Reducing Congestion with Low-Clearance Underpasses at Urban Intersections: Investigation and Case Study

LOW-CLEARANCE UNDERPASSES CAN REDUCE TRAFFIC CONGESTION AT INTERSECTIONS WHERE OTHER ALTERNATIVES HAVE BEEN EXHAUSTED. FOUR SUCH UNDERPASSES ALONG A CONGESTED ARTERIAL IN HONOLULU, HI, USA, WERE MODELED WITH INTEGRATION. RESULTS SHOWED THAT LOW-CLEARANCE UNDERPASSES WOULD BE SIGNIFICANTLY LESS EXPENSIVE COMPARED WITH STANDARD UNDERPASSES.

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GRADE SEPARATION AT URBAN INTERSECTIONS

Some urban intersections are so severely congested that no further improvement is possible with at-grade traffic management measures. However, grade separation (underpasses or overpasses) at intersections usually is ignored as a congestion countermeasure despite the long list of potential benefits. These benefits include:[1–5]

- Uninterrupted access that benefits traffic and emergency vehicles;
- Higher capacity for current and future traffic demand;
- Smoother traffic flow;
- Reduced crashes;
- Reduced vehicle delay, resulting in time and fuel savings and pollution reduction; and
- Potentially lower maintenance and liability costs compared with signalized intersections.

Low-clearance (or substandard) grade-separated facilities reduce the size of grade-separated structures and are more suitable for dense urban environments.[6] Based on European experience, the limited height of low-clearance underpasses has not been a major problem.[7] Common factors influencing the design of and rationale for providing low-clearance facilities include the avoidance of land acquisition, the condemnation of new lanes and the associated cost savings.[8]

These considerations have led a number of major cities, including Amsterdam, The Netherlands; Boston, MA, USA; Madrid, Spain; Melbourne, Australia; Paris, France; and Singapore, Republic of Singapore, to implement underpasses or tunnels to reduce noise and emissions at street levels and allow traffic to bypass congested areas.[9]

In both the 1994 and the 2001 editions of *A Policy on Geometric Design of Highways and Streets*, the section on urban arterials specifies that: "New or reconstructed structures should provide 4.9 m clearance over the entire roadway width. Existing structures that provide 4.3 m clearance, if allowed by local statute, may be retained."[10]

Underpasses with a 2.4-meter (m) height clearance are restrictive. However, they can serve all passenger cars, vans and sport utility vehicles and offer the required 0.3-m, or 1-foot (ft.), margin of safety for future resurfacing or pavement debris.

However, a number of large passenger and freight vehicles cannot use low-clearance underpasses. These include some minibuses and urban transit buses, all panoramic and double-decked buses and all trucks (except for empty flatbed trucks).

Typically, the proportion of large vehicles on urban arterials is small, as in the case of the study area presented in this feature (see Table 1). If low-clearance underpasses are designed, at-grade through lanes or alternative routes must be provided for large freight and passenger vehicles, as shown in Figure 1.

The research presented in this feature focused on low-clearance underpasses because of their compact size and lower cost. The results showed that, specifically, a two-lane, low-clearance underpass under a six-lane arterial street with 5-percent grade approaches on both sides would be shorter by about 96 m (320 ft.), or 39 percent, compared with a standard underpass.

In addition, according to Table 2, a low-clearance underpass would be considerably less expensive to construct than a standard underpass: approximately $4.8 million versus $7.8 million.

CASE STUDY METHODOLOGY

A case study was conducted to analyze the benefits of implementing low-clearance grade separations at four key intersections along a congested arterial network in Honolulu, HI, USA. Separate base case network models were built for weekday morning and weekday evening conditions. Then, four congested intersections were modified by inserting underpasses. The results enabled comparisons of the network with and without grade separations. The main elements of the methodology were:

- Traffic simulation model selection;
- Network representation;
- Base network modeling;
- Modeling the network with four underpasses;
- Large vehicle modeling;
- Signal timings and phasing modeling; and
- Approximate evaluation of construction costs and benefits.

Table 1. Vehicle classification survey in Waikiki, HI, USA.

Vehicle class	Morning peak	Large vehicles (morning)	Afternoon peak	Large vehicles (afternoon)
Motorcycle	0 percent		1 percent	
Taxi	6 percent		9 percent	
Passenger car	76 percent		80 percent	
Pick-up truck	5 percent		4 percent	
Single-unit truck	4 percent	4 percent	1 percent	1 percent
Semi-trailer truck	0 percent	0 percent	0 percent	0 percent
Tour shuttle/tour van	5 percent		2 percent	
Tour bus	2 percent	2 percent	2 percent	2 percent
Public bus	2 percent	2 percent	1 percent	1 percent
Total	**100 percent**	**8 percent**	**100 percent**	**4 percent**

SOURCE: Kaku Associates. *Waikiki Regional Traffic Impact Plan: Summary Report*. City and County of Honolulu, HI, USA, Department of Transportation, December 1995.

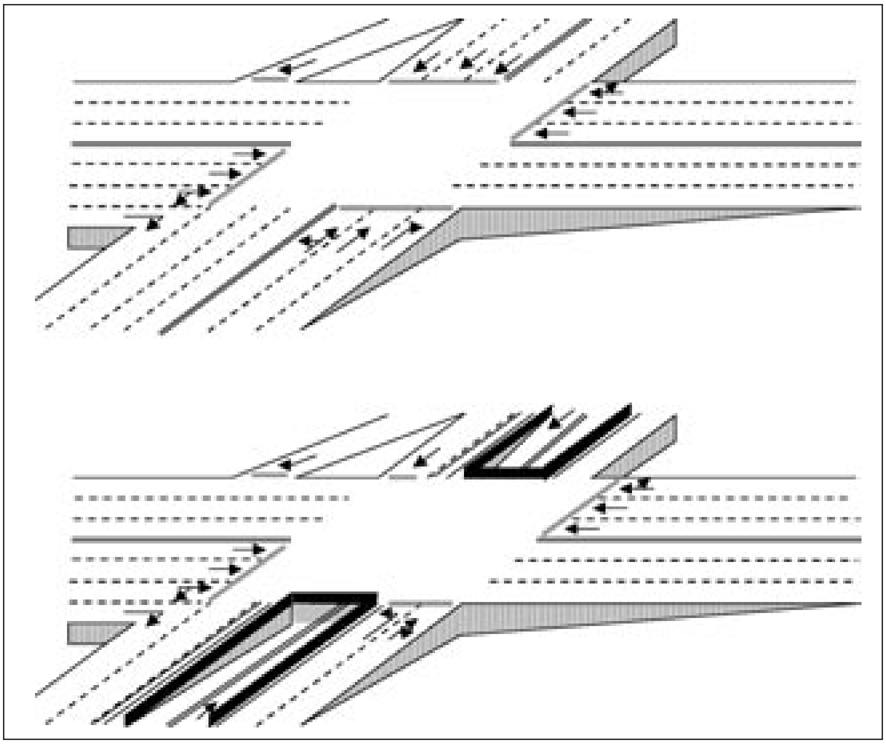

Figure 1. At-grade intersection and prototype low-clearance underpass.

The analysis of grade separations was conducted using the integration traffic simulation model. This model was used primarily due to its flexibility in assigning origin-destination volumes and signal timings; ease of movement restrictions for specific types of vehicles, such as large vehicles that cannot use low-clearance underpasses; and prior successful use in Honolulu.[11]

The two main arterial routes in the network were Kapiolani Boulevard and Atkinson Drive. Figure 2 shows these two routes along with the locations of the four proposed underpasses. Although the analyzed network did not include all of the cross streets in the area, it was determined that several secondary cross streets were not key to model integrity. (All but two of the cross streets were unsignalized; the other two were low-volume, minor street T-intersections.)

Important secondary intersections of the subject route with University Avenue and Kona Street (which provides access to the convention center's parking and loading docks) were included to ensure realistic delays due to cross street traffic signals. Figure 2 also shows the network system with data from peak evening conditions.

The total network length was 34 kilometers (21.1 miles). The total traffic traveling through the network was 13,800 vehicles per hour (vph) for the morning peak period and close to 15,000 vph for the evening peak period.

The objective was to simulate existing traffic conditions network-wide and compare the simulation results of the models designed with underpasses inserted at four intersections. Morning (7:00 a.m. to 9:00 a.m.) and evening (3:30 p.m. to 6:00 p.m.) base cases were developed. Both were modeled with data from midweek days. The morning and evening systems were dissimilar with respect to signalization phasing and timing, lane usage, turn prohibitions and traffic demand.

The volumes by origin and destination were taken from the Waikiki Regional Traffic Impact Plan and the

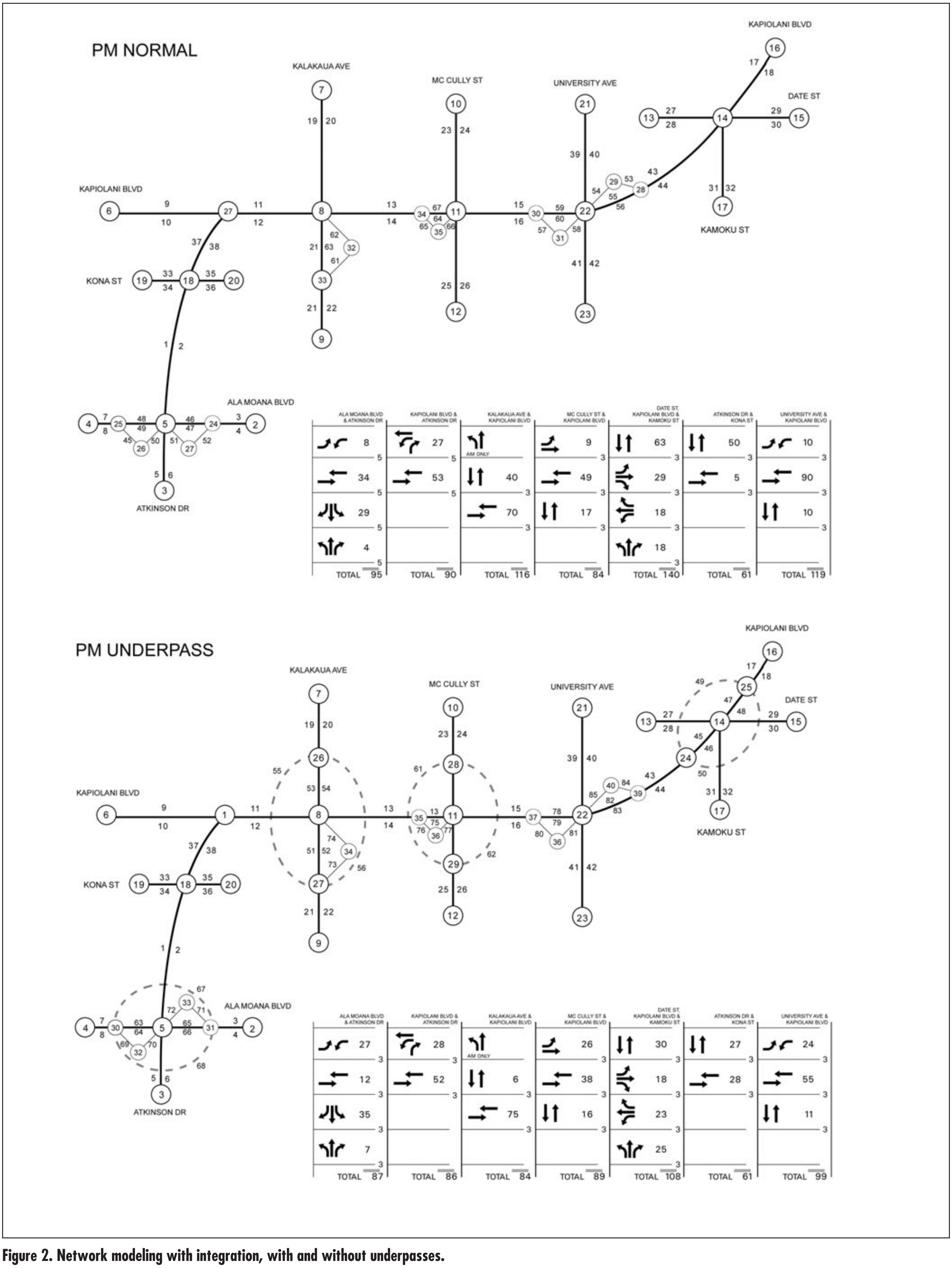

Figure 2. Network modeling with integration, with and without underpasses.

Hawaii Convention Center Transportation Impact Assessment.[12–13] Then, these volumes from the mid-1990s were adjusted to uniform year 2000 values based on Oahu, HI, metropolitan planning organization forecasts.

Modeling the underpasses was challenging. Two extra nodes were added at each intersection where an underpass was fitted. These nodes were set at the beginning of the left-turn lanes, except for the underpass at Kapiolani Boulevard and Date Street, which was set 125 m (416 ft.) from the center of the intersection. These two theoretical nodes were placed on opposite sides and connected with two two-lane links—one link/lane for each direction of flow.

Ten percent of the vehicles in the system were modeled to be large vehicles that surpassed the height limit and were not eligible to use the underpasses. The model parameters did not allow these large vehicles to access the underpass lanes. By design, however, the large vehicles could use the at-grade lane(s) to reach their destination (see the bottom of Figure 1).

Other vehicles also could use the at-grade lane(s) for left and right turns, if they were permitted (based on prevailing demand or desired traffic policy.) This dual-routing method is useful in normal as well as unusual traffic conditions, such as parades, special events, flooding, or incidents in an underpass.

Signal phasing and timing were verified by a simultaneous field study that covered the four intersections.[14] The initial signal timing was an exact replica of average field settings. Then, signal timing was set for computer optimization every five minutes by integration to approximate the city's traffic actuated signal settings. Identical signal processes were used in both the morning and the evening, with and without underpasses.

Selected major costs and benefits were expressed in monetary terms to evaluate all aspects uniformly. Changes in delay, speed and travel time between existing and proposed intersection designs provided the base for assessing the benefits of the underpasses.

Underpass construction costs were difficult to locate in the literature. It was found that the construction cost of a four-lane grade separation in the state of Illinois in 1965 was $140,000.[15] In 1982, Van Every determined that, in the absence of a detailed estimate, the average cost of a grade separation was $1 million.[16] A 1994 study by Rutter and Hodgson found that the average cost of a grade separation was $1.56 million.[17] A creek underpass on Diagonal Highway in Boulder, CO, USA, was budgeted at $1.9 million in 2003.[18] The 1997 budget for a planned arterial underpass under railroad tracks in Carbondale, IL, was $9.2 million.[19]

Due to the limited and widely varied cost information available, sizing and cost information was sought from the State of Hawaii Department of Transportation, which helped create the estimates in Table 2.

Table 2. Underpass construction cost estimates (2003).

Cost item	Standard underpass (16 feet)	Low-clearance underpass (8 feet)
Retaining walls	$2,750,000	$900,000
Underpass	$1,440,000	$1,440,000
Excavation	$592,880	$213,850
Backfill	$494,116	$178,250
Asphalt pavement	$83,903	$51,000
Base and sub-base	$81,106	$49,300
Traffic signals	$180,000	$180,000
Traffic control	$1,000,000	$750,000
Striping and signing	$65,000	$65,000
Mobilization	$668,693	$382,740
Subtotal	**$7,355,698**	**$4,210,140**
Overheight alarm	$0	$250,000
Dewatering	$125,000	$90,000
Utilities—water	$122,400	$74,400
Utilities—sewer	$130,560	$79,360
Utilities—telephone	$73,440	$44,640
Other	$56,000	$42,000
Subtotal	**$507,400**	**$580,400**
Total	**$7,863,098**	**$4,790,540**

Table 3. Network-wide summary: average two peak weekday hours.

	Morning peak	Morning peak + underpass	Percent difference	Afternoon peak	Afternoon peark + underpass	Percent difference
Travel time (hours)	1,303	1,209	-7 percent	1,266	1,067	-16 percent
Fuel consumption (liters)	5,880	5,674	-4 percent	6,034	5,279	-13 percent
Number of stoppages	29,457	26,054	-11 percent	31,570	21,734	-31 percent
Hydrocarbon emissions (kilograms)	101.8	96.9	-5 percent	105.7	89.6	-15 percent

As shown in Table 2, if no utility relocation work were necessary and no automated detection and alarm system for approaching overheight vehicles were installed, a 4.8-m (30-ft.) wide by 2.4-m (8-ft.) tall underpass under a six-lane, 29-m (96-ft.) arterial would be likely to cost about $4.2 million, or $4.8 million with utility relocations and an automated height detection and alarm system. A round cost of $5 million was assumed for the purpose of evaluating the proposed low-clearance underpasses.

Delay savings can be used in economic analysis by assigning a monetary value to time savings. The excess fuel consumed by each vehicle also was estimated and added to the savings. The main assumptions and values used in the

Table 4. Travel time, fuel and cost benefits for the four examined intersections.

Priority	Intersection	Travel time	Fuel	Total
1	Kapiolani Boulevard and Kalakaua Avenue	3,096	5,164	$8,260
2	Kapiolani Boulevard and Date Street	1,321	2,687	$4,008
3	Kapiolani Boulevard and McCully Street	1,516	2,180	$3,696
4	Ala Moana Boulevard and Atkinson Drive	445	228	$673

analysis were as follows:[20–23]

- Average vehicle occupancy = 1.25 persons
- Value of travel time (passenger vehicles and light trucks) = $7.80 per hour
- Commercial vehicle travel time = $19 per hour
- Proportion of large vehicles that cannot use the underpasses = 10 percent
- Cost of a gallon of fuel (U.S.) = $1.50

All estimates reflected one morning and one afternoon peak hour during 250 work days in one year.

Based on these assumptions and values, the results provided a lower bound estimate for the expected savings (only 250 out of 365 days per year and only two peak hours out of 24 hours per day). In addition, the potential benefits from reducing stops, rear-end and right-angle collisions and pollution were not monetized and were not included in the sums of benefits presented below.

SIMULATION RESULTS

The results included travel time estimates, fuel consumption estimates, vehicle stoppages and pollution estimates in terms of hydrocarbon emissions. Only the first two measures of effectiveness were monetized and included in economic comparisons.

Table 3 shows that underpass users would realize considerable travel time savings. With the construction of underpasses, the morning peak conditions would be expected to yield a total travel time savings of 94 vehicle-hours per hour, which reflects a 7-percent reduction from existing conditions. The evening peak conditions would be expected to yield a total travel time savings of 199 vehicle-hours per hour, which reflects a 16-percent reduction from existing conditions.

Combining the morning and evening peak hours, the total travel time savings would be 293 vehicle-hours in two hours, which reflects an 11-percent reduction from existing conditions. An equation was formulated to determine the dollar equivalent to travel time savings:

$$\text{travel time savings} = [250\ VO] \times \{TT\ [90\%\ (V)\ \$_{PC}] + [10\%\ V\ \$_{LV}]\} \quad (1)$$

where
VO = average vehicle occupancy;
TT = travel time in vehicle-hours;
V = total volume;
LV = volume of large vehicles;
$\$_{PC}$ = value of time of all traffic volume excluding large vehicles; and
$\$_{LV}$ = value of time for large vehicles.

This equation provides that on any given business day, for one morning and one evening peak hour of traffic, motorists would be expected to realize a savings of $3,262. Over a period of 250 working days, motorists would be expected to realize a savings of more than $815,495.

The proposed underpasses also would reduce fuel consumption and other motoring costs. During the morning peak period, the underpasses would be expected to yield a 3.5-percent reduction in fuel consumption; during the evening peak they would be expected to produce a 12.5-percent reduction. Overall, the underpass system would be expected to provide an 8-percent reduction in fuel consumption per business day during two peak hours.

Specifically, the morning peak savings were estimated at $923 per day; the evening peak savings were estimated at $3,386 per day. For 250 working days per year, the fuel savings for motorists utilizing the simulated corridor would be just shy of $1.1 million during two peak hours.

Underpasses also would be expected to reduce the number of vehicle stoppages by 11 percent in the morning peak period and 31 percent in the evening peak period.

Overall, the underpass system would reduce vehicle stops by 21 percent during two peak hours. A reduction in stoppages also would reduce the number of rear-end crashes; the elimination of conflicting through movements likely would reduce right-angle crashes.

Microsimulation results help prioritize the installation of underpasses at candidate intersections. Based on economic estimates, Table 4 shows the priority of underpass applications in the examined intersections in terms of weekday savings for two peak hours and in U.S. dollars.

The sample drawing in Figure 1 represents the intersection of Kapiolani Boulevard and Kalakaua Avenue (going underneath in the bottom drawing), which, as shown in Table 4, would be expected to provide the highest benefits among the four examined locations.

The location selection and the sequence in which underpasses are implemented should be evaluated carefully with simulation on an extended network. This is necessary because the relief of an upstream bottleneck may cause an onrush of traffic to downstream bottlenecks, which may produce delays that negate upstream benefits.

However, this is not a concern in this case because the first three underpasses run in a north-south direction along the main arterial (Kapiolani Boulevard), which runs in an east-west direction; the main arterial would benefit by longer green times throughout the examined length once underpasses were placed in service.

CONCLUSIONS

Intersections with heavily loaded conflicting directions are a major source of congestion, delays and pollution. Grade separation can relieve congestion at locations where other traffic engineering techniques have been exhausted or are politically or aesthetically undesirable. Grade separation benefits usually exceed the costs of construction due to significant travel time and fuel savings and reductions in vehicle stoppages and pollution.

Low-clearance grade separation is a potent congestion countermeasure. Given that more than 85 percent of vehicles in the Honolulu area under study were passenger cars and pick-up trucks, low-clearance grade-separated facilities would reduce the size of needed structures and would be feasible in Honolulu (and comparably tight urban environs).

European experience also has revealed that limited height is not a major problem for underpass implementation. In this case study, surface lanes were provided at all locations where underpasses were fitted, eliminating issues of rerouting large vehicles.

The case study undertaken on a heavily congested corridor in Honolulu showed that underpasses could be expected to produce large benefits. Significant congestion relief would result from the implementation of underpasses at four critically congested intersections. The total travel time during the morning and evening peak hours could be expected to be reduced by 11 percent, the use of fuel could be expected to be reduced by 24 percent and network-wide stoppages could be expected to be reduced by 24 percent.

The proposed underpasses likely would cost about $5 million each and induce considerable additional delays during construction. Using conservative assumptions, the expected benefits would outweigh the implementation costs after two to five years of operations for three of the four candidate locations examined. ■

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