Urban Intersection Congestion Reduction with Low Clearance Underpasses: Investigation and Case Study

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Accepted for publication in ITE Journal

Honolulu, Hawaii
Original form: October 28, 2002
In revised form: May 5, 2003
In final form: September 9, 2003

ABSTRACT:

Low clearance underpasses can reduce traffic congestion at intersections where other alternatives have been exhausted. Low clearance (2.4 m or 8 ft) underpasses are more compact and economical to build than standard (4.9 m or 16 ft) underpasses.

Four low clearance underpasses along a congested arterial in Honolulu were modeled with Integration. Travel time and fuel savings benefits accrued during two peak hours on workdays are expected to outweigh implementation costs in two to five years. Low clearance underpasses were estimated to be about 40% shorter in length and cost approximately $3 million less to construct compared with standard underpasses.

Keywords: low clearance grade-separation underpass signalized intersection

GRADE SEPARATION AT URBAN INTERSECTIONS

Several urban intersections are so severely congested that no further improvement is possible with at-grade traffic management measures. Grade separations (underpasses or overpasses) at intersections are usually ignored as a congestion countermeasure despite the long list of potential benefits such as[1,2,3,4,5]:

- Uninterrupted access benefits traffic and emergency vehicles.
- Higher capacity available for current and future traffic demand.
- Smoother flow of traffic.
- Reduction in crashes.
- Vehicle delay reduction results in time savings, fuel savings and pollution reduction.
- 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 environs[1]. Based on European experience, the limited height of low clearance underpasses has not been a major problem[1]. Common factors influencing the design and rationale to provide a low clearance facility are the avoidance of land acquisition or condemnation for new lanes and the associated cost savings[1]. These considerations have led a number of major cities including Amsterdam, Boston, Madrid, Melbourne, Paris and Singapore to implement underpasses or tunnels, because these reduce noise and emissions at street levels and permit traffic to bypass congested areas[6].

Both the 1994 and 2001[7] AASHTO Green Book section on Urban Arterials specify 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." Underpasses with a 2.4 m height clearance are restrictive. However, they can serve all passenger cars, vans and all sport utility vehicles and offer the required 0.3 m (1 ft) margin of safety for future re-surfacing or debris on the pavement. Examples of vehicles that can travel safely inside a low clearance underpass include the Lincoln Navigator (height = 1.91 m), Chevrolet Suburban (1.99 m), Ford Expedition (1.96 m), Dodge Caravan (1.75 m) and Dodge/Ford/GM variants of 15 passenger or cargo vans (2.03 m).

A number of large passenger and freight vehicles such as an Eldorado 25 passenger mini-bus (3 m), Gillig Phantom urban transit bus (3 m), and all panoramic or double decked buses (3.6 to 4.5 m) cannot go through a low clearance underpass. Also, all trucks except for empty flat-bed trucks cannot use a low clearance underpass. Typically, the proportion of large vehicles (LV) on urban arterials is small, including the area of the case study presented herein (Table 1). If low clearance underpasses are designed, then at-grade through lanes or alternative routes must be provided for freight or passenger LVs, as shown in Figure 1.

The emphasis of this research was on low clearance underpasses because of their compact size and lower cost. Specifically, a 2-lane low clearance underpass under a 6-lane arterial street with 5% grade approaches on both sides would be shorter by about 96 m (320 ft) or 39% compared with a standard underpass. In addition, according to Table 2, it will be considerably less expensive to construct: $4.8 million versus $7.8 million for a standard underpass.

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. Separate base case network models were built for weekday morning and 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.
- Network with four underpasses modeling.
- Large vehicle modeling.
- Signal timings and phasing modeling.
- Approximate evaluation of construction costs and benefits.

The analysis of grade separations was conducted using the Integration traffic simulation model mainly because of its (1) flexibility in assigning origin-destination volumes and signal timings, (2) ease of movement restrictions for specific types of vehicles such as LVs which cannot use the low clearance underpasses, and (3) prior successful use in Honolulu.[8]

The two main arterial routes in the network are Kapiolani Boulevard and Atkinson Drive. They are shown in Figure 2 along with the locations of the four proposed underpasses. Although the analyzed network does not include all of the cross streets in the area, it was determined that several secondary cross streets (all but two are unsignalized and the other two are low volume, minor street T-intersections) were not key to model integrity. Secondary important 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 is 34 km (21.1 miles). The total traffic traveling through the network is 13,800 vph for the morning and close to 15,000 vph for the evening peak period.

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

The volumes by origin and destination (O-D) were taken from the Waikiki Regional Traffic Impact Plan[9] and the Hawaii Convention Center Transportation Impact Assessment[10]. Then, these volumes from the mid-1990s were adjusted to uniform year 2000 values based on Oahu MPO forecasts.

The modeling of 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 2-lane links, one link/lane for each direction of flow.

Ten percent of the vehicles in the system were modeled to be large vehicles (LV) which surpass the height limit and are not eligible to use the underpasses. The model parameters do not allow these LV access to the underpass lanes. By design, however, these LV can use the at-grade lane(s) to reach their destination (Figure 1, bottom). Non-LV may also use the at-grade lane(s) for left and right turns, if they are 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 incident in the underpass.

Signal phasing and timings[9] were verified by a simultaneous field study that covered the four intersections. 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 in order to approximate the city's traffic actuated signal settings. Identical signal processes were used in both the morning and evening with and without underpasses.

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

Underpass construction costs were difficult to locate in the literature. We found that the construction cost of a 4-lane grade separation in the State of Illinois in 1965 was $140,000[11]. Van Every determined that in the absence of a detailed estimate the average cost of a grade separation would be $1 million in 1982[12]. A 1994 study by Rutter and Hodgson found that the average cost of a grade separation was $1.56 million[13]. A creek underpass on Diagonal Highway in the City of Boulder was budgeted at $1.9 million in 2003[14]. An arterial underpass under railroads trucks was planned for Carbondale, Illinois; the 1997 budget for it was $9.2 million[15]. Due to the limited and widely varied cost information available, we sought sizing and cost information from the Hawaii State DOT which helped us create the cost estimates in Table 2. If no utility relocation work is necessary and no automated detection and alarm system for approaching overheight vehicles is installed, an 4.8 m (30 ft) wide by 2.4 m (8 ft) tall underpass under a 6-lane (29 m or 96 ft) arterial is 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 propose of evaluation of the proposed low clearance underpasses.

Delay savings can be used in economic analysis by assigning a monetary value to the time savings. The excess fuel consumed by each vehicle was also estimated and added to the savings. The main assumptions and values used in the analysis were as follows[2,12,16,17]:

- 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 LV that cannot use the underpasses = 10%
- Cost of a U.S. gallon of fuel = $1.50
- All estimates reflect one morning and one afternoon peak hour during 250 work days in a year.

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

SIMULATION RESULTS

The results include 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.

Underpass users will realize considerable travel time savings (Table 3). With the construction of underpasses, the morning peak conditions are expected to yield a total travel time savings of 94 veh-hr/hr, which reflects a 7% reduction from existing conditions. The evening peak conditions are expected to yield a total travel time savings of 199 veh-hr/hr, which reflects a 16% reduction from existing conditions. Combining the morning and evening peak hours, the total travel time savings would be 293 veh-hr in two hours, which reflects an 11% reduction from existing conditions.

An equation was formulated to determine the dollar amount equivalent to travel time savings:

$$\text{Travel Time Savings} = [250\ VO] \times \{TT\ [90\%\ (V)\ \$_{PC}] + [10\%\ V\ \$_{LV}]\}$$

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

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

The proposed underpasses would reduce fuel consumption and other motoring costs. During the morning peak, the underpasses are expected to yield a 3.5% reduction in fuel consumption, whereas in the evening peak they are expected to produce a 12.5% reduction. Overall this underpass system is expected to provide an 8% reduction in fuel consumption per business day during two peak hours. Specifically, the morning peak savings are estimated at $923 and the evening peak at $3,386 per day. For 250 working days per year, the fuel savings for the motorists utilizing the simulated corridor would be just shy of $1.1 million during two peak hours.

Underpasses are also expected to reduce the number of stoppages. Specifically, underpasses are expected to reduce the number of vehicle stops by 11% in the morning peak hour and by 31% in the evening peak hour. Overall the underpass system would reduce vehicle stops by 21% during two peak hours. A reduction of stoppages should also reduce the number of rear-end crashes and the elimination of conflicting through movements is likely to reduce right-angle crashes.

Microsimulation results help to prioritize the installation of underpasses at candidate intersections. Based on economic estimates, the priority of underpass application in the examined intersections is shown below in terms of weekday two peak hour savings in US dollars.

Priority	Intersection	Travel Time	Fuel	Total
1	Kapiolani & Kalakaua	3096	5164	$8260
2	Kapiolani & Date	1321	2687	$4008
3	Kapiolani & McCully	1516	2180	$3696
4	Ala Moana & Atkinson	445	228	$ 673

The sample drawing in Figure 1 represents the intersection of Kapiolani Boulevard with Kalakaua Avenue (going under in the bottom drawing) which, as shown in the table above, is expected to provide the highest benefits among the four examined locations.

The selection of location and 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 on-rush of traffic to downstream bottlenecks which may produce delays that negate upstream benefits. However, in this case this is not a concern because the first three underpasses run in the north-south direction along the main arterial (Kapiolani Blvd.) which runs in the east-west direction; the main arterial will benefit by longer green times throughtout the examined length once underpasses are placed in service.

CONCLUSIONS

Intersections with heavily loaded conflicting directions are a major source for 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 because of significant travel time and fuel savings and reduction in vehicle stoppages and pollution.

Low clearance grade separation is a potent congestion countermeasure. Considering that over 85% of vehicles in the area of Honolulu examined are passenger cars and pick-up trucks, low clearance grade-separated facilities would reduce the size of structures needed and would be feasible in Honolulu and comparably tight urban environs. European experience also revealed that the limited height in not a major problem for underpass implementation. In this case study, surface lanes were provided at all locations were underpasses were fitted, thus eliminating issues of rerouting large vehicles.

The case study undertaken on a heavily congested corridor in Honolulu showed that underpasses are 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 hour is expected to be reduced by 11%, the use of fuel is expected to be reduced by 24%, and network wide stoppages are expected to be reduced by 24%. The proposed underpasses are likely to cost about $5 million each and induce considerable additional delays during construction. Using conservative assumptions, the expected benefits will outweigh the implementation costs after two to five years of operations for three of the four candidate locations examined herein.

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TABLE 1. Vehicle Classification Survey in Waikiki [9]

Vehicle Class	AM Peak	AM LVs	PM Peak	PM LVs
Motorcycle	0%		1%	
Taxi	6%		9%	
Passenger Car	76%		80%	
Pickup Truck	5%		4%	
Single-Unit Truck	4%	4%	1%	1%
Semi-Trailer Truck	0%	0%	0%	0%
Tour Shuttle/Tour Van	5%		2%	
Tour Bus	2%	2%	2%	2%
Public Bus	2%	2%	1%	1%
Total	100%	8%	100%	4%

TABLE 2. Underpass Construction Cost Estimates (2003 $)

Cost Item	Standard (16 ft.)	Low Clearance (8 ft.)
Retaining walls	$2,750,000	$900,000
Underpass	$1,440,000	$1,440,000
Excavation	$592,800	$213,850
Backfill	$494,116	$178,250
Asphalt Pavement	$83,903	$51,000
Base and subbase	$81,106	$49,300
Traffic signals	$180,000	$180,000
Traffic control	$1,000,000	$750,000
Stripping and signing	$65,000	$65,000
Mobilization costs	$668,693	$382,740
SUBTOTAL	**$7,355,618**	**$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**
GRAND TOTAL	**$7,863,018**	**$4,790,540**

TABLE 3. Network-wide Summary: Average Two Peak Weekday Hours

	AM	AM + U	% Diff	PM	PM + U	% Diff
Travel Time (hours)	1,303	1,209	-7%	1,266	1,067	-16%
Fuel (liters)	5,880	5,674	-4%	6,034	5,279	-13%
Stoppages (number)	29,457	26,054	-12%	31,570	21,734	-31%
Hydrocarbon (kg)	101.8	96.9	-5%	105.7	89.6	-15%

Note: AM = morning peak, PM = afternoon peak, U = underpass

FIGURE 1. At-Grade Intersection and Prototype Low Clearance Underpass

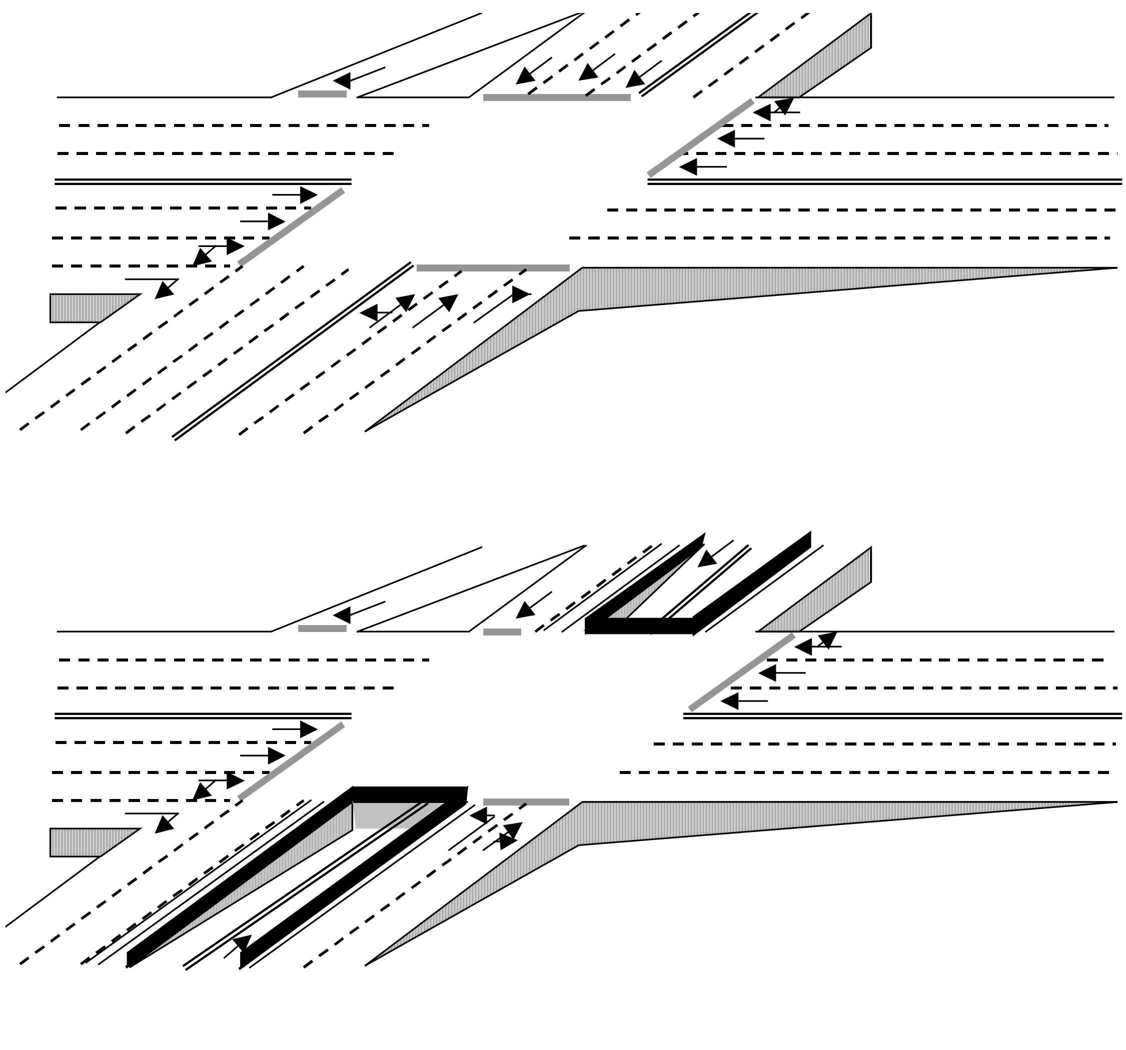

FIGURE 2. Network Modeling in INTEGRATION with and w/o Underpasses