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Time Dimensional Transportation Management to Decrease the Transformation Cost of Growing Cities

- An example of safety for the moped in a campus under construction works -

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Infrastructure construction is an indispensable work in any growing cities, but disturbances of the additional traffic by construction activities have not been well considered yet in urban planning. In this paper we propose a time dimensional transportation management for mopeds and construction vehicles during the construction of a subway railway in a university campus. Our model will determine the operation schedule of construction vehicles as well as bus transit, providing safe and convenient transportation to the student commuters, through the minimization of the total social cost generated by the bus operation cost, the construction vehicle operation cost, and the accident risk cost, as well as users' disutility. The solution of the model shows that the earlier operation of construction vehicles and more strategic concentrated bus operation give safer and more efficient transportation in the campus.

Key words: *traffic safety, mopeds, university campus, construction works, TDM*

1. INTRODUCTION

Infrastructure is indispensable to achieve growth in any cities. Especially, the increased quantity of passengers within an urban area requires modern transport technologies and infrastructure, such as subway: a rapid underground transit system with high capacity, high frequency service and spatially separated from other kinds of traffic. Tunnel construction works include “cut and cover” and “tunnel boring”. In the construction process, delivering material, as well as soil removal will employ a constant use of heavy construction vehicles. Their operations must be subject to strict time window restrictions, in order to avoid the congestion problem and negative environmental impacts such as air pollution and noise (Taniguchi et al., 1998)[10]. Increase of the traffic accident risk, due to the mixture of large construction vehicles and small and light vehicles such as mopeds, also becomes an important problem from a public health point of view (Mock et. al, 2005)[6].

However, a simple time shifting of construction vehicle operation after the commuting congestion hours does not become optimal, because counter concentration of construction vehicle operation requires an additional operation cost. Instead, we must carefully design the time dimensional arrangements, including the cooperative management of other kinds of traffic. In this paper, we propose a model to determine the construction vehicle and bus operation that minimizes the considered social cost including the traffic accident risk between heavy vehicles (construction vehicles and buses) and mopeds. It also includes the disutility of the students commuting to the campus either by bus or a moped. This model becomes a good example of trials to decrease the transformation cost of growing cities.

2. PROBLEM SETTING

About 9,700 students are commuting to Aobayama Campus of Tohoku University, which is located on a hill, west from Downtown Sendai. More than three fourths of them reside in the downtown and further area and commute through the only direct road access to the campus from the downtown, which have steep curve and slope, as **Figure 1**. The university is suffering from the growing number of the mopeds accidents there, especially the serious accidents with heavy vehicles at the road section in frozen environment in winter. We set an automatic ultrasonic traffic counter instrument at one cross section in the slope on December 2006. In an ordinal weekday morning, around 540 mopeds, 800 passenger cars, and 20 heavy vehicles pass through there. Currently, in Sendai, they are constructing the second subway line that crosses the city from east to west. The construction of the Tozai Line began in 2004, planning to end in 2015. One of the stations will be located in Aobayama Campus. In the construction process involving tunneling, there is an increment of heavy construction vehicles, then the probability of collisions with a light vehicle may increase and also the probability of fatality (Hanowski et al., 2007)[2].

Short-term countermeasure reducing the accident risk may fit this problem, since the change in the traffic composition will not be permanent. The solution can be obtained if we can reduce the time-dimensional interactions between the mopeds and the heavy vehicles (composed by buses and construction vehicles).

Construction vehicles can be restricted to several hours' operation, which would generate an additional operation cost. In the same way, the bus transit vehicles can change their schedule time in order to provide a better commuting service, with additional operation cost. Meanwhile, a modal shift from a moped to the bus transit will provide more safety to the commuter students, but their modal change cannot be mandatory accomplished. In order to design a policy affecting the students' decision, their choice behavior must be known.

Figure 2 illustrates the structure of the model we propose in this paper. The number of encounters of heavy vehicles and mopeds will decrease by changing the schedule of buses and construction vehicles, so will the accident risk. However, it will generate the additional operation cost. Relating to the disutility level of the commuters using bus or a moped, the arrival time choice of the bus users depends on the bus congestion; that of the moped users on the road flow congestion and on the parking lot congestion. Because the modal choice of student commuters must be also in equilibrium, we can describe the framework of the proposed model as a MPEC; Mathematical Programming with Equilibrium Constraints.

3. EQUILIBRIUM CONSTRAINTS

3.1 Bus users' arrival time choice

We focus on the time dimensional choice of student commuters targeting the k-th class, which begins

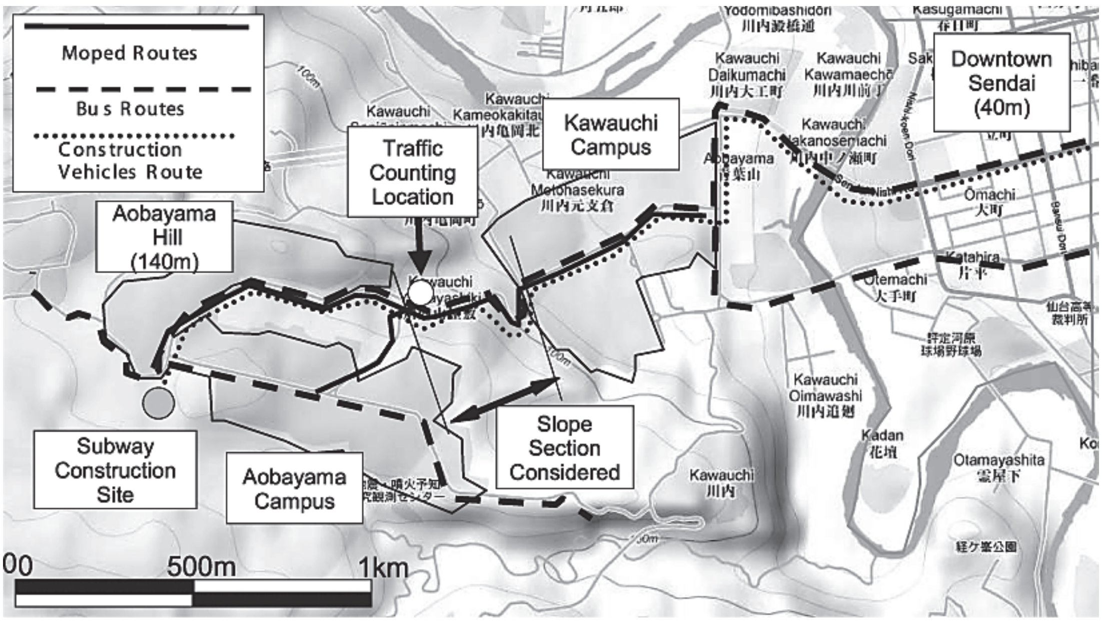

Figure 1 Aobayama Campus of Tohoku University and traffic routes in Sendai City

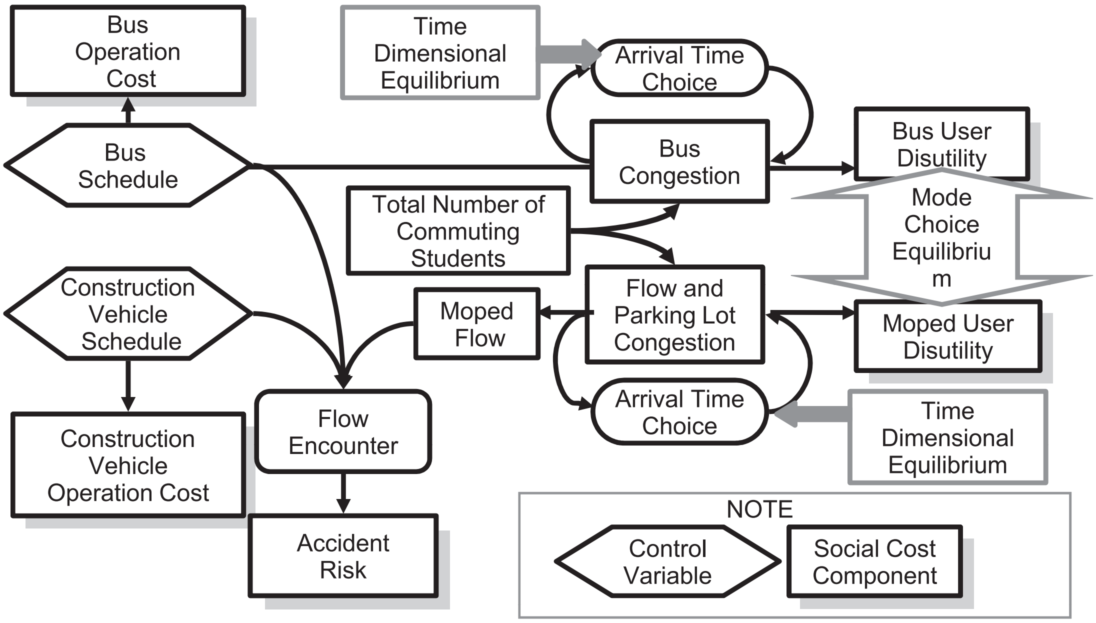

Figure 2 Scheme of the Model Structure

at time T_k at the university campus. They learn the disutility for each arrival time in terms of delay or early arrival through daily trials, and switch their departure time accordingly (Mahmassani and Cheng, 1986)[5]. They also identify the congestion inside the vehicle and time delay from the road flow congestion (Leurent and Liu, 2008)[4]. Using these concepts, their utility to use a bus arriving at the target bus stop in the campus at time t is defined as follows:

$$U(t) = -s(t)^{\eta} - d(T_k - t) + U_0, \tag{1}$$

where, $U(t)$ is utility level of a student using a bus arriving at t ; $s(t)$ is a congestion level of the bus; d is the value of waiting time before beginning the class; U_0 is the factors irrespective to time, including bus fare, for example. Equilibrium condition for the arrival time choice is given as:

$$\begin{aligned} &U(t) = \overline{U} + U_0 && \text{if } s(t) > 0, \\ &U(t) = -d(T_k - t) + U_0 < \overline{U} + U_0 && \text{if } s(t) = 0, \end{aligned} \tag{2}$$

where, $\overline{U}$ is the utility at equilibrium; η is a parameter. This condition says that the student commuter cannot improve his utility, even if he selects another bus schedule. We can obtain the bus congestion at equilibrium as follows:

$$s(t) = [\overline{s}^{\eta} - d(T_k - t)]^{\frac{1}{\eta}}, \tag{3}$$

where, $\overline{s}$ is a bus congestion level at the most preferred arrival time ($t = T_k$). The utility at equilibrium satisfies the following condition:

$$\overline{U} = -\overline{s}^{\eta}. \tag{4}$$

Once the time dimensional bus operation density is given as $B(t)$, the number of bus users is determined by the multiplication of operation density and the congestion level, as follows:

$$\dot{N}(t) = B(t)\, s(t). \tag{5}$$

The cumulative number of bus users up to time t is given in a discrete formulation as follows:

$$N(t) = \sum_0^t \dot{N}(t) = \sum_0^t B(t)\, s(t). \tag{6}$$

3.2 Moped user's departure time choice

Moped users also choose their arrival time, considering the parking congestion and the schedule cost, as modeled by Arnott et al. (1990)[1] and Yoshimura and Okumura (2001)[11]. In order to describe a delay explicitly by the flow congestion, we use a departure time by shifting the usual travel time for the road section considered. Let $x(t)$ be a moped flow departing at time t and $x(t)$ be cumulative mopeds already arrived at the parking lot in the campus prior to the moped departed at t. We can neglect the difference of commuting duration due to the residential location, because it is compensated in the long run by the room rent. The utility level of the student who departed at time t by a moped is defined as:

$$V(t) = -et - c[T_k - (t + \kappa_e \dot{x}(t))] - \lambda_e x(t), \quad (7)$$

where, $V(t)$ is a utility level; e is a unit schedule cost for early departure; c is a unit cost for waiting time before the class; κ_e and λ_e are parameters. The terms that compose equation (7), relate to the cost of leaving home early, the cost of waiting on campus and the discomfort of parking far from the classroom. Because the commuters other than the students use the road much earlier, the delay in the arrival time is related to the encountered moped flow of other students trying to attend the same k-th class.

The equilibrium condition says that no student can increase his utility by changing the departure time. In this sense, the utility at equilibrium is irrelevant to the departure time t , therefore:

$$\begin{aligned} V(t) &= \overline{V}, \quad \dot{x}(t) > 0, \\ V(t) &< \overline{V}, \quad \dot{x}(t) = 0. \end{aligned} \quad (8)$$

In other words, this formulation explains that the student commuters using a moped pay certain cost by leaving home early and must wait before their class starts, but are compensated with less congestion encountered and a more comfortable parking, compared with the commuters who try to arrive close to T_k for the same k-th class.

The differential equation concerning $x(t)$ derived from the equilibrium condition (8) can be solved as follows (with IC_{VE} as the integration constant):

$$x(t) = IC_{VE} e^{\frac{\lambda_e}{\kappa_e c} t} + \left[(T_k - \frac{V}{c}) \frac{c}{\lambda_e} + \frac{(1 - \frac{e}{c})}{\kappa_e} \frac{(\frac{\lambda_e}{\kappa_e c} t - 1)}{(\frac{\lambda_e}{\kappa_e c})^2} \right]. \quad (9)$$

Then the following derivative describing the flow of mopeds becomes:

$$\dot{x}(t) = \frac{dx}{dt} = IC_{VE} e^{\frac{\lambda_e}{\kappa_e c} t} (\frac{\lambda_e}{\kappa_e c}) + \frac{(1 - \frac{e}{c})}{\frac{\lambda_e}{c}}. \quad (10)$$

The time t^* is defined as the departure time of the student who just arrives at the classroom at time T_k, in other words:

$$T_k = t^* + \kappa_e \dot{x}(t^*). \quad (11)$$

When equation (11) is substituted for equation (7) then at time t^*, the equilibrium utility is defined as:

$$V(t^*) = -\dot{e}t^* - \lambda_e x(t^*) = \overline{V}. \quad (12)$$

3.3 Equilibrium condition of modal choice

We assume that students can choose the mode of commuting based on the utility comparison. At the equilibrium, the following condition is satisfied:

$$\overline{V} = \overline{U} + U_0. \quad (13)$$

In the following model, however, we don't assume that this inter-modal equilibrium condition will be automatically satisfied. Instead, we keep the utility level of bus users as constant, and calculate the difference of utility level to be adjusted in order to realize the derived solution. Since the two models are applied to the same student commuters, corresponding parameter values must be equivalent; for example, concerning to the schedule cost parameters, we can say that $d = c + e$. As stated later, the value of parameters d and e/c are obtained through regression analysis. Therefore, the value of parameter c can be calculated as follows:

$$c = \frac{d}{1 + e/c}. \quad (14)$$

4. SOCIAL COST COMPONENTS

The objective of our problem is to minimize the total social cost generated by the bus operation cost, construction vehicle operation cost, accident risk cost, as well as users' disutility.

4.1 Bus operation cost

The bus operation cost is defined as an increased function of the bus operation density as:

$$BOC = \sum_{0}^{T_k} B(t)^{\zeta}, \quad (15)$$

where, BOC is the bus operation cost during the commuting hours; ζ is a parameter. This formula assumes that a concentrated operation of bus in short minutes requires much of hiring cost for bus vehicles and drivers.

4.2 Construction vehicle operation cost

Let $H(t)$ indicate the temporal density of operation of the heavy construction vehicles, in the discrete notation into 5-minutes interval. The heavy construction vehicle operation cost is calculated in a similar way to the bus operation cost:

$$HOC = \sum_{0}^{T_k} H(t)^{\alpha}, \tag{16}$$

where, HOC is the heavy construction vehicle operation cost during the commuting hours; α is a parameter.

4.3 Accident risk cost

We focus the accident risk between the mopeds and the heavy vehicles, especially due to the moped's trail to overtake a heavy vehicle. Such trials frequently lead the motorcyclist into an exposure to the heavy vehicle not only in changing lanes but also in the short gap ahead the heavy vehicle (Harrop and Willson, 1982)[3] (Natalier, 2001)[7], and result in a serious accident. Needless to say, the accident risk is dependent on the road configurations as well as traffic safety educations, but the road improvement works need much of money and time, while the effects of education cannot appear in short term. In this study, we focus the number of possible coalitions are assumed to be proportional to the total number of the encounters between a heavy vehicle and a moped. Heavy vehicle traffic of 5-minutes interval is sum of the bus traffic and the construction vehicle traffic.

$$ARC = \sum_{0}^{T_k} \left[B(t) + H(t) \right] \times \dot{x}(t) , \tag{17}$$

where, ARC is accident risk cost.

4.4 Total social cost

As a total social cost, we include the decrease of utility for both the bus commuters (total number is N) and the moped commuters (total number is M-N, being M the total number of students that must attend a given class). Since there is difference in the units for each cost component, then additional constants β_i are included to allow the sum of different components.

The following equation states the total social cost:

$$TSC = \beta_1 BOC + \beta_2 HOC + \beta_3 ARC - \beta_4 \{\overline{U}N + \overline{V}(M-N)\}, \tag{18}$$

where, TSC is total social cost, used as a objective function in the planning model.

5. PROBLEM FORMULATION AND AN APPLICATION

5.1 MPEC formulation

Let the objective function be the total social cost TSC. The control variables are the bus operation and the construction vehicle operation, that is, $B(t)$ and $H(t)$. We focus on the analysis during the commuting hours before the beginning time of the first class at the university. We use a time t defined from 7:00 in the morning, and T_k=110 (minutes), indicating 8:50 A.M. All variables are discrete in 5 minutes interval. We consider the equilibrium conditions of equations (3),(4),(9),(10) and (12). All the M students must arrive at the campus before T_k; designated number of construction vehicles TH must reach the construction site; and the number of the bus fleets is also limited as TB. Then the MPEC formulation is:

$$\min_{B(t),H(t)} \beta_1 \sum_{0}^{T_k} B(t)^{\eta} + \beta_2 \sum_{0}^{T_k} H(t)^{\alpha} + \beta_3 \sum_{0}^{T_k} [B(t)+H(t)]\dot{x}(t) - \beta_4 [\overline{U}N + \overline{V}(M-N)], \tag{19}$$

subject to the equilibrium conditions, equation (3),(4),(9),(10),(12), and constraints about the total number of the student commuters, of the bus operations and of the construction vehicle operations.

$$N(T_k) + x(t^*) = M, \tag{20}$$

$$\sum_{0}^{T_k} B(t) \le TB, \sum_{0}^{T_k} H(t) \le TH. \tag{21}$$

We keep the utility level of bus users as constant. Further in the actual calculation, we use $x(T_k)$ instead of $x(t^*)$ in equation (20).

5.2 Parameters and quantitative conditions in Aobayama campus

Figure 3 shows the observed number of buses and the counted number of mopeds at the counting cross sections, in 5 minutes interval from t=0 (7:00A.M.) and t=T_k=110 (8:50 A.M.).

Regarding the parameters concerning with the bus transit, a regression analysis was done based on the data from the passengers counters in the bus vehicles through the slope sections (Nava et al., 2009)[8]. The results are $\eta = 1.47$, $d = 1.75$ and $\overline{U} = s^{-\eta} = -454.45$ from the data on Monday April 12th 2006.

On the other hand, parameters concerning with the moped flow are obtained through a regression analysis for the traffic count data on December 2006 (Nava

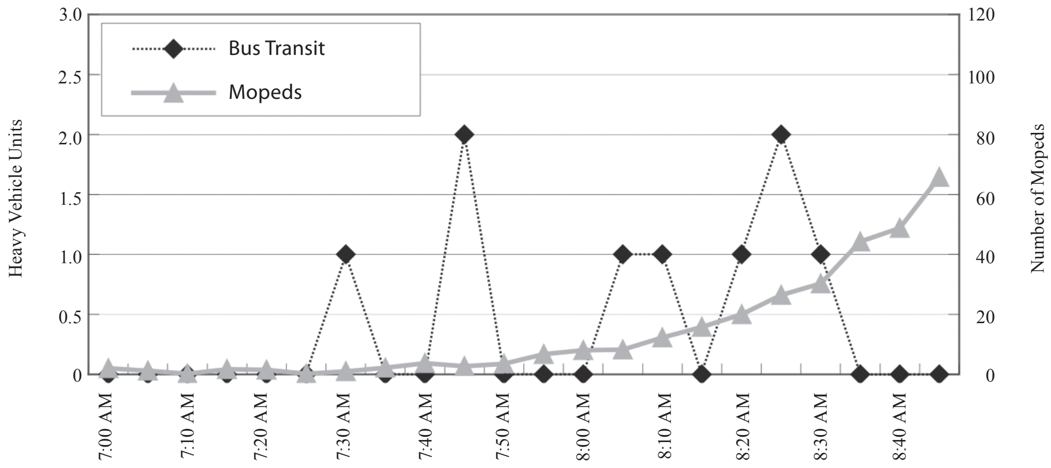

Figure 3 Observed Traffic Data

and Okumura, 2009)9). The values of the parameters are κ=1.016, λ/c=0.125, IC_{VE}=3.996×10^{-4} and e/c=−0.589, obtained from the traffic count data of mopeds on weekdays in December. From equation (12) and (14), c=4.08, $\overline{V}/c$=−117.26 and $\overline{V}$=−489.14 were obtained. Through equation (4) and (13), we found that $\overline{U}$=−454.45 and U_0=−34.68.

Other parameters concerning with the operation cost are open to a future empirical estimation. In the following application, we set ς=1.68 and α=2.5. The values of β_i are: β_1=15, β_2=10, β_3=1 and β_4=0.01. The values of the constants β_i say that the increase of the construction vehicle operation is easier than that of the bus operation, in terms of the easiness of subcontract for the additional transportation service.

At last, quantitative constraints are set reflecting the present situation. At present, the number of students commuting by bus and a moped are 542 and 306, respectively. Therefore, we set M=850 in our calculation. Similarly, the total numbers of buses and construction vehicles operated are set as TB=9, TH=8, respectively.

5.3 Optimized solution

The Solver in Microsoft Excel is used to obtain the solution of the total cost minimization problem. Several initial values are prepared and we exclude local optimal solutions. **Figure 4** shows the obtained operation pattern of buses and construction vehicles, as well as mopeds. The values of the social cost components at the optimal solution are shown in **Table 1**, comparing with those calculated from the traffic

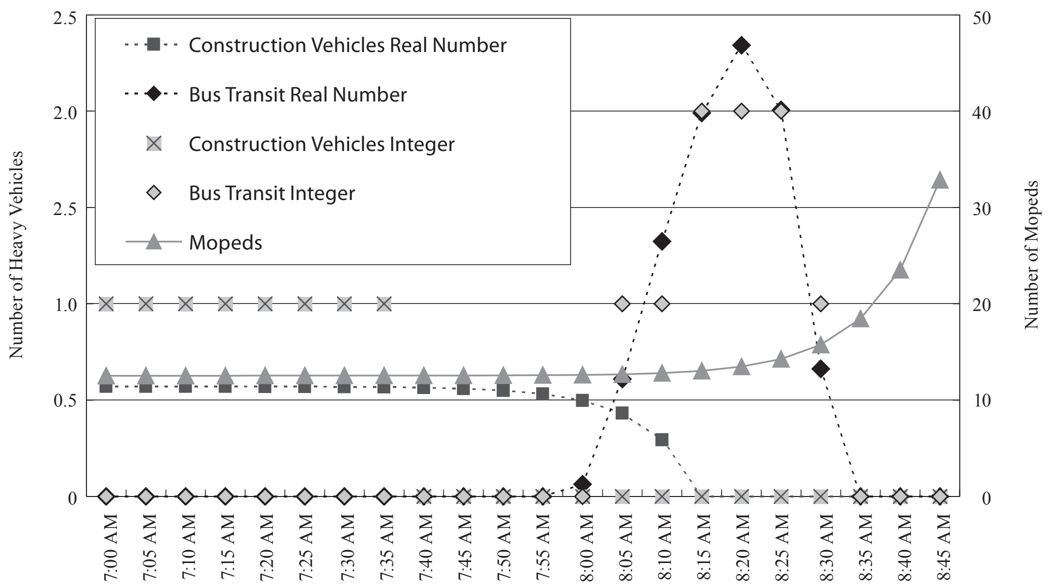

Figure 4 Vehicle Flow by Type After Minimization

Table 1 Observed and Minimized Costs

Cost component	Observed	Minimized (real)	Minimized (Integer)
Accident risk cost ARC	257.5	237.4	223.2
Bus operation cost BOC	171.2	117.4	189.4
Const. veh. op. cost HOC	80	26.4	80
Bus user's utility U	2465	2408	2410
Moped user's utility V	1743	1530	1530
Total social cost TSC	4717	4320	4433

flows observed at the present.

Figure 4 shows that the optimal operation of the heavy construction vehicles must start earlier in the morning and diminish before the moped flow increases. Bus operation must be concentrated on the middle of the proposed timeline, in order to capture many users. This solution is obtained not as integer but as real number. Therefore a direct implementation to determine the realistic operation plan of buses and construction vehicles cannot be done, but still, we can learn the direction of the improvement from the solution. According to the values in **Table 1**, these operation strategies are accomplished by the smaller operation cost than the present situation. The reason of this cost reduction is however, partly owing to lack of integer constraint of solutions, then, the reduction becomes smaller under in an feasible integer solution near to the real number solution, as also shown in **Table 1**.

From the observed data and the result of the minimization problem, the arrival rate of the students can be plotted in **Figure 5**. Based on **Figure 5**, during the first 40 minutes of the timeline (from 7:00 to 7:40 A.M.), the observed number of arrivals is lower than the optimal rate of arrivals. This implies that students are not willing to arrive at early hours, the same happens between 7:55 and 8:25 A.M. The rest of the observed arrivals are close to the optimized solution.

From the result, the operation policies of heavy vehicles can be proposed as follows. Allowing the construction vehicles to be operated at an early hour diminishes the accident risk, because the concentration of mopeds occurs near the beginning of the class at 8:50 A.M. Also, a better timetable for bus transit system can be proposed between 7:45 and 8:25 A.M., to fit the students' behavior better. In this solution, the utility level of bus users ($\overline{U}+U_0 = -454.45 - 34.18 = -489.13$) is lower than that of moped users ($\overline{V} = -477.99$). It implies a need of an additional policy intervention stimulating the modal shift from mopeds to bus transit, such as, bus fare reduction, reduced parking lot spaces for mopeds, a new parking fee for mopeds, and so on.

The derived solution pattern seems very stable under the change of total number of student commuters, then, applicable to all weekdays having different traffic demand volumes. Current operation schedule of the construction vehicles are already set in time windows between 7:00 and 8:00 A.M. and after 9:00 A.M. We can expect the feasibility of the proposed early operations. On the other hand, the availability of the proposed bus schedule is problematic and must be further investigated, considering the coordination with the schedule of other bus routes.

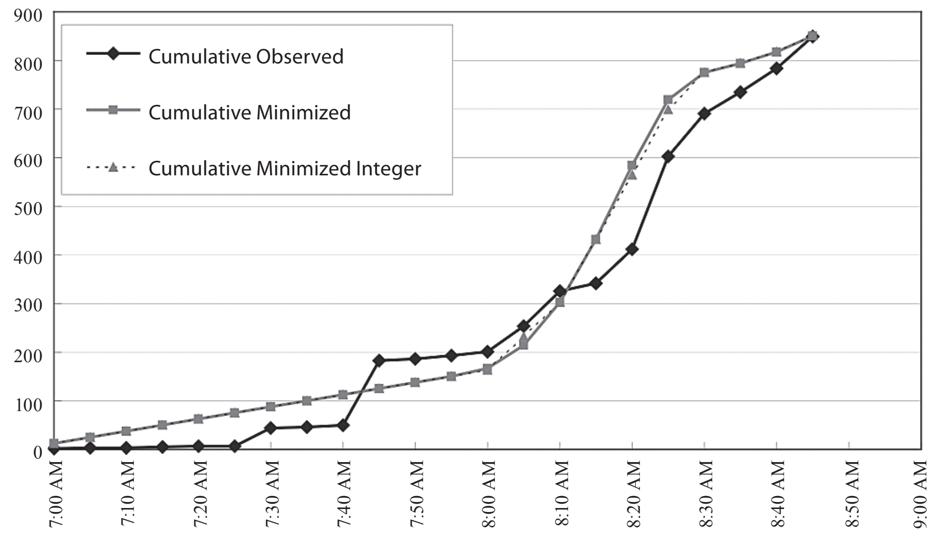

Figure 5 Cumulative Arrival of Students (Observed vs Minimized)

6. CONCLUSION

Although landscape with construction works is not exceptional but very normal in a transforming city, troubles from the additional traffic by construction vehicles have not been well considered yet in urban planning. Especially related to the university campus where most of the student commuters rely on a moped, heavy construction vehicles may increase the accident risk, including the probability of a fatality. In order to decrease the traffic accident risk, time dimensional transportation management should be installed.

In this paper, we proposed a planning model of bus and construction vehicle operations securing safe and convenient traffic environment for mopeds, during the construction of a subway railway in a university campus. Our model includes equilibrium conditions for arrival time choice of mopeds and bus users. In the concurrent empirical analyses on bus use and mopeds flowing to Aobayama Campus, several parameter values in the proposed model were determined. In our formulation, we consider not only the disutility regarding a new kind of operation for construction vehicles and the accident risk, but also the disutility of the student commuters. The solution of the model shows that the earlier operation of construction vehicles and the more strategic concentrated bus operation give safer and more efficient traffic situation in the campus.

In a general sense, this analysis had shown the importance and viability of a short-term management for a safer traffic in the urban construction process. The proposed model provides a good starting block for an effective time dimensional transportation management.

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