□ 論 文 □

다이아몬드 인터체인지 디자인에 있어서 費用節減的인 決定과 라이프 싸이클 費用分析

COST EFFECTIVE DECISIONS AND LIFE-CYCLE COST IN DIAMOND INTERCHANGE DESIGN

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CONTENTS

要 約

通常的인 다이아몬드 인터체인지(Conventional Diamond)는 設計가 容易하고 建設費가 低廉하여 一般的으로 인터체인지 設計에 널리 利用되고 있다. 그러나 周邊地域이 開發되고 交通量이 增加하면 이의 設計改善이 要求되지만, 隣接地域이 이미 開發되었거나 혹은 社會的, 財政的인 이유로 인하여 施設敷地로 追加로 要求되는 空間의 確保는 制約을 받는 경우가 많다. 그러므로 인터체인지를 建設할 때 다른 유형의 인터체인지 設計를 처음부터 考慮할 必要가 있다.

交通需要와 패턴이 靜的(Static)이라면 設計類型의 決定은 간단하다. 그러나 交通需要와 패턴은 靜的이 아니므로 라이프 싸이클 (Life cycle)費用을 考慮한 接近方式이 必要하게 된다. 이 方式은 인터체인지 라이프 싸이클 동안의 각종 費用要素와 總 現在價値를 考慮하여 각종 인터체인지간의 相對的인 長點을 評價하는 것이다.

Ⅰ. Introduction

The literature related to diamond interchanges does not emphasize the spatial design (layout) but rather emphasizes signal optimization, given a pre-existing problem. This is logical, for conventional diamond interchange are common and efficient low-cost solutions for low-to moderate-volume interchange. However, as development takes place and traffic volume increases, the land needed for enhanced designs has already been taken by the very development patterns which generate the need for the enhanced designs. Thus one of the primary remedies available is signalization.

This paper is written to explore the relative advantages of various diamond interchange configurations when total "life cycle" costs taken account, so that logical decisions on initial configurations can be better supported when appropriate.

If demand level and pattern were static, then the selection of configuration is trivial, for the basic configurations differ markedly in their capacities. However, the demand is not static, so that the "life cycle cost" approach is needed. Further, the delay costs are not linearly related to demand levels or pattern, so that extensive simulation work was needed to support the cost estimates.

The end products of this dissertation are :

+ a better understanding of the factors which influence the operation;
+ a LOTUS spreadsheet which can be used for life cycle cost estimating, to better consider the alternative ;
+ the simulation work which supports the demand/delay and other relations used in the spreadsheet.

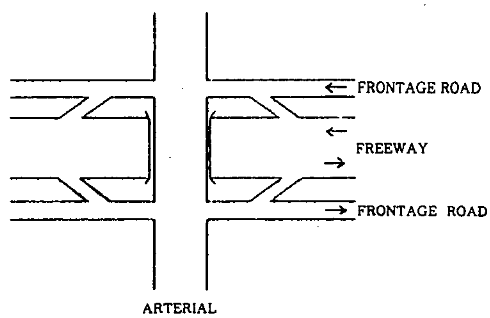
Ⅱ . Designs And Factors Considered

1 . Designs

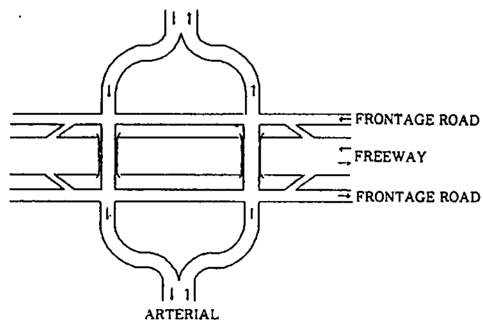
Three basic diamond configurations considered :

+ conventional diamond ;
+ split diamond ;
+ stacked diamond.

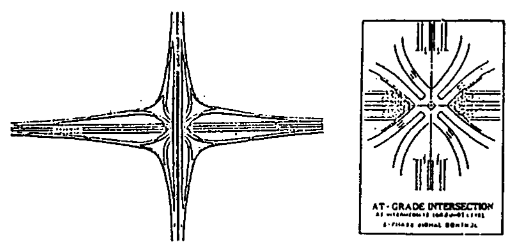
Figure 1 shows the three configurations. Within each configuration, a number of lanes are considered, with layouts differing in number of lanes and other geometrics(primarily spacings).



A. CONVENTIONAL DIAMOND INTERCHANGE



B. SPLIT DIAMOND INTERCHANGE



C. STACKED DIAMOND INTERCHANGE

FIGURE 1. THREE DIFFERENT CONFIGURATIONS IN DIAMOND INTERCHANGE

2 . Traffic Patterns

As will be demonstrated, the traffic pattern determines the nature of the interchange. Over the life of an interchange, traffic pattern can change. Indeed, it is so common that the phrase "can change" is most logically replaced by "generally does change".

3. Life Cycle Cost

In considering life cycle costs, the following factors and costs are considered :

1) Factors
+ N years ;
+ traffic pattern ;
+ growth rate ;
+ initial volume ;
+ design configuration and layout

2) Costs
+ Capital cost
  - roadways and ramps
  - bridges
+ land cost
  - acquisition cost(capital)
  - access function of road
+ facility maintenance and operation cost
+ traffic operation cost
  - user travel time and delay
  - fuel
  - other vehicle costs
+ accident cost
  - fatal rate per million-vehicle-mile(MVM)
  - injury rate per MVM
  - property damage rate per MVM

Ⅲ. Key Issues

This chapter addresses key issues which influence the overall design selections, or are basic principles.

1. Major Traffic Pattern

The traffic patterns are an extremely important factor to consider determining the nature of the interchange. The traffic patterns in the diamond interchange can be determined by considering location of interchanges relative to the developments in area, both intensity and location of development. Therefore, the major traffic patterns can be classified by the highly directional flows to traffic attractions which are central business district(CBD) or local development(L).

Figure 2 shows six combinations in which the flows direct to the CBD or to local development. Especially, these traffic patterns with high left-turn movements on the bridge critically impact on the capacity of interchange. Traffic Pattern 1 and 4 show that flows which are directed to the CBD or to local developments. These cases can be commuter trips from residential areas to working areas in the CBD or to local developments. Traffic Pattern 2 and 3 show flows to freeway and to arterial which are dominant. These cases can happen where the arterial is served by a major road to be connected to local developments or residential areas. Traffic Pattern 5 and 6 are combinations of above cases. These cases can happen where the areas are fully developed such as urban areas.

2. Relative Capacities

Turning movements are often high in the interchange. Especially, left-turn movements on the bridge are a critical factor impacting on the capacity of the interchange. Table 1 shows relative capacities of each configuration according to changes in the percentages of left-turns.

1) Conventional Diamond Interchange

The conventional diamond interchange generally provides exclusive left-turn lanes

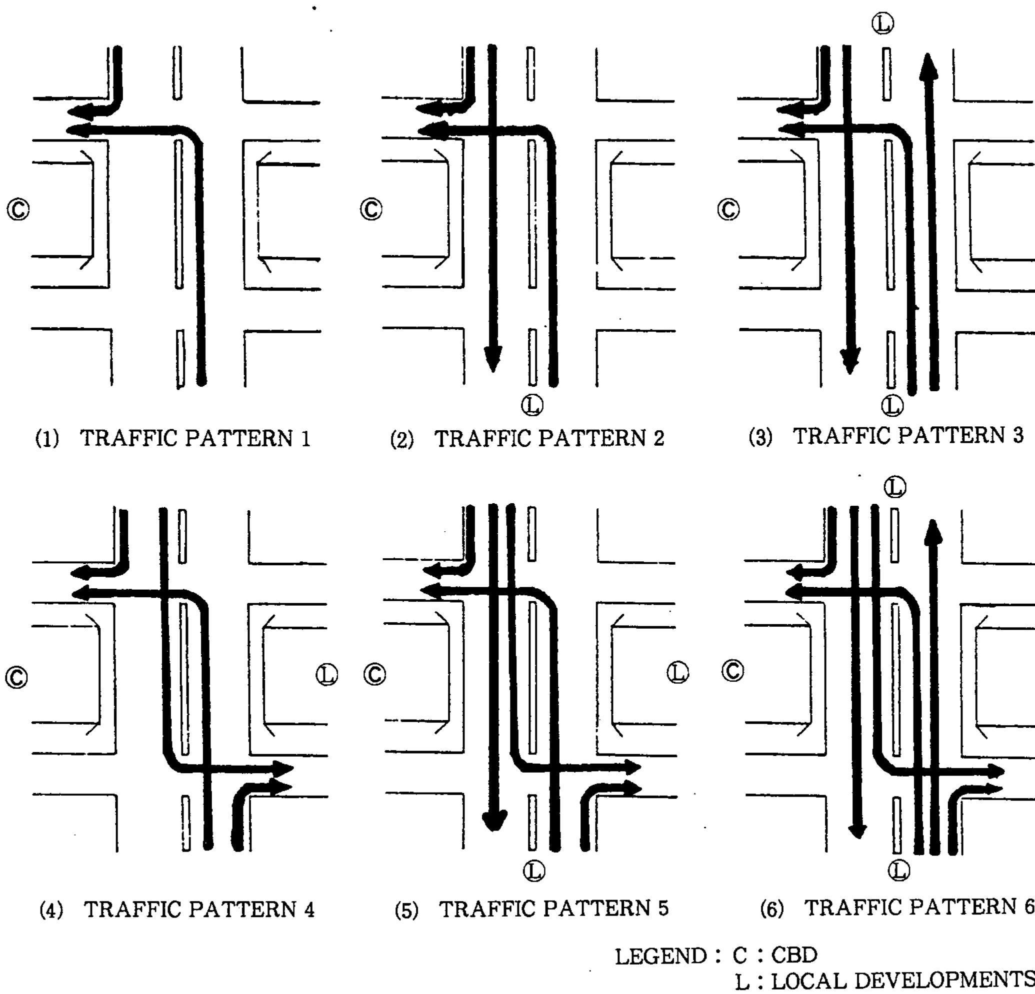


FIGURE 2. SIX FUNDAMENTAL TRAFFIC PATTERNS

on the bridge. Therefore, it must operate with three or more signal phase as volume increase. Storage rooms for left-turn movements in this design are limited due to the length of the bridge. There is a high probability of spillback on the bridge when high left-turn movements exist.

Given dimensions, the range of the capacities is between 560 vphpl and 1180 vphpl. The capacity for 35% left-turn is only 60% of that for 5% left-turn. Therefore, the conventional diamond interchange is rather sensitive to changes in the percentages of left-turns.

2) Split Diamond Interchange

The split diamond interchange has several advantages in handling high left-turn movements. It can operate a two-phase signal system in a one-way street system. Therefore, it converts left-turn movements in the conventional diamond interchange into through movements. As a result of this, the left−turn conflicts are eliminated and the interchange provides more storage room and green time for left−turn movements, therefore producing less delay.

The range of the capacities is between 1240 vphpl for 5% left−turn and 910 vphpl for 35% left−turn. It means that the split diamond is insensitive to changes in the percentages of left−turns. The enough spacing should be provided where expect high left−turning movements on the bridge.

TABLE 1 . RELATIV CAPACITY BASED UPON NETSIM MODEL

Types of Facility	Conventional		Stacked
Layout	Case C6	Case C8	
	2 THRU 1 EX LT	2 THRU 2 EX LT	2 Lanes Ramp 2 Lanes Viaduct
Storage Room For LT	15 Veh	30 Veh	
Percentage of Left−Turn	(vphp1)	(vphp1)	(vphp1)
5%	950	1180	1240
10%	890	1060	1240
15%	820	980	1230
20%	720	890	1230
25%	650	780	1220
30%	610	740	1210
35%	560	690	1210
Types of Facility	**Split**		
Layout	Case S3S	Case S3M	Case S3L
	1 THRU 1 LT & TH 1 EX LT	1 THRU 1 LT & TH 1 EX LT	1 THRU 1 LT & TH 1 EX LT
Spacings	600′	1800′	5400′
Storage Room for LT	80Veh	160Veh	430Veh
Percentage of Left−Turn	(vphp1)	(vphp1)	(vphp1)
5%	1240	1240	1240
10%	1220	1220	1220
15%	1190	1190	1190
20%	1160	1160	1160
25%	1040	1100	1100
30%	980	1070	1070
35%	910	990	1020

Note : *Spacings : Length Between Two Bridges
*EX : Exclusive
*LT : Left Turn
*Veh : Vehicle
*All Values are Rounded

3) <u>Stacked Diamond Interchange</u>

This interchange can handle high flows to and from the freeway with a two-phase signal operation. The range of the capacities is between 1210 vphpl and 1240 vphpl for 5% left-turn to 35% left turn. Therefore, it is not impacted by changing of left-turn percentages and can handle capacity flows with high left-turn movements in the arterial. However, it is an expensive structure and can not handle the flows on the frontage road with a two-phase signal system.

Conclusively, left-turn movements in the conventional diamond interchange is a critical factor in reducing the capacity, while the split diamond interchange can handle the high left-turn flows with enough storage room. The stacked diamond interchange can also handle the high left-turn flows, but it can't handle the flows on the frontage road and requires a three-level structure.

3. <u>Signal Progression</u>

In order to determine signal progression in split diamond interchange, it is necessary to find out an optimal offset given a traffic pattern.

1) <u>Determination of Offset</u>

An offset equation for the split diamond interchange can be developed by a "loop" based on prevailing traffic patterns refer to Figure 3. The following steps are how to determine offsets for each node. For an objective of setting the signal progression to expedite the indicated flows :

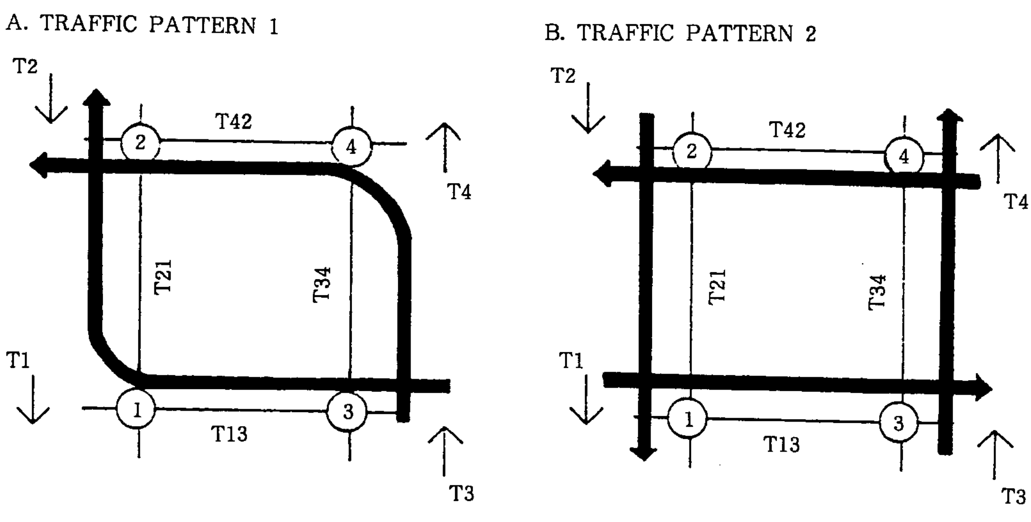


FIGURE 3. OFFSET DETERMINATION

<u>Step 1</u> : Start at node 3 and consider the green initiation to be time $T_3=0$

$T_3=0$

<u>Step 2</u> : Move to node 4 and add T_{34}

$T_3=0+T_{34}$

<u>Step 3</u> : Move to node 2 noting that southbound vehicles will release after the eastbound green is finished.

$T_2=0+T_{34}+T_{42}+g_{EW,2}C$

Step 4 : Move to node 1 and add T_{21}

$$T_1 = 0 + T_{34} + T_{42} + g_{EW,2}C + T_{21}$$

Step 5 : Move to node 3 noting the same as Step 3.

$$T_3 = 0 + T_{34} + T_{42} + g_{EW,2}C + T_{21} + T_{13} + g_{EW,2}C$$

This is either $T_3 = 0$ or a multiple of the cycle length.

Therefore, the following equation can be developed :

$$nC = T_{34} + T_{42} + g_{EW,2}C + T_{21} + T_{13} - g_{EW,3}C \quad (3.1)$$

Where :

T_i : North or southbound offset at node i

T_{ij} : Travel time between node i and j

$g_{EW,i}C$: Green interval for east west bound at node i (include amber and all red)

2) Difference of Stndard Equation

Standard offset equation is given by :

$$nC = T_{34} + g_{NS,4}C + T_{42} + g_{EW,2}C + T_{21} + g_{NS,1}C + T_{13} + g_{EW,3}C \quad (3.2)$$

The basic difference between Equation 3.1 and 3.2 are traffic patterns governing the signal progression. Equation 3.1 expedite the flows of Traffic Pattern 1 (Figure 3.A) and Equation 3.2 expedite the flows of Traffic Pattern 2 (Figure 3.B) which are also the common flows in a network grid system.

3) Effect of Vehicles Queued at Signal

Referring to Figure 3, two types of queues will develop on each node. The minor turning movement from link(4,2) and (1,3), and the minor through movement from the freeway which are random arrival flows. Therefore, a modified offset relation considering queued vehicles at each node are as follows :

Node 3 : $T_3 = 0$

Node 4 : $T_3 = 0 + T_{34} - (Q_4H + L)$

Node 2 : $T_2 = 0 + T_{34} + T_{42} - (Q_2H + L) + g_{EW,2}C$

Node 1 : $T_1 = 0 + T_{34} + T_{42} - (Q_2H + L) + g_{EW,2} + T_{21} - (Q_1H + L)$

Node 3 : $T_3 = 0 + T_{34} + T_{42} - (Q_2H + L) + g_{EW,2} + T_{21} + T_{13} - (Q_3H + L) + g_{EW,2}C$

Therefore, the following equation can be developed :

$$nC = T_{34} + T_{42} - (Q_2H + L) + g_{EW,2}C + T_{21} + T_{13} - (Q_3H + L) + g_{EW,3}C \quad (3.3)$$

Where :

Q_i : number of vehicles queued at node i

H : headway

L : start-up lost time

This is a more general form of equation 3.1.

4. Construction Cost Consideration

In a conventional diamond interchange, a wide bridge might be required according to volume growth. It also impacts on the width of roadway in the interface area between arterial and bridge. While, two relative narrow bridges are required in a split diamond interchange. It also requires a roadway parallel to freeway (if there is no frontage roadway). Therefore, the construction cost of a wide conventional interchange may be bigger or the same as that of a split diamond with two relative narrow bridges.

Two types of investments, which are "build it once" case and widening retrofit" case, can be considered for interchange bridge construction refer to Figure 4. For "Type A" investment, a wide bridge is constructed at the begining of analysis period. Later as the existing bridge has spillback problems due to volume growth, another investment is required to provide more lanes on the bridge ("Type B" investment). In this case, the costs of the bridge widenings generally exceed the costs of routine new bridge construction. However, the construction cost for "Type A" investment (P) might be less than the sum of first construction cost for "Type B" investment (P_1) and the present value of bridge widening cost (P_2). Other cost elements of "Type B" investment will be higher than "Type A" investment as will be demonstrated in case studies.

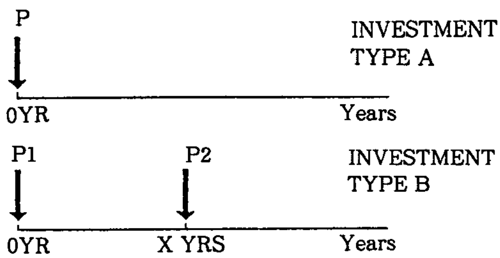


FIGURE 4. TWO TYPES OF INVESTMENTS IN CONVENTIONAL DIAMOND.

5. Cost Indices in Life Cycle Cost

Total input flows over life-cycle for each configuration in the diamond interchanges might be not same because the capacities are different. Input flows impact the estimations of vehicle operating cost and accident cost among various cost elements. Therefore, total present value will be influenced by different input flows.

Two cost indices to be considered are :

*Total present value

*Average cost per vehicle trip

1) Cost Index 1

The first cost index is simply the total present value of all life cycle cost elements ;

$$P = \sum_{\substack{\text{life cycle cost} \\ \text{elements } i}} P_i \qquad (3.4)$$

Total present value is given by the sum of discounted annual costs over life-cycle. This cost index is proper to compare the life cycle costs of different configurations under same traffic pattern (ie, same input flows for each configuration). Total present value for each configuration provides logical decisions on it comparing other designs.

2) Cost Index 2

The second cost index is ;

$$\text{ACPT} = \text{Average Cost Per Trip} = \frac{P}{\text{Average Annual Volume}} \qquad (3.5)$$

Where the volume is a simple undiscounted average of all annual volumes over the analysis period. In order to compare the life cycle costs of different configurations under various traffic patterns, the average cost index is suitable.

This cost index is not a conventional cost index, in that volumes are not discounted or weighted. It is produced as a relative indicator.

6. Split Diamond Interchange in a Land-use Plan

Two types of layout dimensions can be considered in a land-use plan of a split diamond interchange refer to Figure 5. The first design produces shorter travel time and lower parallel roadway construction cost. However, its inside land can not be utilized except as landscape or for some limited purpose. While the second design produces longer travel time and higher parallel roadway construction cost, its inside land can be utilized for other purposes. Its increased land and other costs can be compensated for by the benefits of the interior utilizations.

Figure 6 shows an example of a land-use plan. In general, two types of activities can be considered for a land use in its inside land. One is highway oriented road user activities such as motel, restaurant, auto service stations, etc. and the other is community types of activities such as neighborhood shopping area, and so forth. Both avoid the problem of residential uses near the highway, which is a noise source. This design might not be even perceived by the driver.

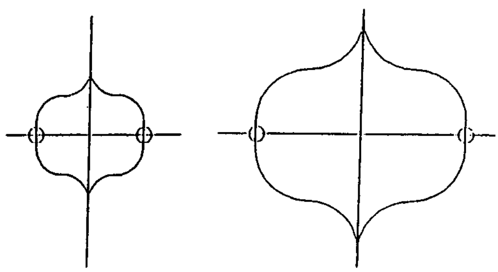


FIGURE 5. TWO TYPES OF LAYOUT DIMENSIONS IN SPLIT DIAMOND INTERCHANGE

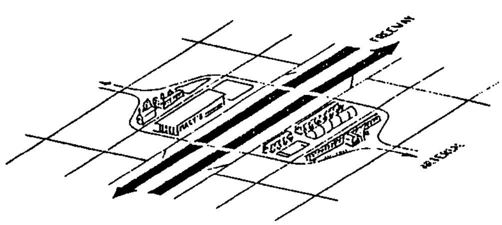


FIGURE 6. A SPLIT DIAMOND WHICH THE DRIVER MIGHT NOT EVEN PERCEIVE AS SUCH

6. Design Considerations

The several design considerations in selecting a basic configuration and a detailed layout were developed :

+ the number of lanes across freeway bridge ;
+ the roadway length parallel to the freeway ;
+ the number of lanes on parallel roadway ;
+ the sensitivity of parallel roadway length to changes in traffic patterns ;
+ the sensitivity of overall performance in each configurations to the percentage of left turns.

Ⅳ. Demand and Delay Relation

It was expected that the delays of an interchange are impacted by demand levels and by traffic patterns. Therefore, the following factors were considered :

+ Growth rates ;
+ Traffic patterns ;
+ Quality of progression ;
+ Layout configurations.

Figure 7 shows the annual delays for three different configurations according to changes in growth rates. The delays of the conventional diamond are more sensitive to changes in growth rates than those of the split diamond. While the stacked diamond is not impacted by changes in growth rates.

Figure 8 shows the average delays of each configuration according to changes in traffic patterns. The average delays of conventional diamond are very sensitive to changes in the percentages of left-turns as interchange volume grow. The average delays of split diamond are relatively insensitive to changes in the percentages of left-turns, and those of stacked diamond are not impacted at three different left turns at all.

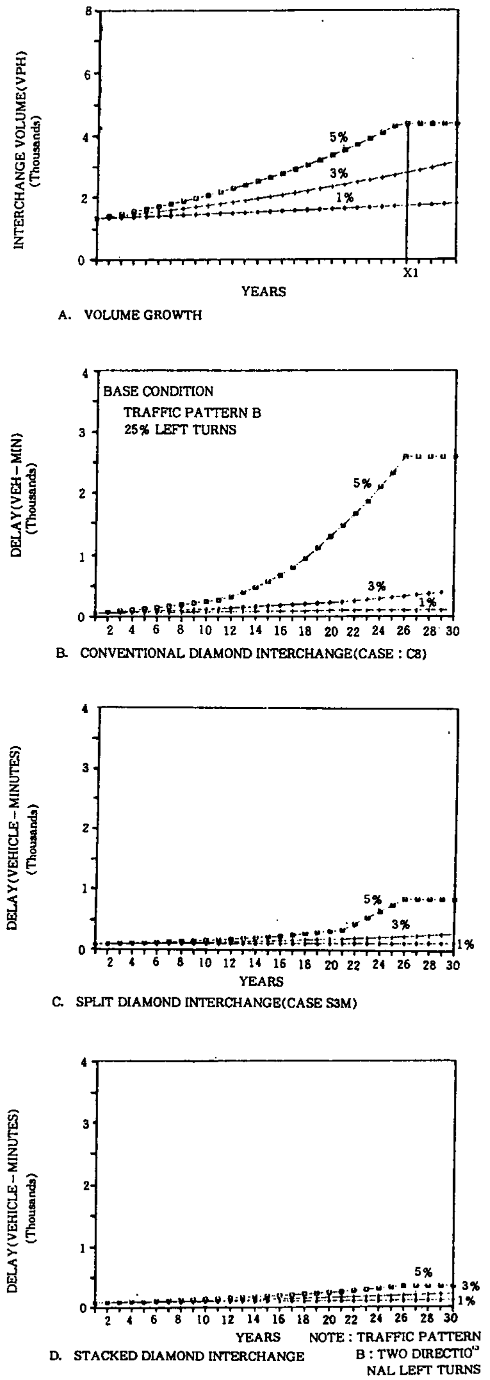


FIGURE 7. DELAYS AS RELATED TO VOLUME GROWTH RATES

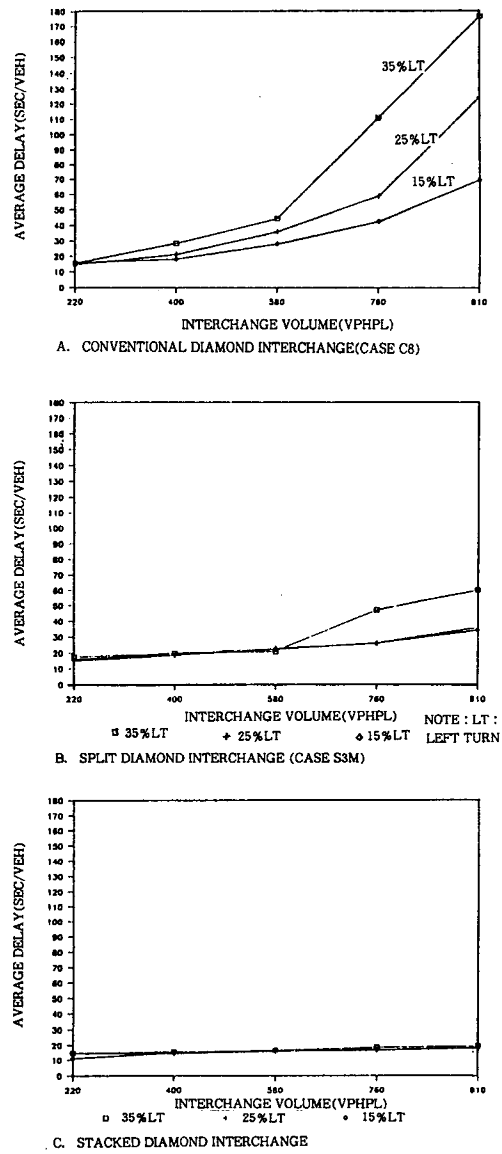


FIGURE 8. AVERAGE DELAYS AS RELATED TO LEFT TURNS

There are two types of flows to be considered in the diamond interchange. One is platoon flows from the arterial and the other is random flows from the exit ramps of freeway. In general, favorable green and offset should be given to major platoon flows in order to minimize the delays of the interchange. Therefore, random movements will develop queued vehicles at the interchange signal. Minor movements will also contribute to queues at signal. The random movements effect on the delays of the link(parallel roadway) in the split diamond. These effects can be also found the same as those of turn−in flows on regular links. Those effects can be also found at the bridge section in conventional diamond ; comparing arterial through traffic to those random flows. Figure 9 shows average delays for the link (the parallel roadway in split diamond) over a range of offset for an illustration case. As turn−in flows (random arrival flows) increase, the average delays increase around optimal offset. The difference between optimal and worst are significant. The average delays at optimal offsets are about five times as much as those at worst offsets ; of course, this is why each case had the signalization selected by use of a signal optimization program.

The interchange−related delays will generally decrease, as more lanes are added on the bridge in the conventional diamond or parallel roadway spacings approach the preferred values in the split diamond.

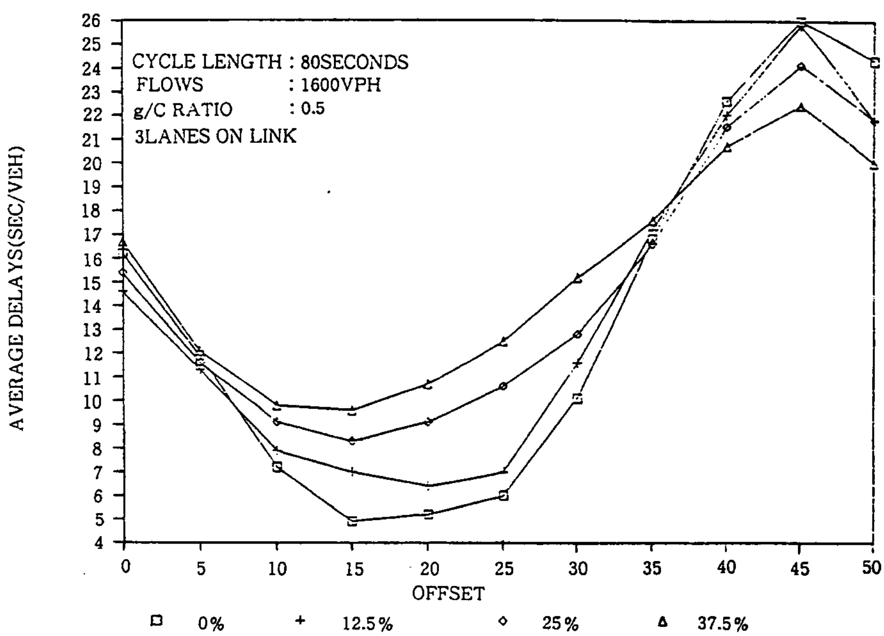


FIGURE 9. QUALITY PROGRESSION ACCORDING TO TURN−IN FLOWS IN SPLIT DIAMOND INTERCHANGE

V. Life Cycle Cost Model

The life cycle cost model is an methodology that evaluates the relative advantages of various interchange designs by considering the total present value of an interchange over life cycle, considering all identifiable cost elements. The process of this model is as follows : (Refer to Figure 10)

Step 1 : Identify basic layouts among all plausible interchange disigns, considering traffic pattern and growth ;

Step 2 : Compute costs for facilities, based upon available information ;

Step 3 : Conduct traffic operational evaluations for these basic layouts, to generate a tactical data base ;

Step 4 : Analyze traffic operational results and estimate quantitative costs for each layout ;

Step 5 : Use analysis method(e.g. present value)

Step 6 : Generate standard displays to determine the relative efficiency of each layout, and select an appropriate alternative based upon life cycle principles. Draw conclusions on life cycle cost versus historic capital cost approaches.

An extensive simulation and optimization effort supports the estimate of cost elements for the life cycle cost model. The life cycle cost can be estimated on yearly base and present value base by using a LOTUS spreadsheet. The yearly base analysis identifies the performance of each alternative on year by year basis during the analysis period, and identifies the effects of each cost element on total costs. The present value for each alternative provides logical decisions on the most cost-effective choice.

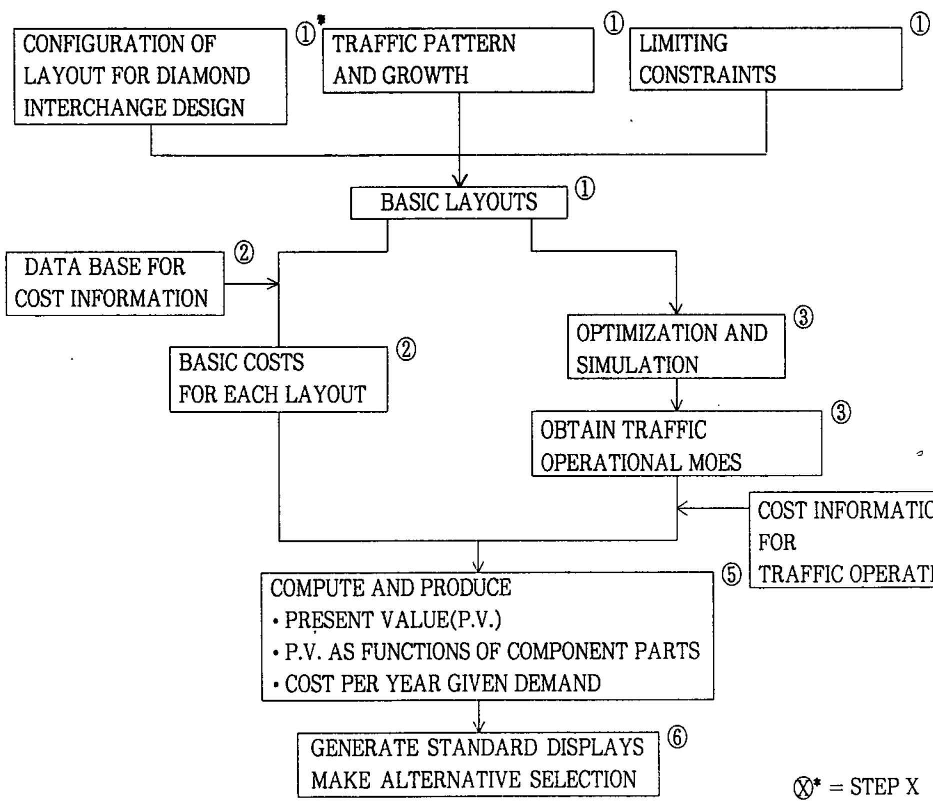


FIGURE 10. FLOW DIAGRAM FOR LIFE CYCLE COST MODEL

Ⅵ. Case Studies

1. Effect of Traffic Patterns

Figure 11. shows average cost for two designs according to different left-turns. In terms of average costs of life cycle costs, the conventional diamond is more sensitive to changes in percentages of left-turns than the split diamond.

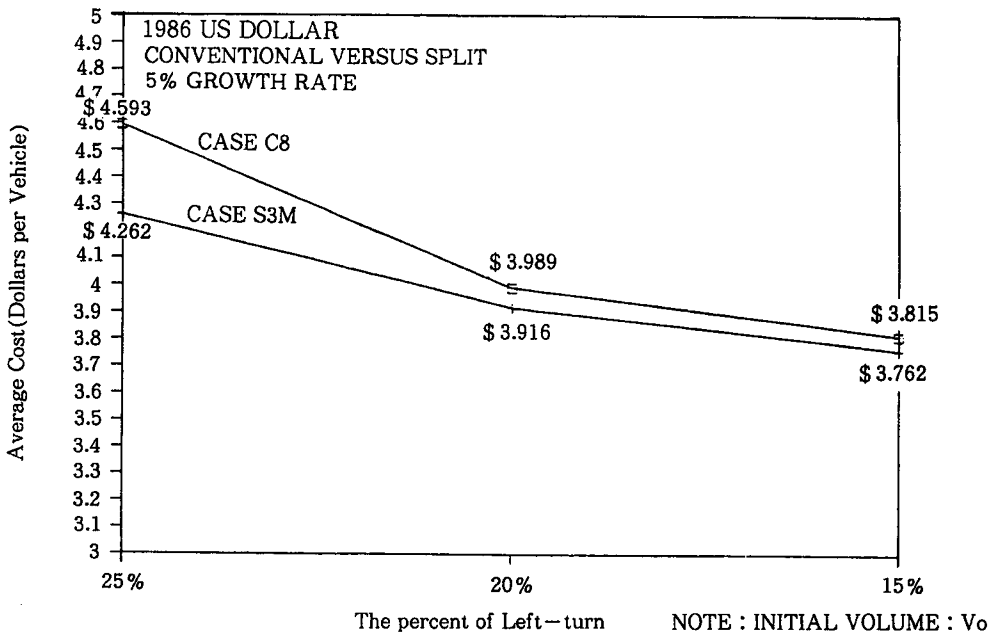


FIGURE 11. AVERAGE COST BASED ON PRESENT VALUE FOR TWO DESIGNS, CASE STUDY 1

2. Consideration of "Widening Retrofit" case

The widening retrofit case can be compared to "build it once" case for both conventional diamond and split diamond. Total capital costs for three designs are as follows :

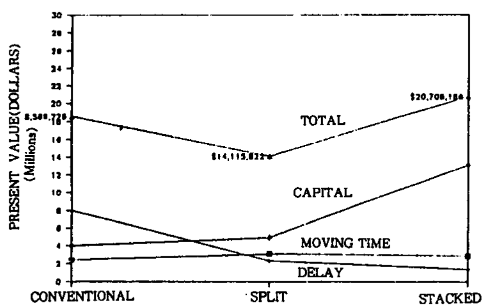
	Present Value Capital Cost	Total Present Value	Average Cost
Widening Retrofit Conventional	$ 3.4 Million	$ 16.8 Million	$ 4.808/veh
Build It Once Conventional	$ 4.0 Million	$ 16.1 Million	$ 4.586/veh
Split	$ 5.0 Million	$ 15.0 Million	$ 4.262/veh

Note : This case is for Traffic Pattern B, 25% LT and 5% Growth Rate. 1986 US DOLLAR BASE

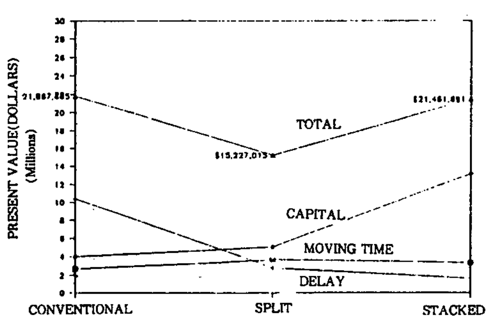
Among the three designs, capital cost for the first design is less than other designs, but average costs for this design are highest due to high delay costs during spillback of existing bridge, due to the construction periods, and due to spillback of even the enhanced design.

3. Consideration of Stacked Diamond Interchange

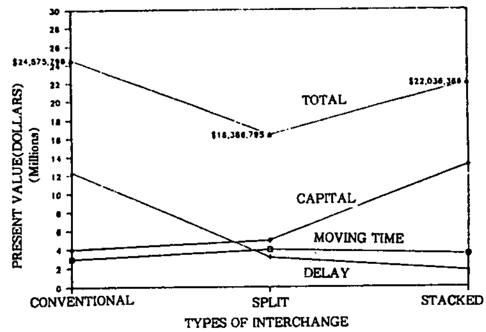
The stacked diamond is an extremely expensive design with a three−level structure. When this design is compared to other designs under low initial volumes, total present value of this "stacked diamond" design are always the highest among those of other design, due to high capital cost when the initial volume is low. When the initial volume is 1.6Vo, this design is better than the conventional on total present value basis, however, its total cost is still higher than that of the split diamond at any initial volume. Refer to Figure 12. Therefore, the stacked diamond is recommended at the design location where one expects high traffic growth and where the split diamond is not feasible, primary when rehabilitating or retrofitting within very constrained spaces.



(1) INITIAL VOLUME Vo



(2) INITIAL VOLUME 1.3Vo



(3) INITIAL VOLUME 1.6Vo

NOTE : TRAFFIC PATTERN A, 35% LEFT TURNS
CONVENTIONAL : CASE C8
SPLIT : CASE S3M
1986 US DOLLAR BASE

FIGURE 12. PRESENT VALUE OF THREE DESIGNS FOR DIFFERENT INITIAL VOLUME

Ⅶ. Conclusion

The life cycle model which was developed in this paper can be used for the purpose of evaluating the relative advantages of various diamond interchange designs. To be more specific, this model considers all cost elements related to interchange construction and operation, for specified annual demand level and traffic pattern. This model can estimate total present value over life cycle for each alternative configuration. Logical decisions on the choice of appropriate initial design can be better supported when appropriate. For the cases studied, the capital cost of the conventional diamond is typically about $4 million, but its total present value of life cycle costs is about $19 million. Under the same skinners, the split diamond typically produces about $5 million of capital cost and $16 million of total present value of life cycle costs. Thus, use of life cycle cost frequently results in a different selected design and a net saving of $3 million, expressed in present value, for an additional $1 million capital costs investment.

Further, the split diamond gets about 25 % more capacity and less sensitive to traffic patterns and sudden growth. Properly designed, it can also utilize inside land. The stacked diamond is extremely expensive design in capital cost. Therefore, it recommended only where the split diamond is not feasible.

The differences in alternatives selected in the various cases studied emphasize that the life cycle cost approach is efficient, powerful and essential tool.

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