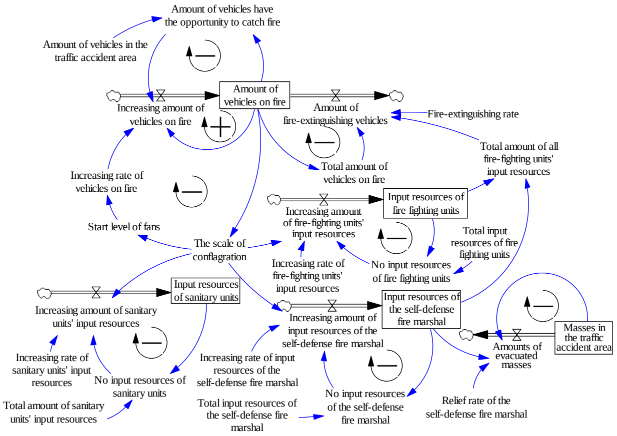

Figure 12. A system dynamic flow diagram for the DERS in the long highway tunnel

4. CONCLUSIONS AND SUGGESTIONS

4.1 Conclusions

1. Through analysis of the definition of problems, the interested objects that would be influenced by vehicle fires in a tunnel, the various subjects generated, and tunnel emergency response operations are combined. Various subjects are presented in the mode of system archetype, in order for rescue personnel to know the variance in different fire stages, and the people in the accident area, according to the emergency response operation, and carry out rescue operations based on the characteristics of the system archetype, in order to reduce the damages resulted from vehicle fires in a tunnel.
2. The causal feedback loop diagram is constructed according to the analysis of the problem definition of vehicle fires in a tunnel, for rescue units to understand the relations among the factors of a fire, personnel, and inputted rescue resources in vehicle fires in a tunnel. By realizing the general view of the system of fires through positive-negative relevance, they can make decisions, and then, perform acts aimed at primary factors to carry out prompt rescue operations.
3. When a vehicle fire occurs in a tunnel, there are five main systems according to the system dynamic flow diagram. With the causal feedback loop diagram, the rescue units can clearly know the operations of the integrated system, restrain the growth elements of vehicle fires in a tunnel, and carry out prompt fire fighting operations to reduce the losses caused by the disaster.

4.2 Suggestions

1. This study has completed the initial conversion of all relevant information and mathematical expressions, but still requires more actual fire experimental data. With more accurate data in the future, the system can reflect actual situations more realistically.
2. This study discusses vehicle fires in tunnels, and covers various emergency-situations in tunnels; however, the control variable designed is still limited. It is hoped that there will be more in-depth discussions and applications in the future to perfect tunnel safety management.

5. ACKNOWLEDGMENTS

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