2008~2009 剑桥国际高中系统动力学小组活动情况

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活动形式： 小组讨论、调查研究、撰写论文

活动成果： 应用系统动力学研究生活中的交通拥堵问题，并写出论文《Investigating Traffic Congestion Using a System Dynamics Model》，受到国际系统动力学协会邀请参加 26 届国际系统动力学大会，并做大会发言。

活动论文： 见下页

Investigating Traffic Congestion Using a System Dynamics Model

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Abstract

Transport congestion is a problem commonly seen in downtown areas, such as *Xin Jie Kou*, which is the central business district of the city where the authors live. This paper seeks to simulate real-life situation in a system dynamics model, and hence understand the different factors that influence urban traffic congestion levels and their inter-relationships. Then it will examine the effects of some common policies used by the government to alleviate the traffic problems. Finally, this paper will evaluate the limitations of the system dynamics model. This paper is to help us better understand seemingly complex traffic problems in a clear, systematic and dynamic way.

Throughout our study, we resort to the STELLA software for model construction, simulation and analysis. Because most of the variables in discussion are hard to quantify, some of the values are arbitrarily indicators of real-life variables. For simplification, we have only looked at key areas and factors that are the most strongly related to this topic.

Keywords

Traffic Congestion, System Dynamics Model, Policies

Introduction

The history of transport development has in some ways been the history of people fighting traffic congestions. With ever increasing number of cars coming into use, vehicles are blocking more and more streets, paralyzing traffic systems of big cities. Congestion directly stops cars from flowing properly, and may further affect many aspects of our daily life; rising of cost of transport, pollution, drop of real work hours are just a few of them. This paper focuses on the traffic condition of a typical downtown area such as *Xin Jie Kou* during a short period of time. Based on some important causal relationships and assumptions, we will use a system dynamics model to investigate various factors that contribute to or alleviate congestion and examine some common policies to improve traffic in rush hours.

Simplified Model

Figure 1 is a simplified version of our model. This model will show the major interactions between the most important variables in this model.

The number of cars on road changes with time during 24 hours. These changes are brought about by inflow and outflow of cars. Caution has to be taken that in this paper, inflow and outflow does not simply mean the process of drivers driving into and out of the downtown area. In our model, inflow means the rate of cars appearing on the roads of the area we are investigating, whereas outflow refers to the rate of cars disappearing in this area. These rates can be approximated by variations of sinusoidal waves (Please see Figure 2). The two peaks simulate the two rush hours each day. The phase difference between the two waves is determined by the traffic condition on road. Consider a driver that has to commute to the downtown area to work. His average journey time, i.e. the time between his car appearing and disappearing on road, is determined by how congested the road is.

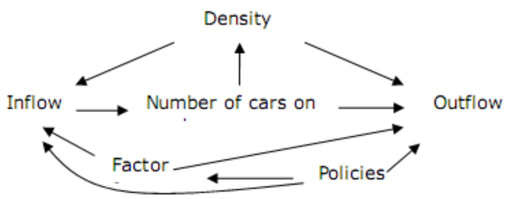

Figure 1

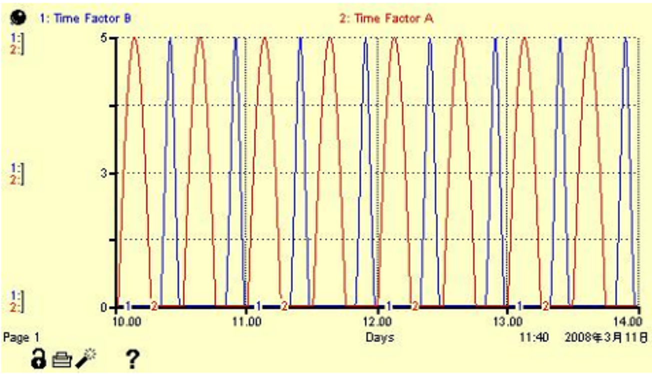

Figure 2

An important parameter we looked at here is the traffic density, i.e. total number of cars divided by road capacity, which is a constant in each run of simulation. Density rises or falls accordingly with changes in inflow and outflow, and can affect inflow and outflow. Density, road pricing, parking space and other factors and policies interact within the system dynamically, and cause congestion to worsen or improve according to their relative power to influence the whole picture. Policies can also achieve the ideal outcome by influencing the factors that affect inflow and outflow. In the remaining parts of this paper, we will use time-series graphs of traffic density as indicator of how the traffic congestion level changes with time.

Complete Model

After understanding how the whole picture works, we introduce our complete model.

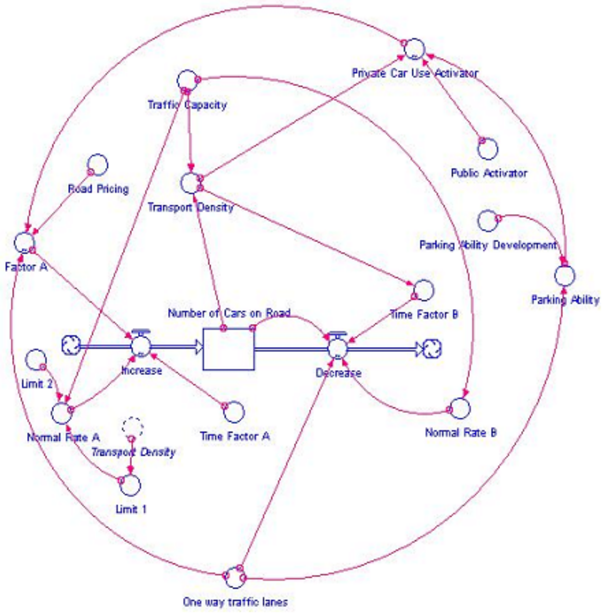

Figure 3

Below is a summary of the relationship between some key factors and parameters:

Number of cars on road	INITIAL VALUE = 4000
An arbitrary value that represents the number of cars on road at any time	
Increase	Graph of Factor_A*Normal_Rate_A*Time_Factor_A
Represents the rate of cars "appearing" on road	
Decrease	Graph of if Number_of_Cars_on_Road>0 then Normal_Rate_B*Time_Factor_B* One_way_traffic_lanes else 0
Represents the rate of cars "disappearing" on road	
Factor A	Graph of One_way_traffic_lanes/Road_Pricing*Private_Car_Use_Activator; its value is calibrated on a 0-1 scale.
Factor A is influenced by the number of one-way lanes, which will increase the rate of cars appearing on road. Private Car Use Activator represents an encouragement for people to use private cars. Road Pricing negatively affects Factor A, because high price means less quantity demanded for road use.	
Limit 1	When Limit 1 is in operation, Limit 1 = if Transport_Density>50 then 0.5 else 1. Otherwise, Limit 1 = 0.5
Represents the transport policy that only allows cars with an even/odd number as the last number of their plates to enter during peak hours; can be switched on or off.	
Limit 2	INITIAL VALUE = 5
Represents the policy that forbids traffic inflow into the downtown area; can be adjusted on the interface	
Normal Rate A	= Traffic_Capacity
Represents the traffic inflow into the city; determined only by traffic capacity and traffic policies; cannot be changed in the short term	
Normal Rate B	= (Traffic_Capacity-Limit_2)*Limit_1*20/9
Represents the traffic outflow out of the downtown area; determined only by traffic capacity; cannot be changed in the short term	
Parking Ability	= Unidirectional_Lanes*Parking_Ability_Development
Parking ability can be increased if some previously double-way lanes are changed into one-way lanes. Parking ability can also be increased by the variable Parking Ability Development.	
Private Car Use Activator	the graph of Transport_Density/Parking_Ability*Public_Activator; its value is calibrated on a scale of 0-1; it has a negative relationship with Transport_Density/Parking_Ability*Public_Activator
When the traffic condition is bad, we assume that people will be less willing to use private cars. An affordable and efficient public transport system can also discourage people from driving. In contrast, when there are many parking lots available in people's destinations, they are assumed to use their cars more.	

Parking Ability Development	INITIAL VALUE = 5
An arbitrary value that represents the development of parking ability in the downtown area	
Public Transport Activator	INITIAL VALUE = 1
Represents the general quality of the public transport system; can be changed in the long run	
Road Pricing	INITIAL VALUE = 1
Represents the level of road pricing in the downtown area; this can take the form of Electric Road Pricing as seen in Singapore; the level of road pricing can be altered as a congestion-alleviating policy	
Time Factor A	= if (sin(time*12.56))>0 then 5*(sin(time*12.56)) else 0 when Limit 1 is not under operation = if (sin(time*12.56))>0 then 2.5*(sin(time*12.56)) else -2.5*(sin(time*12.56)) when Limit 1 is under operation
This function is created to simulate the fact that cars appear on road twice a day during morning and evening peak hours.	
Time Factor B	= if sin(time*12.56-Transport_Density/20)>0 then 5*sin(time*12.56-Transport_Density/20) else 0 when Limit 1 is not under operation = if sin(time*12.56-Transport_Density/10)>0 then 2.5*sin(time*12.56-Transport_Density/10) else -2.5*sin(time*12.56-Transport_Density/10) when Limit 1 is under operation
This function is created to simulate the fact that cars disappear on road twice a day after people get to their destination. We have formulated a phase difference which is determined by Transport Density. The idea is that when the congestion level is high, it takes people a longer time to commute.	
Traffic Capacity	INITIAL VALUE = 50
This has an arbitrary value that represents the general transportation ability. Traffic capacity development can be increased in the long run as a traffic development policy.	
One-way traffic lanes	INITIAL VALUE = 3
This variable also has an arbitrary initial value 3, and can be changed as part of the government's policy to alleviate traffic problems.	

Table 1

Simulation

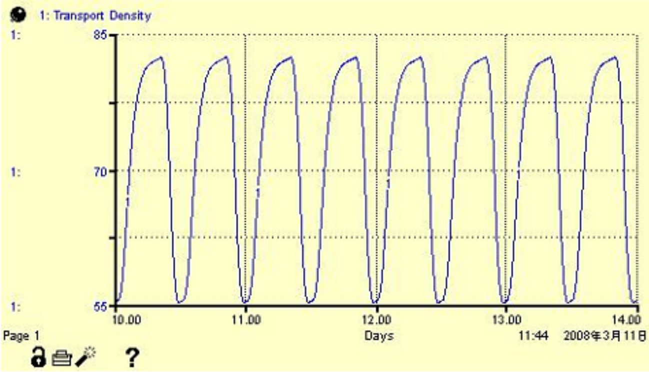

Figure 4

The diagram above shows how transport density varies with time daily. There are two peaks per day, representing two rush hours when cars flow is the greatest. The cars on the roads during these hours accumulate gradually first, and then are dissipated gradually. Inevitably, almost all cities see this kind of traffic density pattern, the only difference being the height of the peaks and the width of the peaks. The former value tells us how dense the traffic is during the busiest time. The latter tells us how long the busy time is. Congestion is a situation when the peak is too high i.e. cars are so densely packed in the roads that they cannot move. The desired situation is one in which the peaks are lower while rush hours can be stretched, namely vehicle flows are more evenly distributed during a day. This diagram can largely represent the real-life situation, and shows that our model is generally an accurate one. This will allow us to use this model to examine different policies and government actions that try to alleviate traffic problems.

Policies and Government Actions Affecting Congestion in the Model and Their Real-Life Interpretations

Factors and Policies Affecting Congestion in the Model	Real-life interpretations
Limit 1	The policy which dictates that when traffic congestion enters a certain level, only cars whose plates end with odd (or even) numbers can enter
Limit 2	The policy that stops or discourages some type of cars from entering the downtown area. For example, in Nanjing where the authors live, heavy lorries cannot enter *Xin Jie Kou*, the center business district of Nanjing. Another example is the practice of building roads that surround the downtown area so cars whose destinations are not this area may be diverged onto other roads.
Road Capacity Development	This may take the form of new road construction and the expansion of existing roads, e.g. more lanes per road.

Parking Ability Development	This may take form of expanding parking lots, developing parking towers and underground parking lots and using the more efficient modern automatic parking systems.
Public Transport Activator	Public Transport Activator is a parameter that indicates the willingness of people to use public transport systems, e.g. subways and buses. Public Transport Activator can be increased by developing the efficiency and affordability of the public transport system.
One-way lanes	One-way lanes can increase the flow rate of transport, but can also increase the parking space available in Nanjing, because the two sides of one-way lanes can serve as parking spaces.
Distributing working hours over a time slot	The policy which encourages different schools and firms to spread their working hours. For example, it has been suggested that if schools both start and end 2 hours later than businesses in Nanjing, traffic congestion levels during peak hours can be alleviated. A similar policy is to encourage some firms to start their working day at 8AM and others to start at 10AM.

Table 2

Testing Alternative Factors and Policies

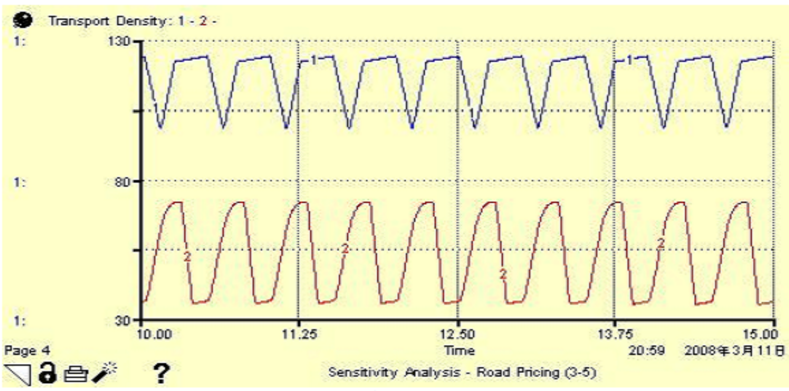

Figure 5

1. Road Pricing. Curve 1: Road Pricing = 3. Curve 2: Road Pricing = 5.

If drivers are charged for using roads, fewer drivers will use the roads. This mostly influences the inflow rate. Decreasing number of cars now flow into the roads; as a result, the peak value for transport density decreases. The simulated outcome is consistent with the expected one.

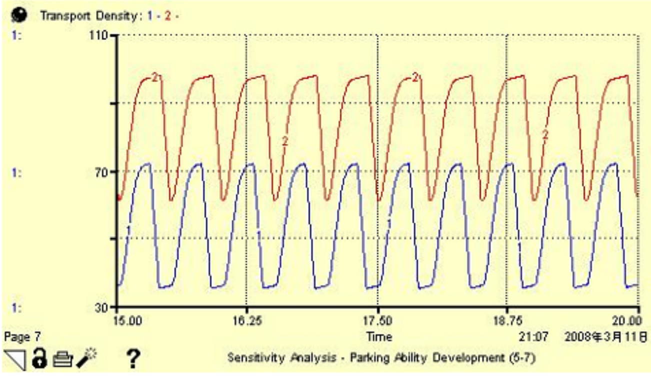

Figure 6

2. Parking Ability. Curve 1: Parking Ability Development = 5. Curve 2: Parking Ability Development = 7. Quite surprisingly, parking lots that are built to reduce the number of cars on road, in fact increases transport density. This is because with more parking spaces, more cars are willing to flow into the system, thinking that it is easy to park their cars. Inflow rate rises, leading to rise in transport density. Density in the feedback loop will control the number of private cars on road, but there is a delay before this control comes into effect. Therefore following an increase in parking space, congestion problem will worsen.

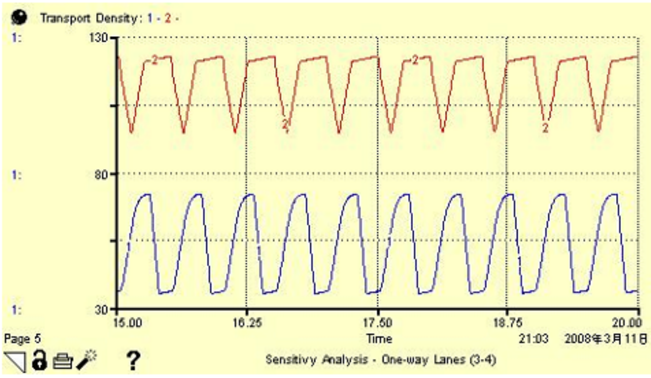

Figure 7

3. One-way lane. Curve 1: One-way Lanes = 3. Curve 2: One-way Lanes = 5

One-way lane is supposed to increase the number of lanes in one direction, causing cars to flow faster. It was believed that it can reduce congestion. However, the simulation shows just the opposite result. One-way lane causes the more cars to flow in. Several reasons account for this: first, not only the outflow increases, but the inflow also increases, which means it is as easy for cars to get out as they get in; second, one-way lane can make more parking space alongside the streets. These parking spaces as discussed in the previous paragraph lead to more cars coming in. The net result is that transport density rises.

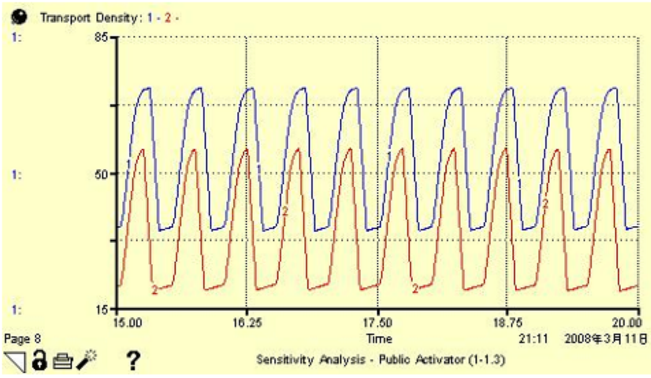

Figure 8

4. Public Transport Use Activator. Curve 1: Public Activator = 1. Curve 2: Public Activator = 1.3.
The increased value of Public Activator indicates the development of the public transport system. As a result, we have seen that the peak value of congestion in a given day drops, so does the general level of traffic congestion. This is because people are less willing to use their private cars, hence reducing the inflow of cars and traffic density in the downtown area under investigation.

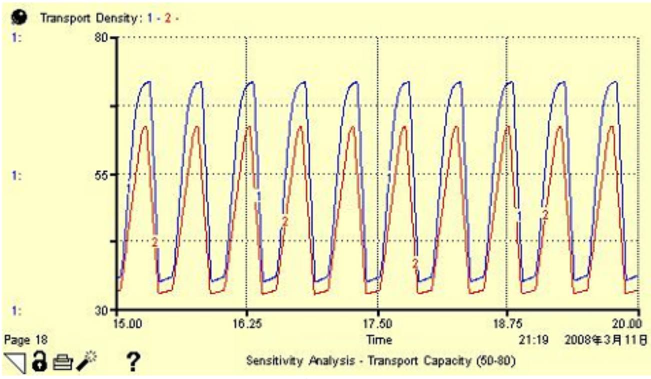

Figure 9

5. Transport Capacity Development. Curve 1: Transport Capacity Development = 50. Curve 2: Transport Capacity Development = 80.
It was usually expected that the government should expand roads to alleviate traffic congestion problems. However, our model shows that this policy can only generate a result that hardly matches the finance and manpower needed to undertake major road construction projects. Using the system thinking, we can infer that once the congestion level decreases because of new road construction, more people will be using private cars. Therefore, a policy designed to decrease traffic density will make it increase again after a short-term drop. This is the result of a negative feedback loop in the system dynamics model.

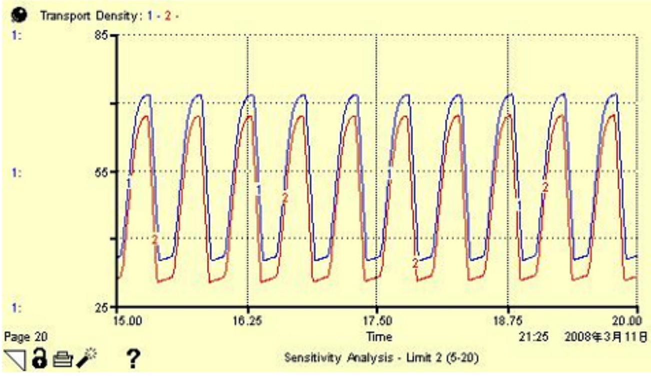

Figure 10

6. Limit 2. Curve 1: Limit 2 = 5. Curve 2: Limit 2 = 20.

It can be seen from the model that discouraging or preventing some cars from entering the downtown area can reduce the transport congestion level by a relatively small proportion. However, the effect is not so significant. This is because the decreased traffic density resulted from blocking some type of vehicles from entering the area serves as an incentive for people to use qualified private cars more frequently, leading the congestion level back to a little below the initial value again. This reflects the behavior of a goal-seeking feedback loop.

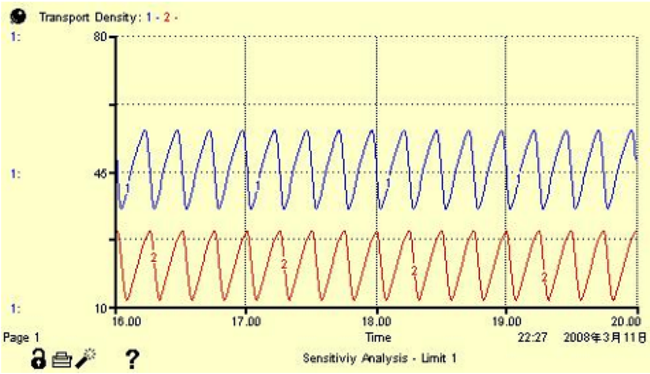

Figure 11

7. Limit 1. Curve 1 = Limit 1 Operating. Curve 2: Limit 2 Not Operating
If during peak hours, only cars whose plates end with odd (or even) numbers are allowed to enter the central business district, congestion levels are significantly decreased. This is because inflow of cars into the area we are looking has decreased. Effective as this policy may be, it is indeed a very blunt one, and should only be used during major occasions, such as holiday times.

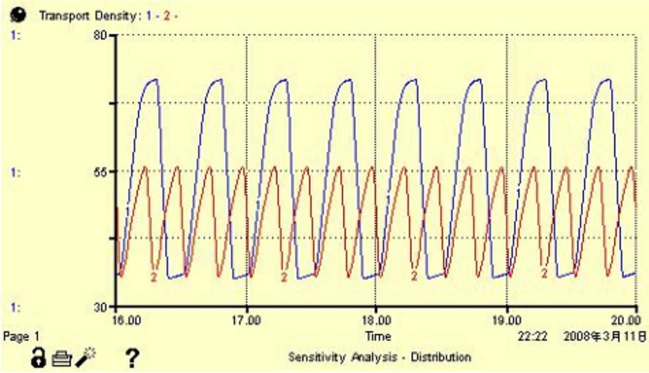

Figure 12

8. Re-distribution. Curve 1: Distribution Policy Not Operating. Curve 2: Distribution Policy Not Operating By varying parameters Time Factor A and Factor B, we can simulate the policy that spreads the start time of businesses over a time slot. If this policy is operating, cars "appear" and "disappear" on roads four instead of two times a day. This is the most effective policy in terms of reducing congestion levels. Cars are more evenly distributed in the time slots. Total number of cars flowing in the system remains unchanged while the peak value of density has decreased quite dramatically. The total area under Curve 1 and Curve 2 remain approximately the same, which can reflect the idea of this policy. However, the problem with this policy is that it might be difficult to carry out, because affected people have to change their life habits to adapt to it.

Evaluation

1. We did not take the disruption that is bound to happen during the process of road construction and parking space development into account. The confusion and even citizens' discontent with policies such as Limit 1 and Limit 2 were also ignored. Indeed, traffic congestion does tend to worsen for the first few days every time a new policy is put in effect.

2. In our model, the initial value of THE NUMBER OF CARS and TRAFFIC CAPACITY are at large arbitrary values. Therefore, they cannot necessarily represent real-life situations. For example, in real life, we would expect the traffic density during peak hours to be about 10 times of that during trough hours. In this model, however, the maximum level of traffic density is no more than two times of the minimum. Similarly, the simplifying assumption that the traffic volume – time graph is variations of a sinusoidal wave may be far from reality.

3. In order to reflect different effects that different factors have on INCREASE and DECREASE, we had to bundle different factors that affect INCREASE and DECREASE values by calculating the factors' products. Then we arbitrarily calibrated the values of INCREASE and DECREASE against the products on a 0-1 scale. Beneath this simplification is the assumption that INCREASE and DECREASE are affected by the products of the influencing factors. In reality, however, INCREASE and DECREASE might be affected by both the sums and the products of the related factors. We also used this approach in the valuation of other factors. One problem with this approach is that we cannot the guarantee the unit consistency throughout the model. However, investigating how exactly these factors influence the values of INCREASE and DECREASE is beyond the scope of this paper.

4. We have only considered the traffic congestion level of a certain area. However, in reality, the traffic conditions outside this area should not be ignored. For example, by diverging some cars from entering the downtown area, the roads that surround this area might become more congested.

However, despite the limitations of this model, we can at least see how different traffic policies and regulations can influence the general trend of traffic density.

Conclusion

Congestion is an issue that has been discussed quite frequently. There were papers that looked into this topic previously, but few of them actually used model and data to simulate real-life situations. Model construction and simulation distinguish this paper from many others. It goes beyond qualitative discussions to quantitative analysis, and tries to understand the interactions between different variables by considering both positive and negative feedback loops. While data used in this model may be inaccurate, the idea has been applied properly and the simulation can well reflect real-world situations. Using the model we build, we have also understood different effects of transport policies better, in addition to evaluating their effects.

This research experience has enabled us to understand traffic congestion in a systematic and dynamic way. The model we built successfully simulated traffic conditions in the real world and it further helped us investigate the various factors and policies that could influence congestion. Most importantly, through this experience, we began to develop dynamics ways of thinking. Our cognition of the world has not been challenged since we started to think; system dynamics is challenging it now. Though as high school students, we have not fully mastered system dynamics, we are on the right track to modify the way we used to look at things.