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Life-Cycle Cost Analysis on Application of Asphalt and Concrete Pavement Overlay

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Abstract: Concrete pavement proportions are increasing in Korean expressways, resulting in increased maintenance cost. The length of degenerate concrete pavements that have exceeded the design life (20 years) was 1150 km in 2015 and 2605 km in 2020 and is expected to rapidly increase. To extend the service life of concrete pavements, life-cycle cost (LCC) analysis was conducted on asphalt and concrete overlays, based on the different maintenance methods. LCC analysis was performed when the shoulder was used and when it was not used between 6000 and 35,000 AADT traffic according to the two-lane and four-lane traffic. During overlay, one lane was completely blocked, and the value per vehicle was converted into the user cost using the Construction Analysis for Pavement Rehabilitation Strategies software, according to whether the shoulder was used to maintain the number of lanes. In addition, LCC analysis was conducted by examining the construction cost and life-cycle according to each overlay method. When the shoulder was used, the total construction cost decreased, owing to the reduction in user cost, indicating that the implementation of the traffic measure of using the road shoulder improves user satisfaction and cost. The asphalt overlay was observed to be more favorable than concrete overlay in terms of the initial total construction cost. However, under a 20-year cycle, the economic efficiency of concrete overlay was higher than that of asphalt overlay. After repairing the deteriorated target sections of concrete pavements, the overlay method (asphalt or concrete) ought to be selected according to the target service life for beneficial economic effect. Concrete overlay was to obtain about 20% or greater LCC effect compared to asphalt overlay, and at least 5% or more additional LCC effect obtained when the shoulder was used.

Keywords: concrete pavement; pavement rehabilitation; asphalt overlay; concrete overlay; traffic volume; traffic control; life-cycle cost (LCC)

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1. Introduction

Concrete pavements account for approximately 62% of expressway pavements in Korea, out of which 9783 km (97.5%) comprise jointed plain concrete pavements and 189 km (2.5%) comprise continuously reinforced concrete pavements [1–4].

The length of deteriorated concrete pavements that have exceeded the design life (20 years) was 1150 km in 2015 and 2605 km in 2020 and is expected to rapidly increase [5]. In the case of deteriorated concrete pavements, the application of sectional repair leads to an increased rate of early damage owing to the limited structural capability. Furthermore, the number of cases of repeated sectional repair is increasing.

In Korea, it is difficult to extend the service life of deteriorated aged concrete pavements only with sectional repair; extensive reinforcement measures are urgently required [4–6].

In Korea, the maintenance cost for road pavements was approximately KRW 1.2 trillion in 2020, approximately three times higher than that in 2010, which was approximately KRW 0.4 trillion. The maintenance cost for expressways was approximately KRW 650 billion in 2020, which represented 54% of the total maintenance cost for road pavements. Therefore, to minimize the maintenance cost, it is essential to apply the appropriate maintenance to expressway pavements [5–7].

The method of maintenance for concrete pavements in Korean expressways is determined according to the maintenance standards. Owing to the structural limitations of deteriorated concrete pavements, the application of overlay is required rather than sectional repair. However, according to the maintenance standards for expressway concrete pavements, only 100% asphalt overlay is recommended, whereas concrete overlay is not considered [5]. Asphalt overlay is preferred over concrete overlay because it requires lower construction cost, time, and curing period; thus, the traffic blocking time can be reduced. The cost of pavement construction encompasses the costs of construction equipment, material acquisition, design, maintenance and rehabilitation strategies, and operation throughout the service life [8]. The construction, maintenance, restoration, rehabilitation, and reconstruction of new roads, and the preservation of aged pavement, require enormous volumes of materials and nonrenewable energy sources, which exert excessive cost demands that impact the economy [9]. A life-cycle cost (LCC) analysis includes all the phases, starting from materials procurement, through design production, construction, maintenance, restoration, transportation, costs in the work zone, and recycling [10]. LCC analysis is a method based on principles of economic analysis that improves the estimation of the total long-term economic viability of different investment options and finds significant application in pavement management. The LCC analysis method finds significant application in pavement design and management [11–13]. LCC analysis has received increasing attention as a tool that facilitates decision making by transportation agencies toward beneficial economical investments [8]. In developed countries, for the design and maintenance of infrastructures highways, pavements LCC analysis is a reliable approach. The usage of LCC analysis is in selecting the least expensive pavement structure; the sustainability of the nation's highways can be enhanced by minimizing the life-cycle cost of pavements [14–16]. A detailed LCC analysis of concrete and asphalt roads revealed that concrete roads are 20% more economical than bituminous roads over a 30-year analysis period [17].

In Korea, many construction methods have been developed for concrete overlay through research. Visual inspection data on national highways in Korea were used and information about the road section and structural characteristics, location, number of lanes, average traffic (AADT), etc., was collected to estimate the parameters of the exponential hazard function [18]. High-early-strength slag cement was used in the overlay concrete to minimize the traffic blocking time and the concrete overlay showed good performance for one year [19]. To achieve the effective repairs of aged and deteriorated concrete pavements, various overlay methods have been developed, and the most effective type of overlay is necessary to analyze the performance of overlay pavement sections [20]. The non-cutting asphalt overlay could reduce the LCC by 18 to 25% when applying the cutting asphalt overlay and the non-cutting asphalt overlay through economic analysis [6]. Permanent deformation is one of the major destructions which is related to load and which affect the functions of asphalt pavements [21]. Permanent deformation is one of the main reasons because of which pavement depressions happen [22]. However, concrete overlay is applied only to test pavements. Thus, it is necessary to improve the awareness of the application of concrete overlay in the context of Korean expressways.

During overlay in Korea, the lane under construction is typically blocked completely. This causes a reduction in vehicle speed owing to the concentration of traffic in unblocked lanes, which leads to the dissatisfaction of road users [23,24]. Therefore, traffic operation measures that can improve the satisfaction of road users are required during the application of overlay.

This study aimed to examine the applicability of asphalt and concrete overlays through LCC analysis. The value per vehicle in roads with traffic blocking because of overlay was converted into user cost using the Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) software after identifying the number of lanes, traffic volume, and availability of shoulder in Korean expressways. When the shoulder was used, a reduction in user cost was also confirmed. The construction costs of asphalt and concrete overlays were calculated, and the life-cycle of each overlay method was identified from the existing literature. Finally, LCC analysis was conducted by applying the user costs, construction costs, and life-cycles of asphalt and concrete overlays.

2. Method

Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) software was used for this study. CA4PRS software tool helps to select the best construction schedules and minimize traffic delay and agency costs for high-volume highway rehabilitation and reconstruction projects. In this study, user costs were calculated by converting the value of vehicles per hour according to traffic blocking [25]. User cost means the amount converted to the value of the vehicle per hour [25], and the vehicle's speed is lowered depending on the traffic blockage and blocking period. According to the traffic block, the moving speed of the vehicle is lowered and the moving distance per hour of the vehicle is reduced, so the user cost increases. In order to apply the overlay, the user cost was analyzed when the vehicle speed decreased due to the concentration of traffic and the lane was blocked. Economic analysis and long-term life were performed by applying each overlaying method's construction cost and life-cycle. The value per vehicle under traffic congestion caused by lane blocking was converted to user cost for LCC analysis. The construction costs of asphalt and concrete overlays were applied using the "cost by maintenance work" and "pavement maintenance cost" of Korea Expressway Corporation. In this study, the effects of the traffic volume and repair length on the user cost, analysis of user cost according to the number of lanes, calculation of overlay construction cost, total overlay construction cost, total construction cost of overlay using the shoulder and economic analysis were analyzed.

3. Analysis and Results

3.1. User Cost

3.1.1. Effects of Traffic Volume and Repair Length on User Cost

The value per vehicle under traffic congestion caused by lane blocking was converted to user cost for LCC analysis. During asphalt overlay after blocking one lane, traffic volumes of 15,000, 25,000, and 35,000 annual average daily traffic (AADT) were considered. The repair length ranged from 0.3 km, which is the minimum length for the application of concrete pavement overlay by the Korea Expressway Corporation (EX), to 15.0 km, which is assumed to be the repair length from one interchange (IC) to another on expressways.

The LCC analysis was conducted for the traffic volume and the repair length, as shown in Figure 1. The analysis results showed that the user cost tended to increase as the traffic volume and repair length increased. The increased rate of the user cost, however, was higher with respect to the increase in traffic volume than with that of the increase in repair length. Cost saving will be possible when smooth traffic flow is achieved by distributing the concentrated traffic caused by traffic blocking. Traffic distribution will be possible if the number of lanes is maintained using the lane shoulders.

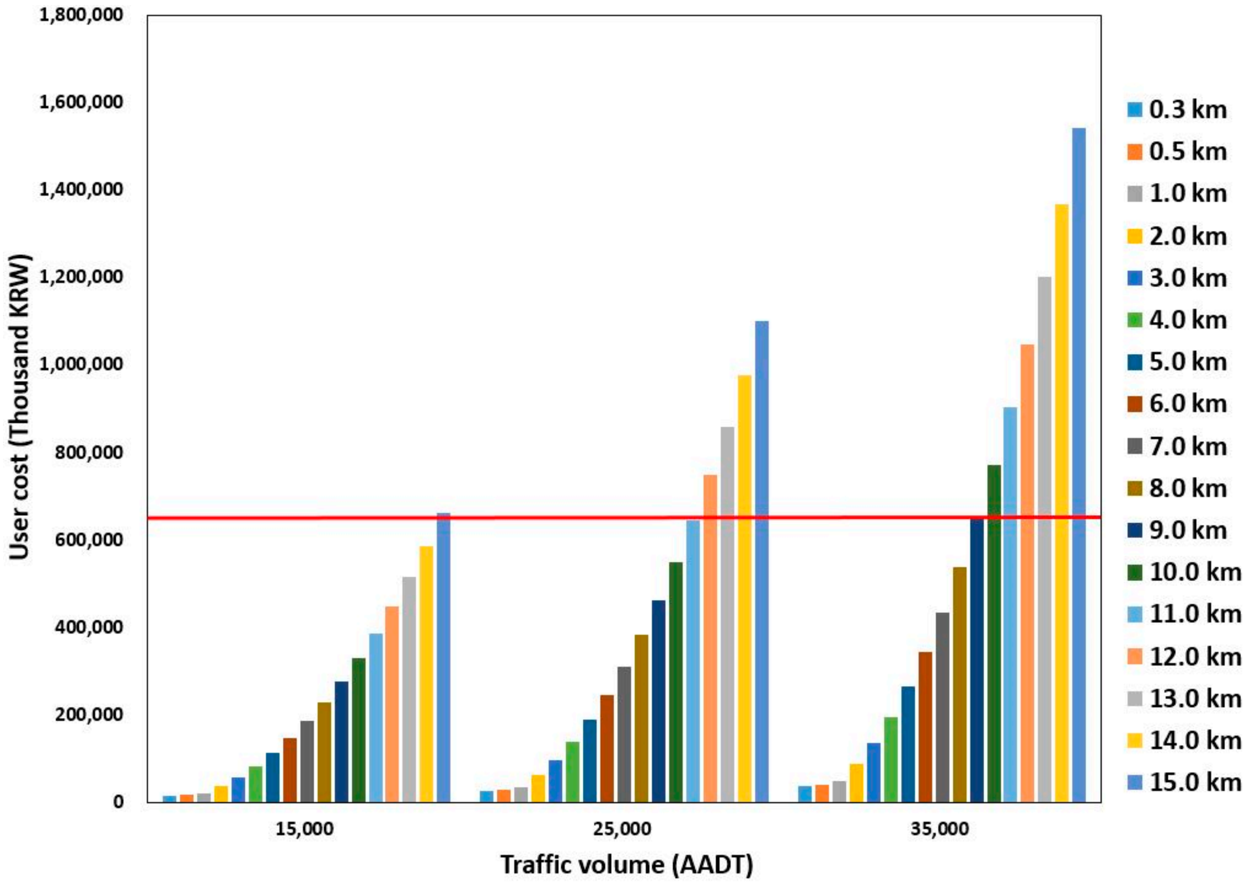


Figure 1. Relationship between traffic volume and user cost maintenance.

3.1.2. Analysis of User Cost According to the Number of Lanes

The AADT of two- and four-lane expressways was examined and applied, and the method of completely blocking one lane was applied. The user cost according to whether the shoulder was used or not was analyzed under the construction of asphalt and concrete overlays by applying the appropriate road-blocking period, as shown in Table 1. For asphalt overlay, 2 days/km for cutting and cleaning, 1 day/km for asphalt laying, and 8 h (22:00–06:00) for curing were applied. For concrete overlay, 2 days/km for cutting and cleaning, 2 days/km for concrete laying, and 3 days for curing were applied.

Table 1. Variables applied to user cost (complete blocking).

Method	Non-Reimbursable			Remuneration				
	Number of Lanes		Speed	Number of Lanes	Speed	Blocking Day	Bypass Rate	
Asphalt Overlay	2 lanes 4 lanes	2 4	100 km/h	2 lanes 4 lanes	1 3	60 km/h	1 km road/3 days + 8 h	10%
Concrete Overlay	2 lanes 4 lanes	2 4	100 km/h	2 lanes 4 lanes	1 3	60 km/h	1 km road/5 days	10%

With respect to the variables for the analysis of the user cost, the vehicle speed before construction, based on two lanes, was assumed to be 100 km/h; the vehicle speed in one lane was assumed to be 60 km/h; and during the complete blocking of one lane, the detour rate was considered as 10%, as shown in Table 1. In four lanes, the vehicle speed before construction was assumed to be 100 km/h; the vehicle speed in three lanes was assumed to be 60 km/h; and during the blocking of one lane, the detour rate was considered as 10%.

1. Case 1—User cost under the application of overlay for two lanes: The traffic volume of two-lane expressways was identified by examining the pavement management system (PMS) data. For the identified traffic volume ranging from 4000 to 11,000 AADT, 6000 and 11,000 AADT were applied for analysis.
2. Case 2—User cost under the application of overlay for four lanes: The traffic volume of four-lane expressways was identified by examining the PMS data. For the identified traffic volume ranging from 15,000 to 35,000 AADT, 15,000, 25,000, and 35,000 AADT were applied for the analysis.

In case 1, Figure 2 shows the user cost analyzed under the traffic volume of 6000 AADT. The user cost of asphalt and concrete overlay tended to increase as the length increased. The user cost of concrete overlay, however, increased more rapidly than that of asphalt overlay as the length increased. Compared to the user cost for the minimum repair length of 0.3 km, the user cost for the maximum length of 15.0 km increased by approximately 3970 and 3640% for concrete and asphalt overlays, respectively. Concrete overlay exhibited approximately 340% higher user cost than asphalt overlay. Figure 3 shows the user cost result of 11,000 AADT for two lanes.

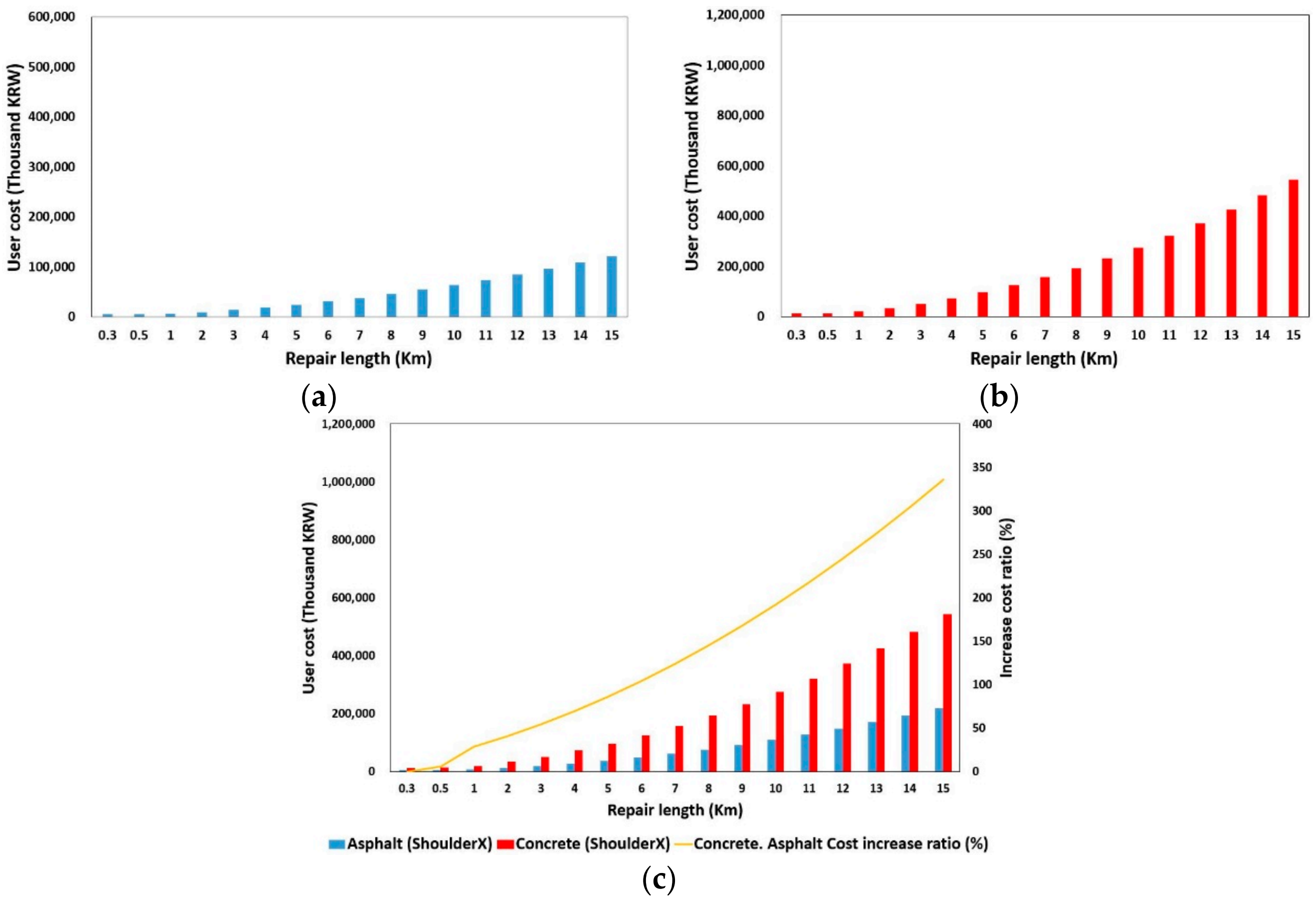
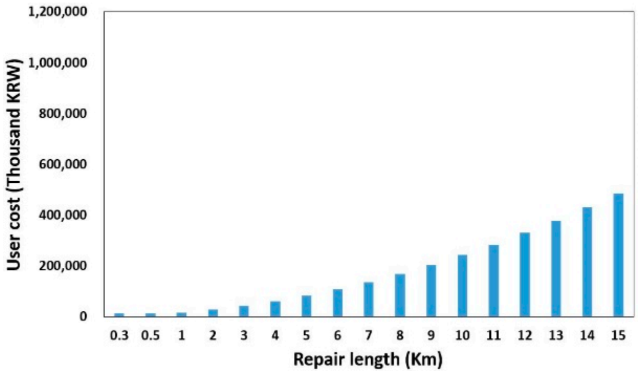


Figure 2. User cost comparison (Shoulder X, 6000 AADT). (**a**) Asphalt overlay user cost (Shoulder X). (**b**) Concrete overlay user cost (Shoulder X). (**c**) Comparison of overlay user cost (Shoulder X).



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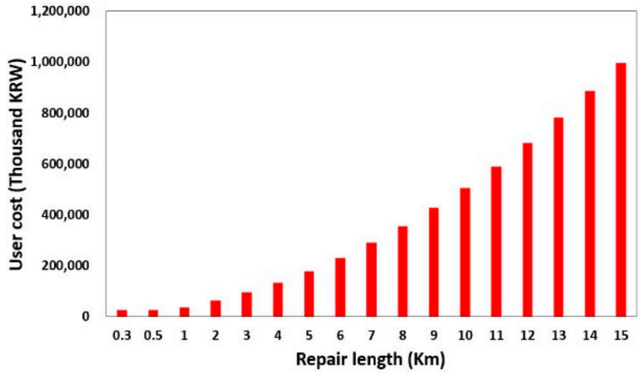

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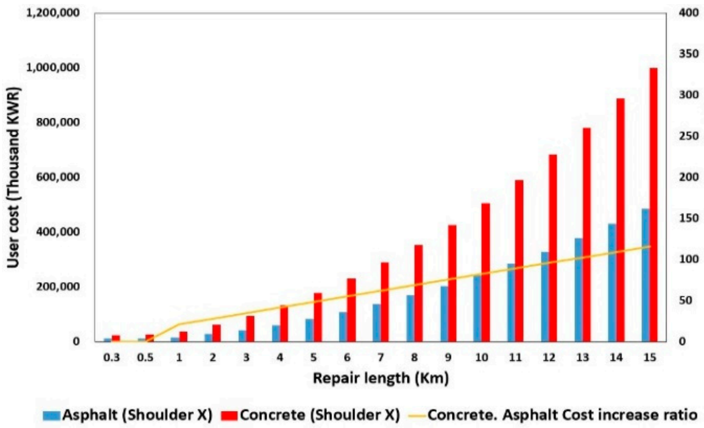

(**c**)

Figure 3. User cost comparison (Shoulder X, 11,000 AADT). (**a**) Asphalt overlay user cost (Shoulder X). (**b**) Concrete overlay user cost (Shoulder X). (**c**) Comparison of overlay user cost (Shoulder X).

The user cost for 6000 AADT tended to increase with increasing repair length, and the user cost increase rate of concrete overlay was higher than that of asphalt overlay. The user cost increase rate for a repair length of 15.0 km, compared to 0.3 km, was approximately 3970 and 3850% for concrete and asphalt overlays, respectively, indicating that the difference was approximately 116%. The difference in user cost increase rate, with respect to the minimum repair length, between asphalt and concrete overlays decreased as the traffic volume increased, despite the increase in user cost. The user cost was observed to be sensitive to the traffic volume, and measures for smooth traffic flow under traffic blocking ought to be implemented.

In Case 2, Figure 4 shows the user cost was analyzed under the traffic volume of 15,000 AADT. For four lanes, the user cost also tended to increase for increasing repair length. The difference in cost increase rate for 15.0 km, with respect to the minimum repair length of 0.3 km, between the concrete and asphalt overlays was approximately 116% (similar to the first case). For the traffic volume of approximately 10,000 AADT or higher, the user cost increase rates of concrete and asphalt overlays were observed to be similar, although the user cost increased as the traffic volume and repair length increased.

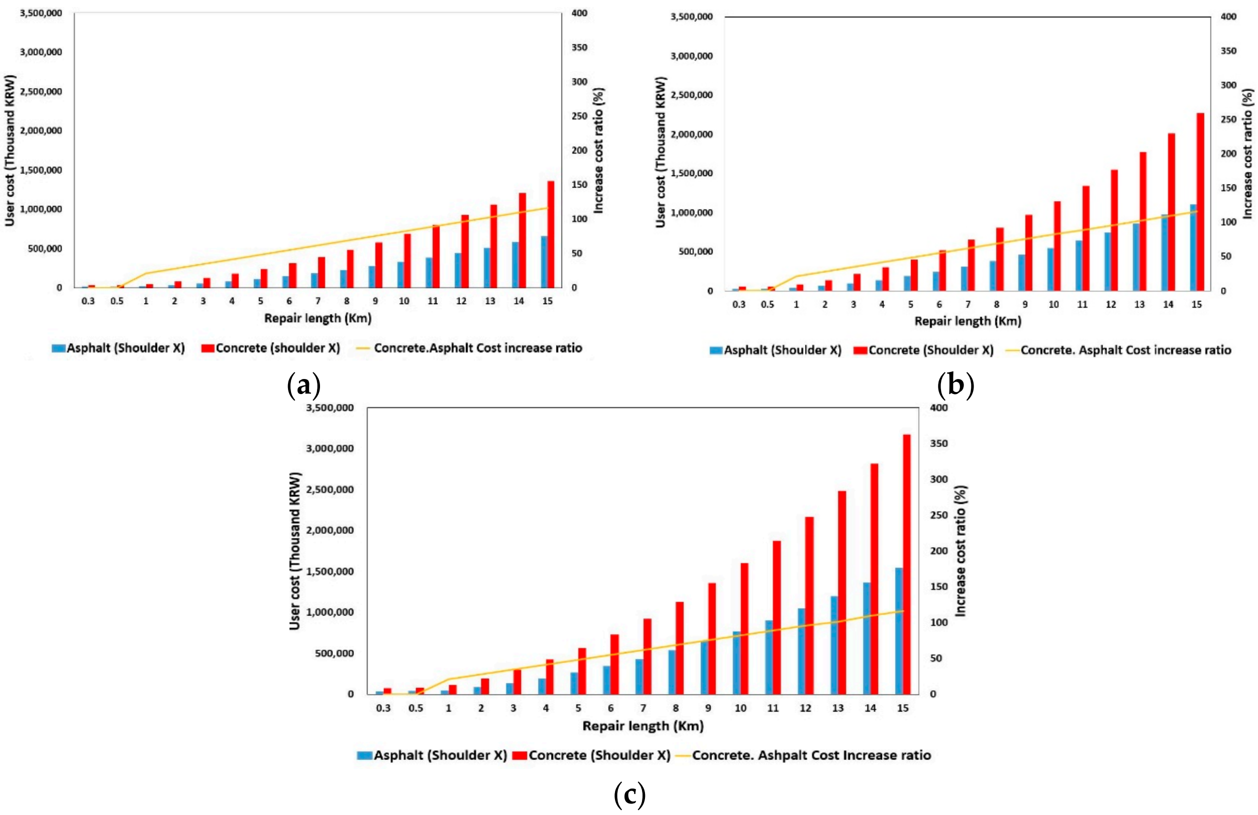

Figure 4. User cost comparison (Shoulder X, 11,000 AADT). (**a**) 15,000 AADT user cost (Shoulder X). (**b**) 25,000 AADT user cost (Shoulder X). (**c**) 35,000 AADT user cost (Shoulder X).

3.2. Calculation of Overlay Construction Cost

The construction costs of asphalt and concrete overlays were applied using the "cost by maintenance work" and "pavement maintenance cost" of the Korea Expressway Corporation. The calculated costs were 180,000,000 and 250,000,000 KRW/km for asphalt and concrete overlays, respectively. Figure 5 show the construction cost by repair length of asphalt and concrete pavement.

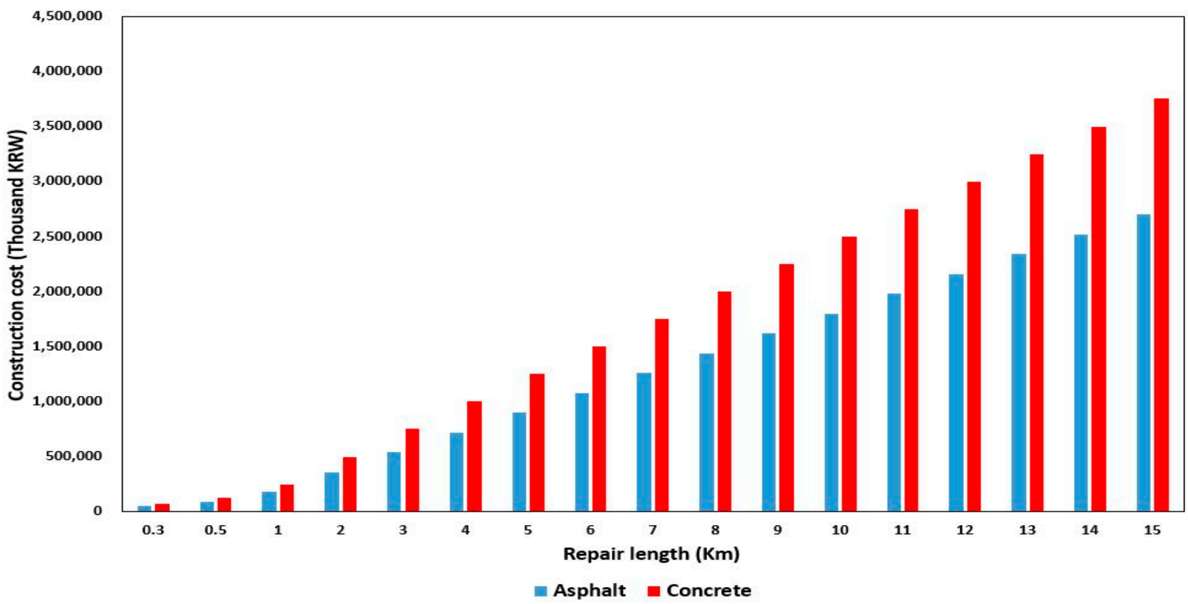

Figure 5. The construction cost by repair length.

3.3. Total Overlay Construction Cost

The total construction cost was calculated by adding the user cost and construction cost according to the traffic volume and the number of lanes. Figures 6 and 7 show the results for two and four lanes.

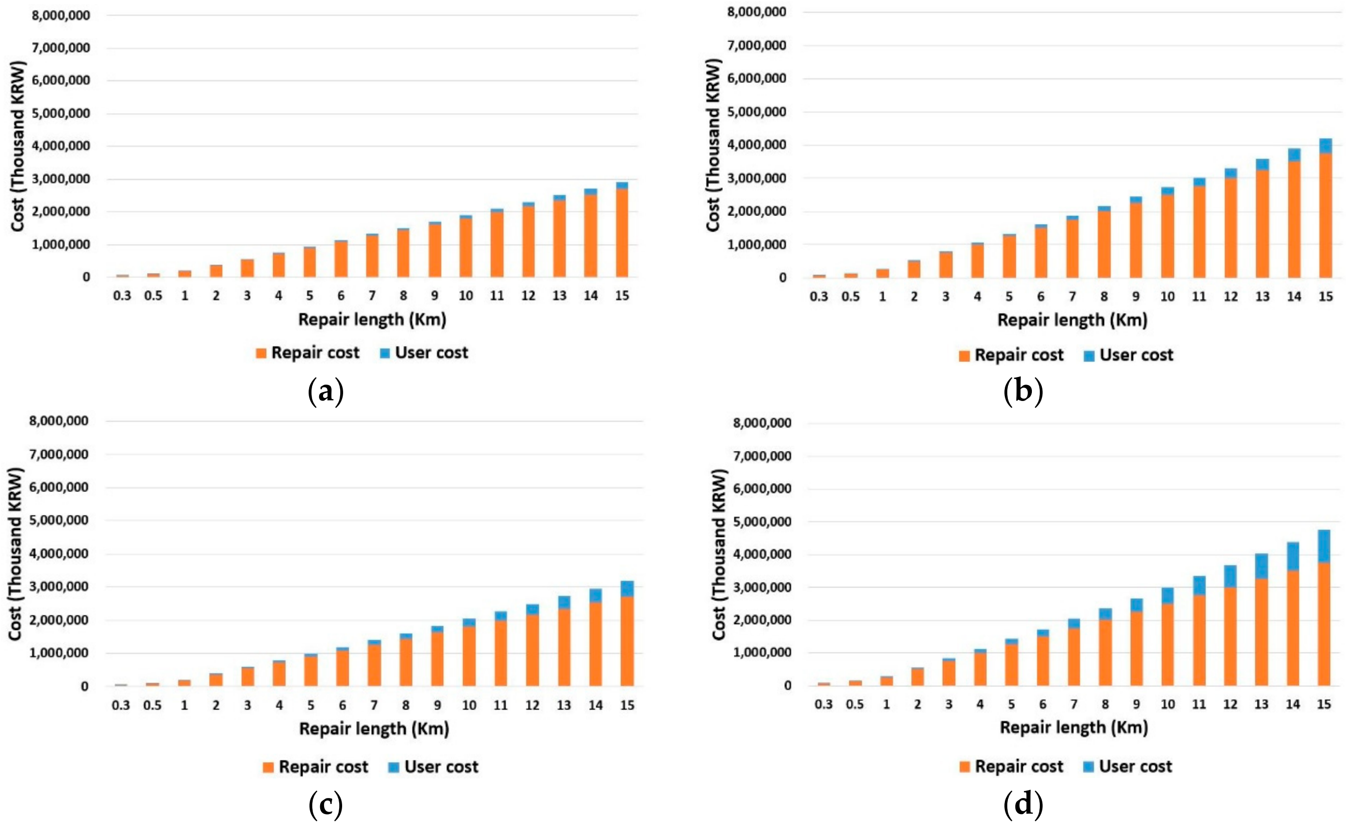

Figure 6. Total overlay Construction Cost (Lane 2). (**a**) Total cost of asphalt overlay (2-lane, shoulder road X, 6000 AADT). (**b**) Concrete Overlay Total Construction Cost (2-lane, shoulder road X, 6000 AADT). (**c**) Asphalt Overlay Total Construction Cost (2-lane, shoulder road X, 11,000 AADT). (**d**) Concrete Overlay Total Construction Cost (2-lane, shoulder road X, 11,000 AADT).

The total construction cost tended to increase with increasing repair length. When the total construction cost was divided into the construction and user cost, it rapidly increased as the traffic volume increased. For concrete overlay, under the largest traffic volume of 35,000 AADT for four lanes, the user and construction costs were similar at 15.0 km, thereby confirming the high total construction cost. As the construction cost was fixed, measures for smooth traffic flow ought to be implemented to reduce the total construction cost of overlay. Measures to maintain the number of lanes using the shoulder ought to be implemented.

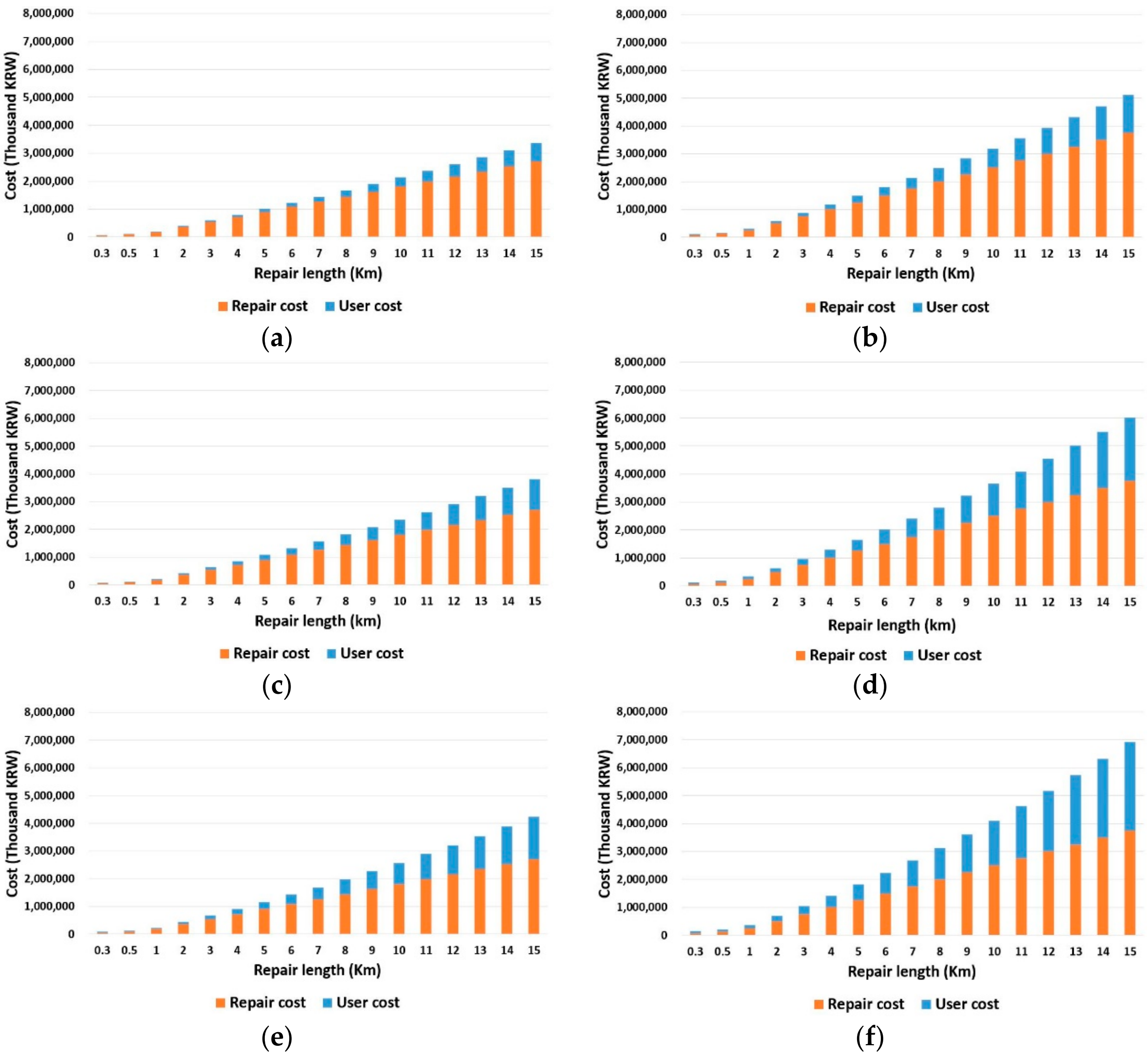

Figure 7. Total Overlay Construction Cost (4-lane). (**a**) Asphalt Overlay Total Construction Cost (4-lane, shoulder road X, 15,000 AADT). (**b**) Concrete Overlay Total Construction Cost (4-lane, shoulder road X, 15,000 AADT). (**c**) Asphalt Overlay Total Construction Cost (4-lane, shoulder X, 25,000 AADT). (**d**) Concrete Overlay Total Construction Cost (4-lane, shoulder X, 25,000 AADT). (**e**) Asphalt Overlay Total Construction Cost (4-lane, shoulder road X, 35,000 AADT). (**f**) Concrete Overlay Total Construction Cost (4-lane, shoulder road X, 35,000 AADT).

3.4. Total Construction Cost of Overlay Using the Shoulder

To save the total construction cost, cost reduction by maintaining the number of lanes using the road shoulders was examined. Table 2 shows the variables that use the road shoulder.

The existing lane width was reduced and the number of lanes before traffic blocking was maintained using the shoulder. A traveling speed of 80 km/h was selected to be caused by the lane width reduction, and a detour rate of 5% was applied owing to the relatively smooth traffic flow. Figure 8 shows the cost saved by using the road shoulder.

Table 2. Variables applied to user cost (use of shoulder).

Method	Non-Reimbursable			Remuneration				
	Number of Lanes		Speed	Number of Lanes		Speed	Blocking Day	Bypass Rate
Asphalt Overlay	2 lanes 4 lanes	2 4	100 km/h	2 lanes 4 lanes	1 3	60 km/h	1 km road/3 days + 8 h	10%
Concrete Overlay	2 lanes 4 lanes	2 4	100 km/h	2 lanes 4 lanes	1 3	60 km/h	1 km road/5 days	10%

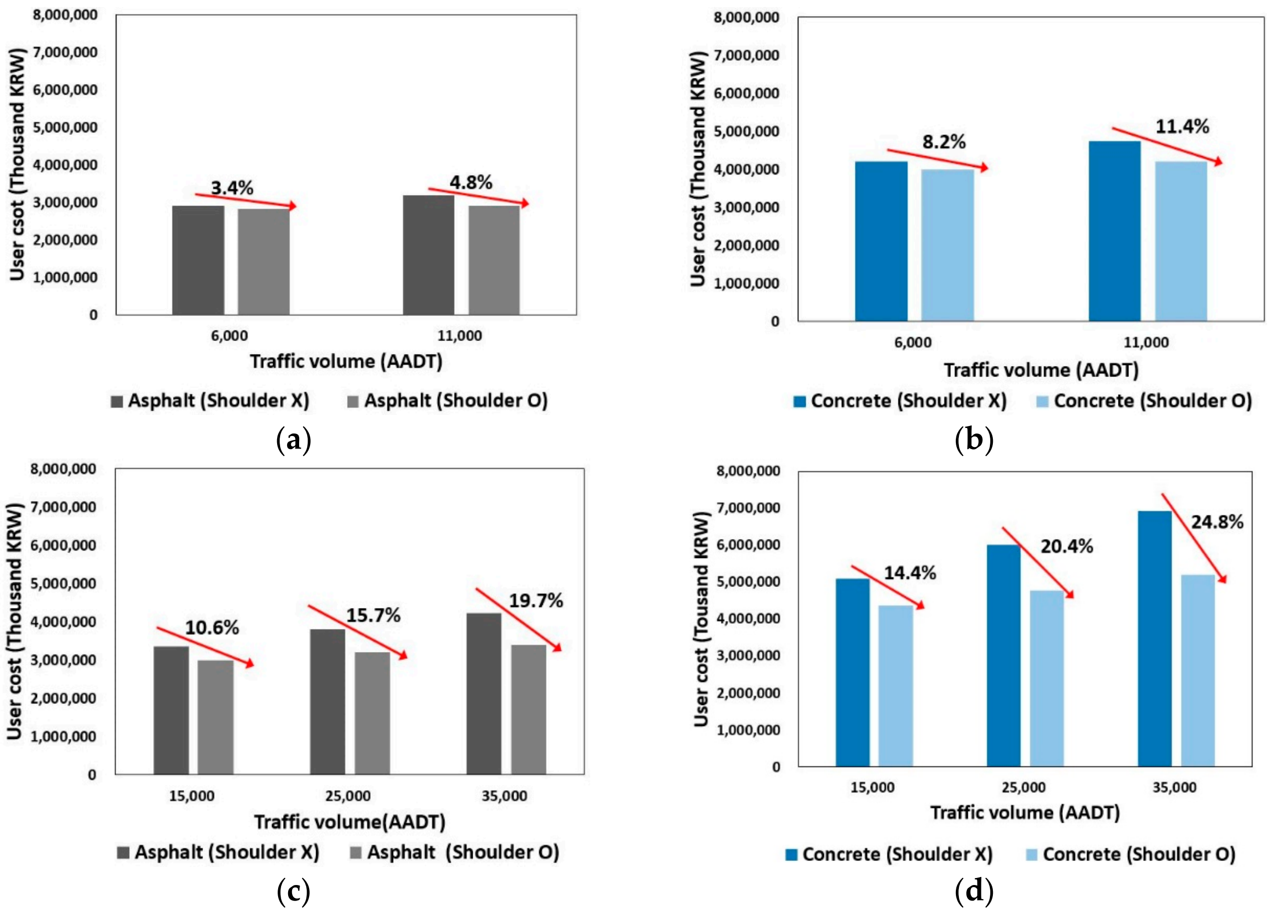

Figure 8. Comparison of the total construction cost of overlay using the shoulder. (**a**) Comparison of total construction user cost using asphalt overlay shoulder (lane 2). (**b**) Comparison of total construction user cost using concrete overlay shoulder (lane 2). (**c**) Comparison of total construction user cost using asphalt overlaid shoulder (lane 4). (**d**) Comparison of total construction user cost using concrete overlaid shoulder (lane 4).

The total construction costs of asphalt and concrete overlays before and after using the shoulder for two and four lanes were compared based at 15.0 km. When the shoulder was used, the total construction cost was reduced by up to 19.7 and 24.8% for asphalt and concrete overlays, respectively. The total construction cost reduction rate of concrete overlay was higher than that of asphalt overlay. However, the total construction cost of asphalt overlay was lower. Asphalt overlay was observed to be more favorable than concrete overlay in terms of the initial construction cost. Economic analysis through LCC analysis is thus essential for each method.

3.5. Economic Analysis

Table 3 shows the results of analyzing Korean expressway PMS data for asphalt overlay. The life-cycle of asphalt overlay was found to be 5.5 years [2]. For concrete overlay, overseas data were examined because of an insufficient number of cases of implementation in Korea, and the life-cycle was found to be 11.0 years [26].

Table 3. Overlay life-cycle.

Method	Life-Cycle
Asphalt overlay	5.5 years
Concrete overlay	11.0 years

These life-cycles of asphalt and concrete overlays were applied, and the economic analysis was conducted for a 20-year cycle, considering long-term performance. Figures 9 and 10 show the results of the economic analysis for each overlay method according to the traffic volumes of two and four lanes for 15.0 km.

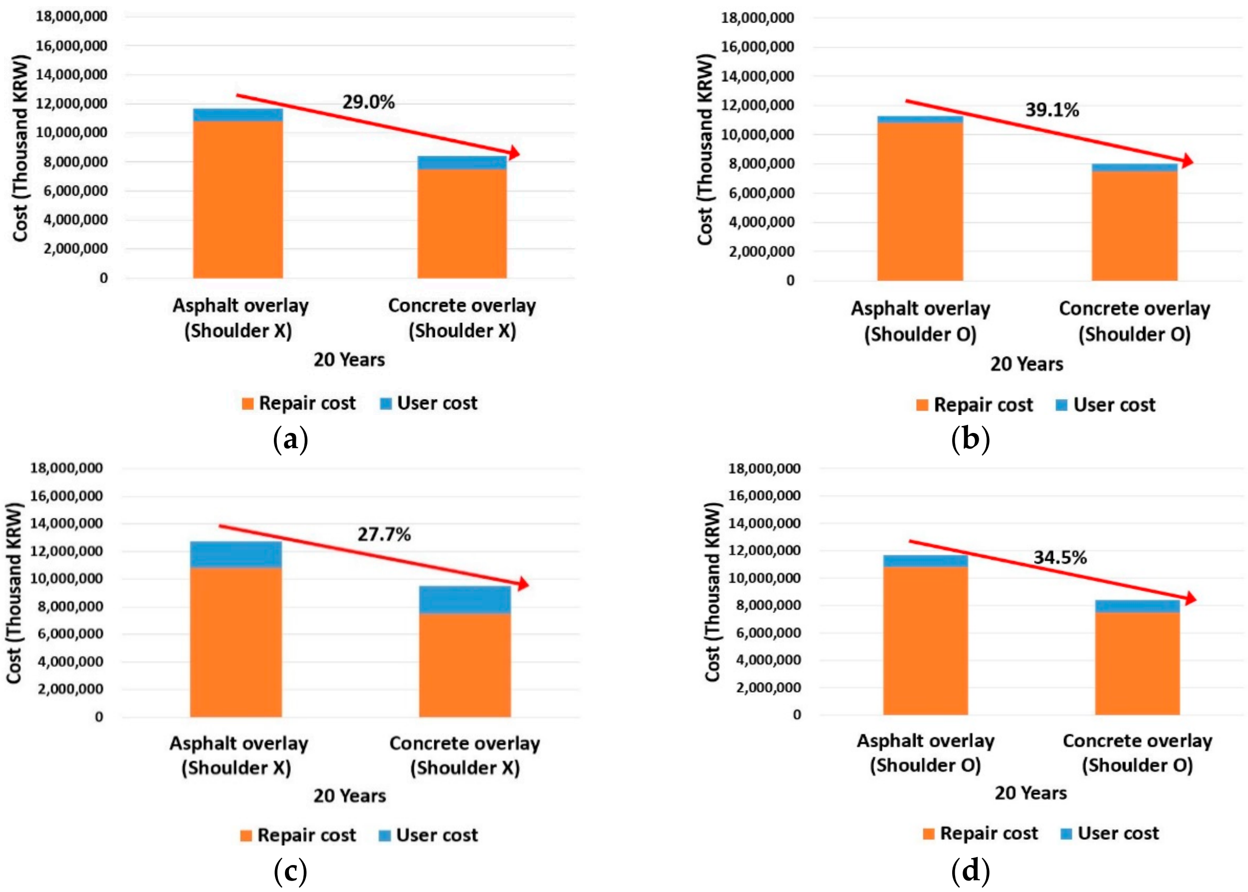

Figure 9. Economic analysis by 2-lane overlay method. (**a**) 2-lane 6000 AADT overlay economical (Shoulder X). (**b**) 2-lane 6000 AADT overlay economical (Shoulder O). (**c**) 2-lane 11,000 AADT overlay economical (Shoulder X). (**d**) 2-lane 11,000 AADT overlay economical (shoulder O).

For two and four lanes under the 20-year cycle, the economic efficiency of concrete overlay was found to be higher than that of asphalt overlay, considering the long-term service life. When shoulder was used, the economic efficiency of concrete overlay could be further improved. The economic efficiency of concrete overlay compared to asphalt overlay according to the number of lanes and traffic volume is summarized in Table 4.

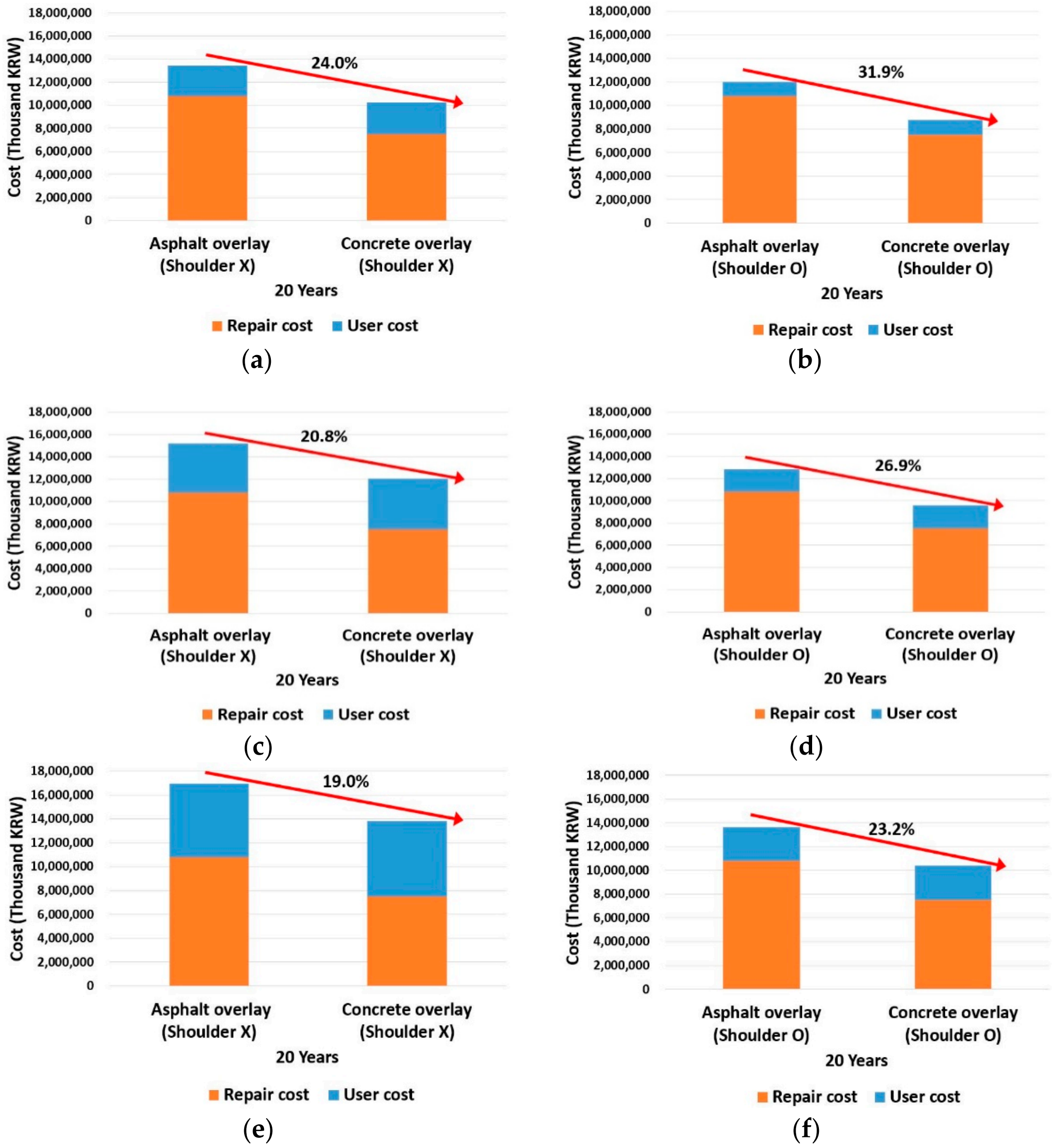

Figure 10. Economic analysis by 4-lane overlay method. (**a**) 4-lane 15,000 AADT Overlay Economical (Shoulder X). (**b**) 4-lane 15,000 AADT Overlay Economical (Shoulder O). (**c**) 4-lane 25,000 AADT Overlay Economical (Shoulder X). (**d**) 4-lane 25,000 AADT Overlay Economical (Shoulder O). (**e**) 4-lane 35,000 AADT Overlay Economical (Shoulder X). (**f**) 4-lane 35,000 AADT Overlay Economical (Shoulder O).

Table 4. Concrete Overlay Economic Efficiency.

Method	Number of Lanes	Traffic Volume (AADT)	Shoulder Use	Cost Difference (%)
Concrete Overlay	2	6000	X	29.0
		6000	O	39.1
		11,000	X	27.7
		11,000	O	34.5
	4	15,000	X	24.0
		15,000	O	31.9
		25,000	X	20.8
		25,000	O	26.9
		35,000	X	19.0
		35,000	O	23.2

A detailed LCC analysis of concrete and asphalt roads revealed that concrete roads are 20% more economical than bituminous roads over a 30-year analysis period [17] and from this study the economic efficiency of concrete overlay was at least 23.2% higher than that of asphalt overlay, depending on the utilization of the shoulder under the 20-year cycle. For the LCC analysis of cut asphalt overlay and non-cut asphalt, the LCC of non-cut asphalt overlay is effective [6], and considering the concrete overlay, long-term LCC can be obtained.

4. Conclusions

In this study, LCC analysis was conducted to examine the applicability of asphalt and concrete overlays for the maintenance of deteriorated concrete pavements on Korean expressways. In addition, construction and user costs were examined with and without a traffic operation measure that uses the road shoulder to maintain the number of lanes under the complete blocking of one lane for overlay application. The conclusions are as follows:

(1) The user cost tended to increase for increasing traffic volume and repair length. The cost increase rate was higher with respect to traffic volume than with respect to repair length, indicating that the application of traffic operation measures is essential for minimizing the dissatisfaction of road users and reduces the cost.
(2) When the shoulder was used for smooth traffic flow, the total construction cost tended to decrease. It was reduced by up to 19.7 and 24.8% for asphalt and concrete overlays, respectively. The economic efficiency is expected to improve through increasing the number of lanes by using the shoulder to distribute the concentrated traffic, rather than utilizing only the unblocked lanes after completely blocking a lane.
(3) When the shoulder was utilized, the LCC analysis results showed cost reductions in both asphalt and concrete overlay. The analysis results before and after the use of the shoulder indicate that the economic efficiency of concrete overlay is higher than that of asphalt overlay.
(4) The initial construction cost of asphalt overlay was found to be lower than that of concrete overlay. However, in the long-term, for a 20-year cycle, the economic efficiency of concrete overlay was found to be higher than that of asphalt overlay. Concrete overlay is expected to be more favorable than asphalt overlay from an economic perspective for increasing repair length.
(5) The LCC analysis results for these overlay methods showed that the overlay method (asphalt or concrete) ought to be selected according to the target service life after repairing the deteriorated target sections of concrete pavements for beneficial economic effect.

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