DEVELOPMENT OF SIMULATION MODEL FOR HIGH OCCUPANCY VEHICLE (HOV) LANE OPERATION ON EXPRESS HIGHWAYS IN KOREA

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abstract: The goal of this study is to develop a model which will simulate and estimate the effectiveness of High Occupancy Vehicle (HOV) lane(s) operation on express highways in Korea. This model utilizes a logit function formed mainly by travel cost and travel time parameters to determine who chooses an HOV lane or a Low Occupancy Vehicle (LOV) lane. This model is then applied to the Seoul-Pusan express highway. At the conclusion of this study, the enforcement of HOV lane operation on express highways is highly recommended. Furthermore, its expected benefits are found to be indebted to not only HOV users but also LOV users.

1. INTRODUCTION

The express highway in Korea, between Seoul and Pusan, provided better living conditions and standards in many aspects, soon after its completion in 1970. However, tremendous increases of traffic flow and car ownerships have caused traffic congestion and air pollution. These problems have taken place not only in urban areas, but also in regional areas.

Despite the expected future demand, limited land use and enormous construction costs for infrastructure are the major factors that frustrate the future development of traffic investment planning. This is why Transportation System Management (TSM) should be developed and utilized in order to use existing infrastructure more effectively in Korea.

This study is focused on the maximization of High Occupancy Vehicle (HOV) operation which is one of the TSM techniques. The main task performed in this paper is to determine the optimal number of lane(s) for HOV operation. A model which performs the above-mentioned task was developed and applied to the Seoul-Pusan express highway corridor in Korea.

2. DEVELOPMENT OF SIMULATION MODEL

2.1 Approaches and Assumptions

In order to develop a model for simulating HOV lane operation on express highways with toll systems, toll booth operation should be considered. Consequently, two different conditions can be identified.

- Traffic demand not exceeding the capacity of toll booth
- Traffic demand exceeding the capacity of toll booth

In reality, most of the .cases fall under the first category, and it implies that the traffic densities before and after the toll booth are the same. In other words, toll booth capacity satisfies the travel demands, and a queue does not formulate before or after the toll booth, only near the toll entrance.

The second case is not practical in a sense. In addition, as the purpose of the simulation model development is purely focused on the HOV lane operation on a segment of express highway, the former case based on operating HOV lane from the toll booth exit was only the one considered in this study.

The assumptions made in this study are as follows:

- The pattern of freeway traffic flow follows Greenshield's linear macroscopic model
- Choice between HOV and LOV follows logit function
- Average daily traffic does not exceed the capacity of the express highway
- The traffic modes on the express highway are restricted to buses, trucks, and passenger cars
- HOV lanes are restricted to buses and trucks
- LOV lanes are restricted to passenger cars

2.2 Model Development

As mentioned in the previous section, HOV lanes start from the toll booth (toll exit). In the simulation, estimation of passenger travel demand was conducted as the first step. Passenger travel demand was categorized into four different cases, i.e., national holidays, special events, peak periods, off-peak periods. For the second step, travel times of HOV and LOV users were calculated by iterations at the equilibrium state. Then, Measures of Effectiveness (MOE), such as the number of HOV lane(s), demand, travel times of HOV and LOV lane users, were obtained.

Flowchart for simulation model is shown in Figure 1. More detailed descriptions regarding the model development are as follows :

1) Pattern of Passenger Demand

First, all traffic demand patterns are categorized into four different cases.

- Case 1: the biggest national holidays, such as Korean New Year's Day and Korean Thanksgiving Day when maximum passenger travel is predicted
- Case 2: weekend and special events when more travel is predicted than peak periods
- Case 3: average peak periods
- Case 4: average off-peak periods

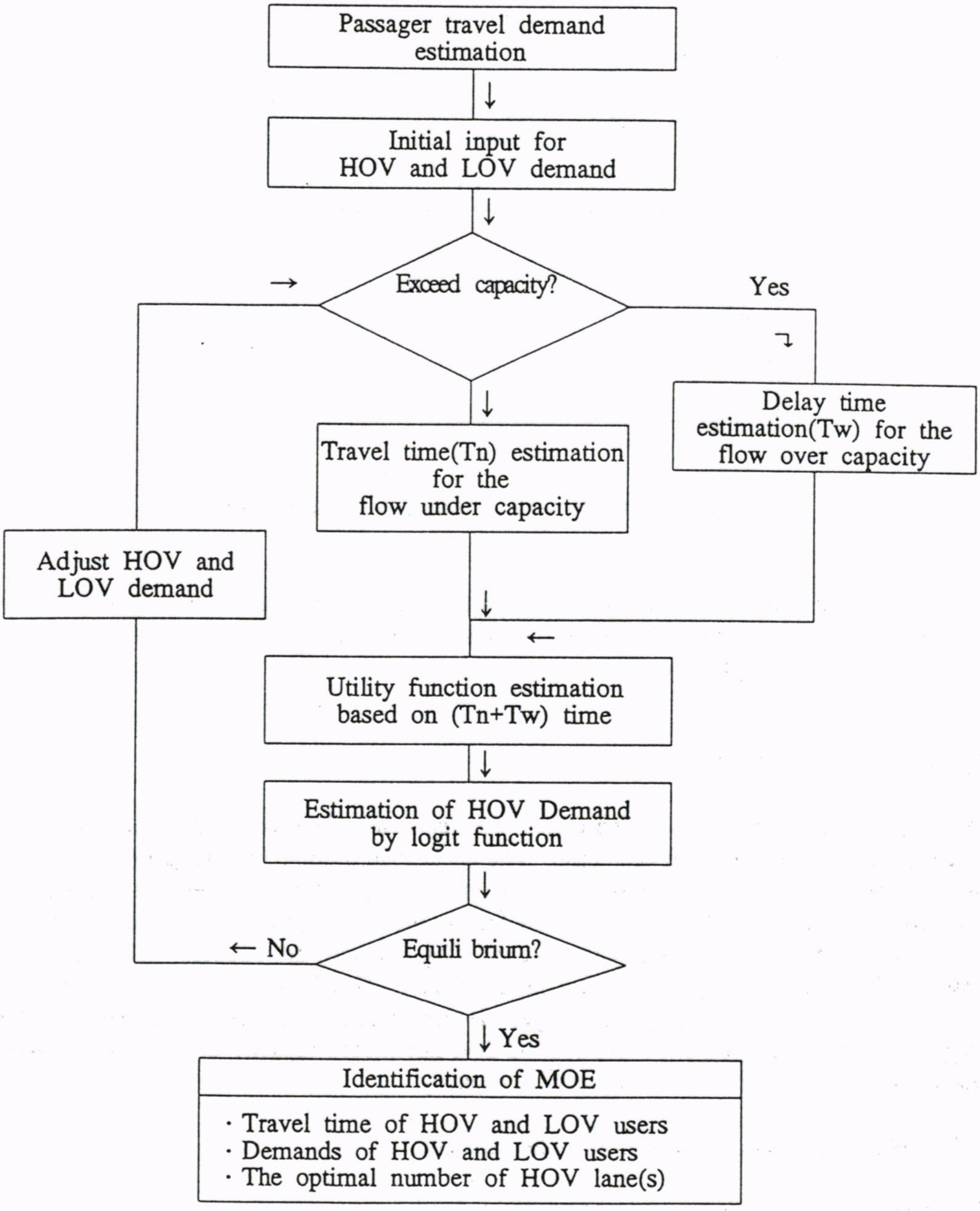

Figure 1. Flowchart for simulation model development

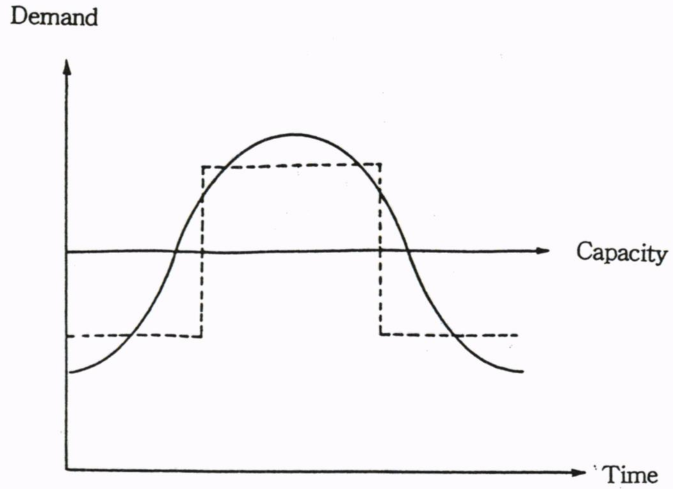

Figure 2. Time-dependent passenger travel pattern

As illustrated in Figure 2, passenger travel patterns of all the cases can be represented by solid lines (follows normal distribution). In this study, solid lines were replaced by dotted lines for the simplicity of calculation.

2) Analysis on Traffic Flow

One of the important factors which affects the decision making on mode choice of HOV and LOV is the travel time in each case. The linear macroscopic flow model (Greenshield model) was adopted for travel time estimation when the demand does not exceed the capacity. Whereas, in order to estimate the travel time when demand exceeds the capacity, conventional link performance functions (e.g., BPR function) are adopted, delay formulas based on flow and density are utilized in this study. This is partially because empirical formula are not developed in Korea yet. Hence, travel times are composed of the summation of travel times, *Tn*, when demand does not exceed capacity, and the travel times (delay time), *Tw*, when demand exceeds the capacity.

① Travel time estimation for the flow under capacity

Travel speed based on flow and capacity can be derived as:

$$Q = K \times V \tag{1}$$

$$V = V_f - \frac{V_f}{K_j} K \tag{2}$$

$$Q_{\max} = \frac{V_f}{2} \times \frac{K_j}{2} = \frac{V_f K_j}{4} \tag{3}$$

Where, Q = Flow (vph)

K = Density (vpk)
V = Speed (kph)
V_f = Free-flow speed
K_j = Jam density
Q_{max} = Maximum flow

From Equation 1, 2 and 3 $V = Vf \dfrac{1+\sqrt{1-Q/Q_{max}}}{2}$ can be obtained.

Thus, travel time (*Tn*) can be determined by distance with the speed known. As is noticed from the above equation, it cannot be used when the traffic demand exceeds capacity.

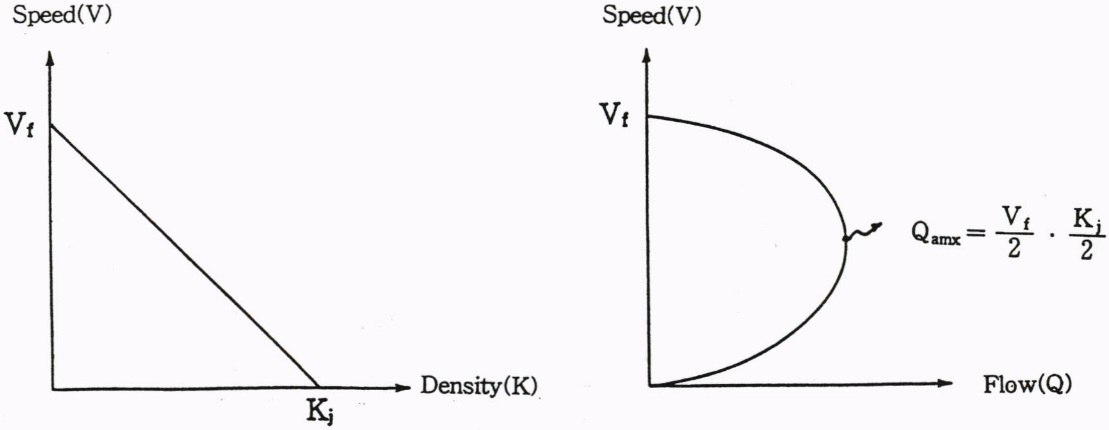

Figure 3. Basic form of speed-flow-density relationships

② Delay time estimation for the flow over capacity

When the demand exceeds capacity, delay will occur. Average delay time can be represented graphically in Figure 4.

Total number of vehicles in queue (veh) and total delay (veh * hrs) can be calculated as Equation 4 and 5

$$D_{Ts} = \int_0^{Ts} (pq - Q_{max})dt = (pq - Q_{max})Ts \qquad 4$$

$$TD = \frac{D_{Ts} \times Tc}{2} \qquad 5$$

where, Ts = Duration when demand exceeds the capacity
Tc = Duration from queue formulation to dissipation

pq = Traffic flow during peak period(vph)
Qmax = Capacity(vph)
DTs = Total vehicle delay(veh) during Ts
TD = Total delay(veh * hrs)

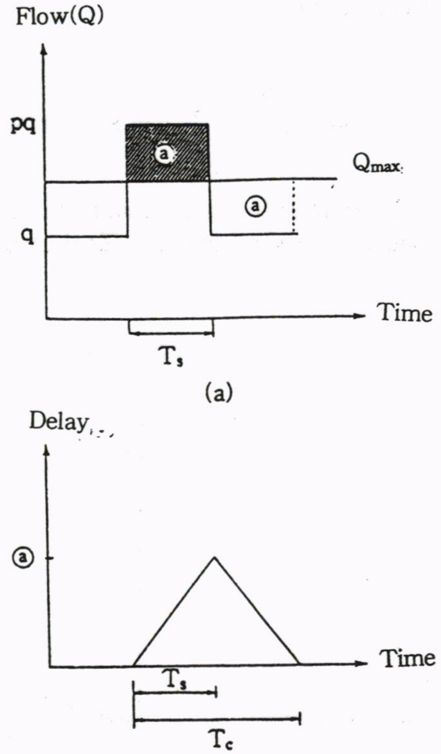

Figure 4. Diagram of delay and total delay analysis

Thus, average delay time (Tw) can be expressed as Equation 6.

$$Tw = \frac{TD}{Q_{max} \times T_c} = \frac{1}{2}\frac{(pq - Q_{max})T_s T_c}{Q_{max} T_c}$$

$$= \frac{(pq - Q_{max})}{2Q_{max}} T_s \qquad 6$$

It is assumed in Equation 6 that demand is constant on an hourly basis. However, it would be more accurate, if the time steps could be divided into more detail, such as 5 min, etc.

3) Choice of HOV and LOV

Logit model, commonly used in Modal Split in Urban Transportation Planning Process (UTPP), can be applied in order to identify the choice of HOV & LOV from the estimated trip demand. In this study, however, two more variables were identified to reflect the reality as closely as possible. They are minimum selection of HOV (Pmimlov) and LOV

(Pminhov). The definition of Pmimlov does not completely conform with Captive Trip Maker (CTM) concepts in transportation planning, but, it is very similar to CTM. In the same manner, Pminlov represents the ratio of trip makers who select LOV (Pminhov = 1 - Pmaxchoice - Pminlov). If this concept is applied to the logit model, it can be represented graphically as shown in Figure 5.

$$P_{hov} = P_{\min hov} + \frac{P_{\max choice}}{1+e^{\Delta Z}}$$

$$\Delta Z = Z_{hov} - Z_{lov}$$

$$Z_{hov} = -\alpha \times T_{hov} - \beta \frac{(TC_{hov} + H_{fare})}{AVO_{hov}}$$

$$Z_{lov} = -\alpha \times T_{lov} - \beta \frac{(TC_{lov} + L_{fare})}{AVO_{lov}}$$

where, Zhov = Utility function for HOV lane
Zlov = Utility function for LOV lane
α, β = Parameters
Thov = Travel time for HOV lane (100 min)
Tlov = Travel time for LOV lane (100 min)
TChov = Toll change for vehicle in HOV (1000 won)
TClov = Toll change for vehicle in LOV (1000 won)
AVOhov = Average vehicle occupancy for HOV
AVOlov = Average vehicle occupancy for LOV
Phov = Probability of selecting HOV lane
Pminhov = Minimum probability of selecting HOV lane
Pmaxchoice = Maximum probability of selecting HOV lane among the choice trip makers
Hfare = Bus fare
Lfare = Passenger car operating cost

Travel time, comfort, convenience, costs (travel cost), etc., should be considered in obtaining a utility function. However, travel time and costs are considered as significant factors that affect the choice of travel mode in this study.

4. APPLICATION OF SIMULATION MODEL

4.1 Approaches

The selection of an optimal number of HOV lanes is simulated for the real application, according to the model developed in the previous chapter. It is applied to the 8 lane-two direction highway segment between Seoul and Daejeon.

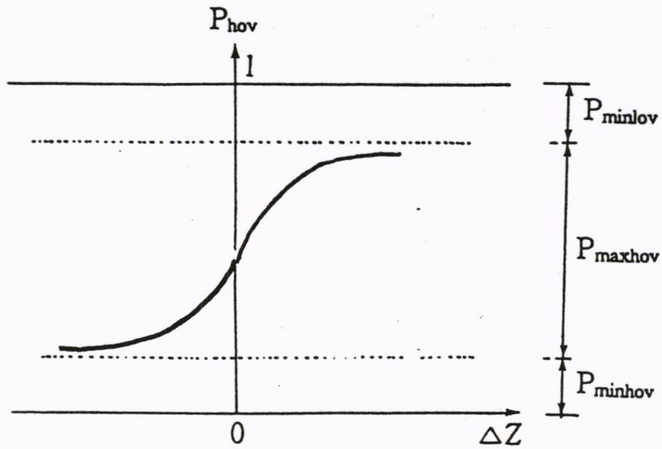

Figure 5. Probability of HOV and LOV choice

4.2 Parameter Selection

1) Demand

Travel demand during peak periods is divided into 4 categories. The demand in each case in estimated to be as in Table 1.

Table 1. Estimation of passenger demand

(Unit: trips/peak hour)

Case 1	Case 2	Case 3	Case 4
80,000	60,000	40,000	20,000

2) Peak hour duration

The duration of peak hours for the four categories are assumed as follows:

Table 2. Estimation of peak hour duration

(Unit : hour)

Case 1	Case 2	Case 3	Case 4
4	3	2	1

3) Average Vehicle Occupancy (AVO)

As mentioned, it is assumed that vehicles using the express highway between Seoul and Deajeon consist of buses, trucks, and passenger cars. Also, HOV Lanes are restricted to buses and trucks only, and LOV lanes are restricted to cars. AVO for passenger cars, trucks and buses are assumed to be 2.5, 0.0, 40 passengers, respectively. Meanwhile, passenger cars' equivalent factor for buses are assumed to be 1.8.

Since AVO in HOV is determined by the ratio of buses and trucks, it is assumed that the ratio of buses and trucks are as illustrated in Table 3. Finalized AVO's in HOV are also included in Table 3.

Table 3. The ratio between buses and trucks resulting in AVOhov estimation

	BUS (%)	TRUCK (%)	AVO_{hov} (passenger/veh)
Case 1	83	17	33
Case 2	75	25	30
Case 3	50	50	20
Case 4	40	60	16

4) Calibration of Parameters

Parameters, α and β in the utility function should be estimated by calibration. For calibration, Seoui-Pusan express highway users were selected, and 652 samples were collected. The results of the calibration is shown in Table 4.

Table 4. Estimation of α, β in utility function

parameter	estimate	standard error of estimation	T-value	R^2	ρ^2
α	-0.5	0.013	-37.03	0.89	0.87
β	-0.06	0.001	-83.79		

5) Other parameters

Other parameters, such as lane capacity, free flow speeds, toll charges, distances, fares and costs are identified for HOV and LOV lanes. These are shown in Table 5.

Table 5. Estimation of other parameters

	Qmax (pcphpl)	Vf (kph)	TC	Distance bet. Seoule and Daejeon (km)	Fare and Cost (won)
HOV	1,800	100	7,500	150	3,000
LOV	1,800	100	4,500	150	7,000

4.3 Result of Model Application

Various analyses, such as estimation of toll charges for HOV and LOV, fares, truck restrictions, etc. can be conducted by developed model. However, the main purpose of the simulation is to perform the combined analyses between various HOV lanes (0 * 3 lanes) and four different cases in this study. The next step is to identify the number of HOV lanes which will maximize the HOV lane operation.

1) Analysis on the number of HOV lanes for each case

Number of HOV lanes, average speed on HOV and LOV lanes, travel time between Seoul and Deajeon are simulated and illustrated in Table 6.

Table 6. Travel time estimation by the number of HOV lane for each case
(Unit : hours, km/h)

		HOV Lane			
		0	1	2	3
Case 1	HOV	4.71(31.8)	4.38(34.1)	2.53(59.3)	1.88(79.8)
	LOV	4.71(31.8)	4.57(32.8)	4.62(32.4)	8.24(18.2)
Case 2	HOV	3.18(39.3)	3.52(42.4)	2.07(72.5)	1.78(84.2)
	LOV	3.18(39.3)	3.64(41.1)	3.53(42.4)	5.56(26.9)
Case 3	HOV	3.28(45.6)	3.14(47.6)	1.84(77.4)	1.73(86.5)
	LOV	3.28(45.6)	3.26(45.9)	3.34(44.8)	4.69(31.9)
Case 4	HOV	2.0(75.1)	1.87(80.1)	1.07(89.8)	1.61(93.9)
	LOV	2.0(75.1)	1.97(76.2)	2.35(63.9)	3.39(44.2)

The numbers in the parenthesis represent speed.

Comparison of travel times with and without HOV lanes between Seoul and Daejeon are conducted in order to identify the optimal number of HOV lanes with respect to the system perspective. The simulation results are shown in Figure 6.

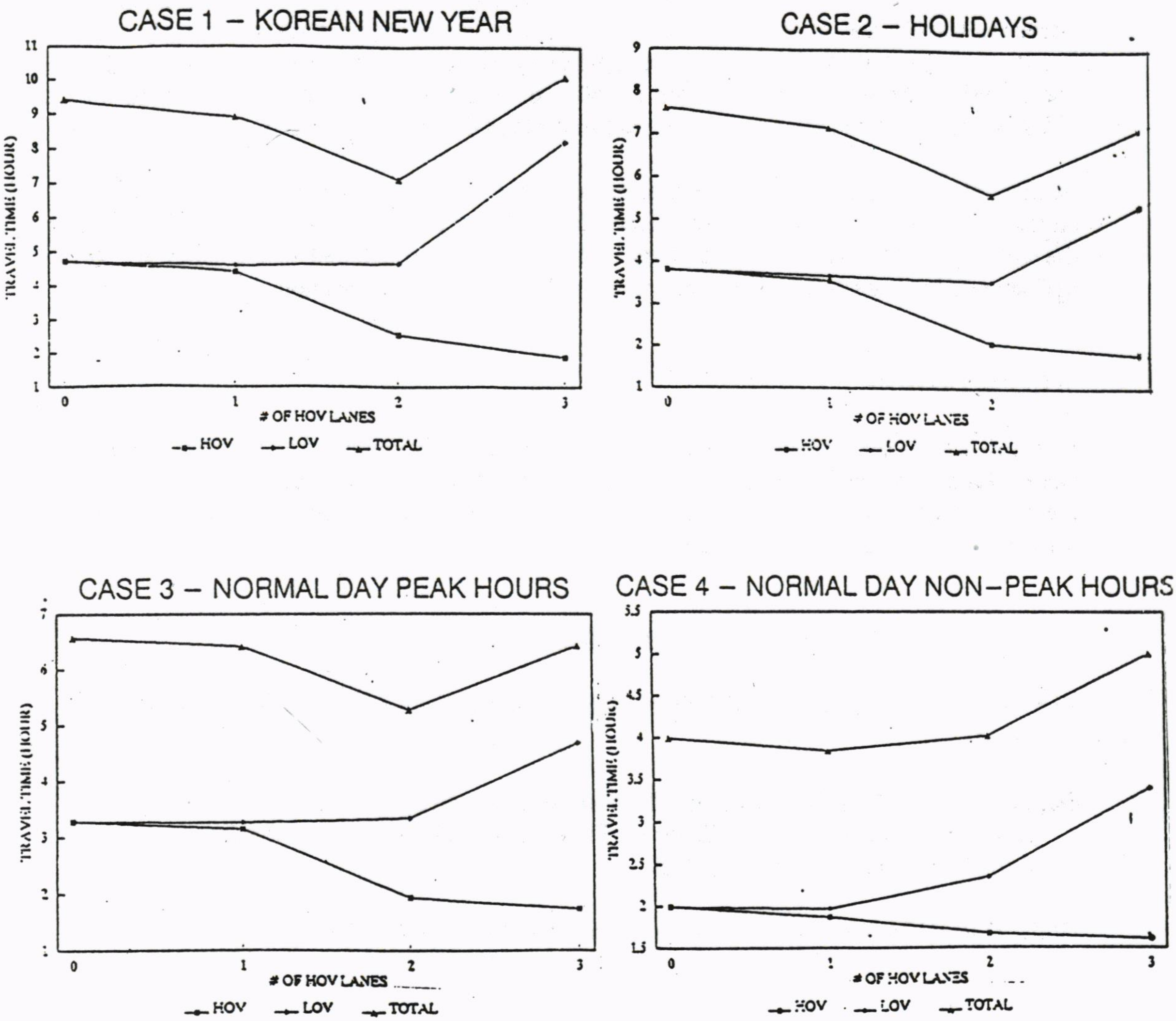

Figure 6. Comparison of travel time with varying HOV lanes for each case

The results of case 1, show that introduction of one HOV lane does not influence much on either the travel times of HOV or LOV users. When two HOV lanes are introduced, there is not much improvement for LOV users, while there is 100% improvement on for HOV users. When three lanes of HOV are introduced, significant improvements are made for HOV users, but, at the same time it causes tremendous delay for LOV users.

Similar results are produced in the analyses of cases 2 and 3. In case 4, it is possible to choose 1 or 2 lanes for HOV lanes. However, changing the number of HOV lanes during the day is not convenient for motorists. Therefore, it is concluded that 2 lanes are an optimal numbers of lanes for HOV operation in the Seoul-Daejeon section.

5. CONCLUSION

It is noted from the various simulation results that the introduction of HOV lanes will aid bus passengers as well as auto travelers. In the case that HOV systems are introduced to the Seoul-Pusan express highway, two lanes are identified as the optimal number of lanes for the system efficiency in HOV lane operation.

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