Relationships Between Operational and Safety Considerations in Geometric Design Improvements

DOUGLAS W. HARWOOD

Traffic operations have an important influence on safety. This paper demonstrates that traffic operational improvement projects can have a positive influence on safety under varied highway conditions. Examples of operational improvement projects on two-lane highways and urban arterials that also reduce accidents are cited. The examples address passing lanes on two-lane highways and use of narrower lanes and center two-way left-turn lanes on urban arterials. These examples primarily concern issues related to the highway cross-section. The safety benefits of these types of improvement projects result partly from an improved level of service and partly from smoother traffic operations with fewer vehicle-vehicle conflicts. Relationships between traffic operations and safety are less well understood for other design elements such as horizontal and vertical alignment. The need for flexibility in geometric design standards to obtain both these traffic operational and safety benefits is illustrated. Further research is needed to establish reliable relationships between traffic congestion (volume-capacity, or V-C ratio) and safety for highway sections and intersections.

It has been accepted for many years that traffic operational considerations have an important influence on the safety performance of geometric design improvements. Many engineers have been taught since their school days that "operations and safety go hand in hand." In other words, smooth traffic operations, at an appropriate level of service, provide safe traffic operations. The purpose of this paper is to explore the practical meaning of this concept for geometric designers.

The important role of traffic operations in safety, although generally accepted, has never been well quantified. Indeed, the structure of our highway improvement programs has tended to encourage us to think about traffic operations and safety as separable issues. Some highway improvements are classified as "safety projects," because the projects are constructed at high-accident locations identified by a computerized accident surveillance system and because categorical safety funds are used in their solution. Other projects are thought of as operational improvements, because they are constructed in response to daily congestion patterns and motorist complaints about delay. In fact, many "safety projects" have a strong operational component, and many operational improvements provide opportunities to bring about substantial reductions in accident rates and changes in accident patterns.

There is a strong temptation to assume that traffic operational issues can be addressed completely with the procedures of the *Highway Capacity Manual* (HCM) (*1*) and that safety issues can be addressed completely by providing a design that meets applicable AASHTO policies (*2,3*). However, in the real world of highway design, there is a clear need for safety analysts to understand the existing operational problems at a site, and for operational analysts and geometric designers to be familiar with the existing accident patterns at a site and the likely safety performance of candidate alternative solutions.

The following discussion illustrates the role of traffic operational improvements projects in improving highway safety by means of examples for both rural two-lane highways and urban arterial streets. The paper also focuses on what is known about the relationships of traffic congestion and safety and what future research is required on this important issue. The examples provided here primarily concern issues related to the highway cross-section. Relationships between traffic operations and safety are less well understood for other design elements such as horizontal and vertical alignment.

OPERATIONAL IMPROVEMENTS ON RURAL TWO-LANE HIGHWAYS

Operational problems on two-lane highways arise because drivers of faster vehicles are delayed by drivers of slower vehicles and find themselves unable to pass. There is a variety of vehicle speeds on two-lane highways because some drivers have lower desired travel speeds than others and because the maximum speed of some vehicles is limited by horizontal and vertical alignment restrictions and vehicle performance abilities. The operational analysis procedures in Chapter 8 of HCM base the level of service for two-lane highways on percent time delay, which is defined as the percentage of their time that drivers spend delayed in platoons behind other drivers while traversing a section of highway. Thus, percent time delay is essentially a platooning measure that represents the imbalance between passing demand and passing supply on a particular highway section.

One of the most effective methods for improving the level of service on a two-lane highway is the installation of passing lanes to provide additional passing opportunities (*4–6*). A passing lane is an added lane in one or both directions of travel on a two-lane highway to improve passing opportunities. This definition includes passing lanes in level or rolling terrain, climbing lanes on grades, and short four-lane sections. Figure 1 illustrates a typical passing lane on a two-lane highway.

Analyses of the operational effectiveness of passing lanes have shown them to be very effective in improving traffic operations on two-lane highways (i.e., increasing the level of service). Passing lanes cut traffic platooning essentially in half over the length of the passing lane. Furthermore, this benefit of reduced platooning car-

Midwest Research Institute, 425 Volker Boulevard, Kansas City, Mo. 64110.

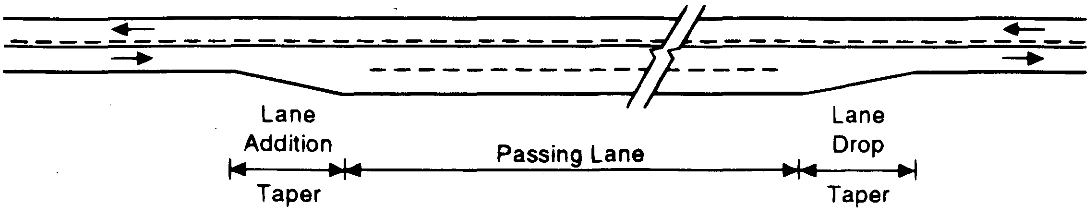

FIGURE 1 Plan view of a typical passing lane section.

ries over onto the downstream roadway and typically persists for 5 to 13 km (3 to 8 mi) downstream of a passing lane (*5,6*).

The key point to be emphasized in this paper is that passing lanes not only have operational benefits, they also have substantial safety benefits. Research has established that installation of a passing lane on a two-lane highway typically reduces total accident rates by 25 percent and fatal and injury accident rates by 30 percent (*4,6*).

The key reason for the substantial reduction in accident experience is the effect of better operations. Passing lanes provide an opportunity for drivers to make passing maneuvers without using the lanes normally reserved for opposing traffic. Passing lanes provide an assured passing opportunity. Drivers know that they will be able to pass in a passing lane whether or not there is traffic present in the opposing direction. If drivers know that passing lanes are provided at intervals, they may be discouraged from making marginal passing maneuvers in the face of opposing traffic on the normal two-lane highway since better passing opportunities will certainly be available in an upcoming passing lane. Advance signing, informing drivers of upcoming passing lanes 3 to 8 km (2 to 5 mi) before they reach the passing lane, may encourage caution in passing.

Passing opportunities on two-lane highways can also be provided by installation of short four-lane sections that function as side-by-side passing lanes. Some engineers have hesitated to use short four-lane sections to provide additional passing opportunities on two-lane highways because four-lane undivided roadways have been considered to have high accident rates. However, the higher accident rate of some four-lane undivided roadways is generally attributable to use at rural or urban sites with substantial roadside development. Where short four-lane sections have been used to provide passing opportunities in relatively undeveloped areas, total accident rates have been reduced by 34 percent and fatal and injury accident rates have been reduced by 43 percent. As in the case of passing lanes, the provision of additional passing opportunities by installation of a short four-lane section has been demonstrated to enhance safety (*4,6*). The accident reduction effectiveness measures cited above include only the passing lane or short four-lane sections themselves plus 0.8 km (0.5 mi) on either side. It is possible that the installation of passing lanes and short four-lane sections may also reduce accident risks by discouraging improper passing at locations remote from the actual passing lane site.

OPERATIONAL IMPROVEMENTS ON URBAN ARTERIALS

Even more dramatic effects of operational improvements on safety can be demonstrated on urban arterials. NCHRP Report 330, "Effective Utilization of Street Width on Urban Arterials" (*7*), provides guidelines for improving traffic operations on urban arterials without changing the total curb-to-curb street width. These guidelines are applicable to streets in developed areas for which geometric alternatives that would require widening of the street are infeasible. Improvement strategies evaluated in the research included projects that involved the use of narrower lanes, median removal, provision of additional through lanes, and installation of a center two-way left-turn lane (TWLTL).

TWLTLs have been found to be a very effective method for improving traffic operations on urban and suburban arterial streets by removing left-turning traffic from the through lanes and eliminating delays to through traffic caused by the turning vehicles at driveways and unsignalized intersections. In addition to their obvious traffic operational benefits, TWLTLs also reduce accidents. In general TWLTLs have been found to reduce accidents on urban and suburban arterials by 35 percent. Even higher accident reductions from TWLTLs have been found on urban and suburban arterials with a high percentage of left-turn and rear-end accidents and on rural two-lane highways (*6,8*).

ACCIDENT REDUCTION EFFECTIVENESS

NCHRP Report 330 found that both operations and safety of urban arterials can be improved by implementing strategies that involve the use of narrower lanes. For example, Table 1 illustrates the accident reduction effectiveness of three improvement strategies:

- Conversion from a four-lane undivided street to a five-lane street with a center TWLTL;
- Conversion from a four-lane divided street with a narrow 1.2-m (4-ft) median to a five-lane street with a center TWLTL; and
- Conversion from a six-lane divided street with a narrow median to a seven-lane street with a center TWLTL.

Figure 2 illustrates each of the cross-sections involved in these strategies. Each of these project types identified above resulted in statistically significant reductions in accident rate with no change in the percentage of fatal and injury accidents, even though through lanes as narrow as 2.7 m (9 ft) were used in some cases to make room for the TWLTL. In other words, any increase in accidents that might be associated with the use of narrower lanes was more than offset by the substantial reduction in accidents associated with the installation of a TWLTL. Since the street cross-section could not be widened, the use of narrower through lanes was the only way to provide space for a TWLTL at these sites.

The lessons to be drawn from this experience are that traffic operational and safety problems are related, and solving traffic operational problems on an arterial highway can lead to safety benefits as well. Furthermore, in situations in which traffic operational prob-

TABLE 1 Accident Reduction Effectiveness of Selected Project Types on Urban Arterials (7)

Project type	Accident rate reduction	
	Expected value (%)	90% Confidence interval (%)
Conversion from a four-lane undivided street to a five-lane street with a TWLTL	44	13-75
Conversion from a four-lane divided street with a narrow median to a five-lane street with TWLTL	53	24-82
Conversion from a six-lane divided street with a narrow median to a seven-lane street with TWLTL	24	11-38

lems exist, solving these problems frequently has a positive effect on safety even when some geometric standards, such as lane width, must be relaxed to do so. Highway agencies should be careful to monitor projects in which narrower lanes are used to make sure that safety problems do not develop and, in doing so, highway agencies should build up experience about what works and what doesn't work in their area.

Nothing said here is intended to encourage indiscriminate use of narrower lanes. However, at the same time, a blanket prohibition against the use of narrower lanes will cause highway agencies to miss opportunities to solve traffic operational problems in a cost-effective manner and to improve safety at the same time. Rational guidelines, based on research and highway agency experience, are needed to guide implementation of such projects. Such guidelines have been developed and are presented in the next section.

GUIDELINES FOR REALLOCATION OF STREET WIDTH ON URBAN ARTERIALS

The following guidelines for projects involving narrower lanes on urban arterials were developed in NCHRP Report 330. These guidelines indicate where geometric design policies can be relaxed without compromising safety in improvements to existing facilities and illustrate the multitude of considerations that affect such decisions:

- Narrower lane widths (less than 3.4 m or 11 ft) can be used effectively in urban arterial street improvement projects in which the additional space provided can be used to relieve traffic congestion or address specific accident patterns. Narrower lanes may result in increases in some specific accident types, such as same-direction sideswipe collisions, but other design features of a project may offset or more than offset that increase.
- Projects involving narrower lanes nearly always reduce accident rates when the project is made to implement a strategy known to reduce accidents, such as installation of a center TWLTL or removal of curb parking. Highway agencies should not hesitate to implement such projects on urban arterial streets.
- Projects involving narrower lanes whose purpose is to reduce traffic congestion by providing additional through lanes may result in a net increase in accident rates, particularly for intersection accidents. Such projects should be evaluated carefully on a case-by-case basis, considering the agency's previous experience with that type of project. Both the traffic operational and traffic safety effects of the project should be evaluated and the feasibility of incorporating geometric improvements at intersections (such as left-turn lanes) to reduce intersection accidents should be considered.
- Lane widths as narrow as 3.1 m (10 ft) are widely regarded by urban traffic engineers as being acceptable for use in urban arterial street improvement projects. Except for one specific project type that is not common (conversion from a two-lane undivided to a four-lane undivided street), all projects evaluated in this study that consisted exclusively of lane widths of 3.1 m (10 ft) or more resulted in accident rates that were either reduced or unchanged. Where streets cannot be widened, highway agencies should give strong consideration to the use of 3.1-m (10-ft) lanes, where they are necessary, as part of a geometric improvement to upgrade traffic operations or alleviate specific accident patterns.
- Lane widths less than 3.1 m (10 ft) should be used cautiously and only in situations in which it can be demonstrated that increases in accident rates are unlikely. For example, numerous project evaluations in this study found that 2.7- and 2.9-m (9- and 9.5-ft) through-traffic lanes can be used effectively in projects to install a center TWLTL on existing four-lane undivided streets. Such projects nearly always result in a net reduction in accident rate. On streets that cannot be widened, highway agencies should consider limiting the use of lane widths less than 3.1 m (10 ft) to (a) project types in which their own experience indicates that they have been used effectively in the past or (b) locations where the agency can establish an evaluation or monitoring program for at least 2 years to identify and correct any safety problems that develop.
- In highly congested corridors, agencies should anticipate that traffic operational improvements on one street, such as provision of additional through lanes, may attract traffic to that street from parallel streets. This may lead to increased traffic volumes and increased accidents on the improved street, but may still reduce delays and accidents in the corridor as a whole.
- Projects that change the geometrics of signalized intersection approaches should be accompanied by adjustments in signal timing (and, in some cases, changes in signal phasing). Traffic volumes on the project (and, possibly, on parallel streets) should be reviewed 1 or 2 months after project implementation to determine if there is a need for further adjustments in a signal timing.
- Truck volumes are an important consideration in the implementation of projects involving narrower lanes. There appears to be general agreement that narrower lanes do not lead to operational problems when truck volumes are less than 5 percent. Sites with truck volumes between 5 and 10 percent should be evaluated care-

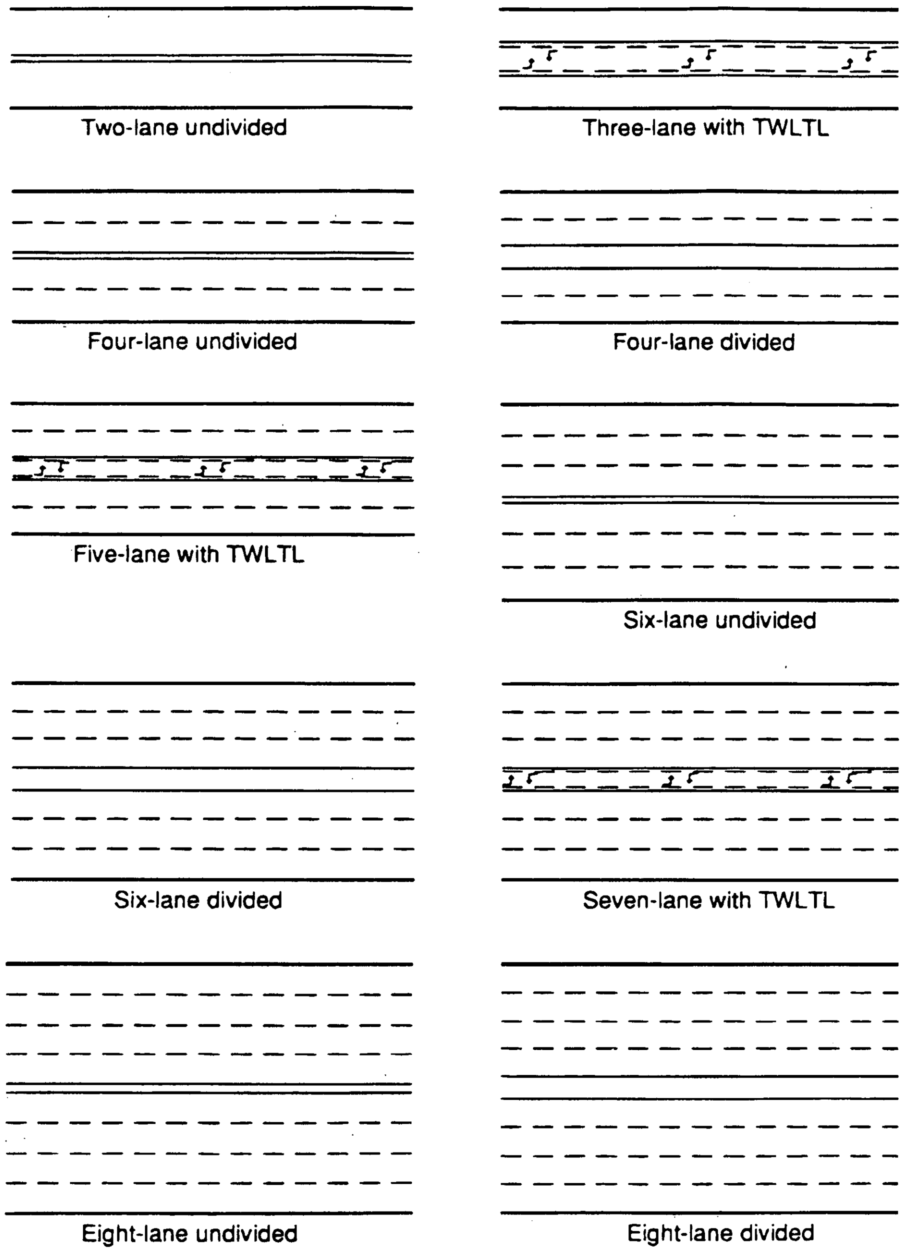

FIGURE 2 Design alternatives evaluated for urban arterial streets (*7*).

fully on a case-by-case basis. Use of narrower lanes should be discouraged on streets with more than 10 percent truck traffic.

- Higher truck volumes may not cause operational problems on streets with narrower lanes if the trucks travel straight through the site without turning.
- Trucks may be a greater concern on streets with horizontal curves than on tangents.
- Tractor-trailer combination trucks may be more critical than single-unit trucks because of their greater width and their greater offtracking.
- Curb lanes should usually be wider than other lanes by 0.3 to 0.6 m (1 to 2 ft) to provide allowance for a gutter and for greater use of the curb lanes by trucks. Center or left lanes for through traffic and TWLTLs can usually be narrower than the curb lane. One city engineer has pointed out that the left lane for through traffic on an arterial street can be quite narrow if it is adjacent to a center TWLTL, which increases the "effective width" of the through lane. The presence of a TWLTL adjacent to a through lane is obviously less restrictive than the presence of a curb or another through lane.
- Narrow lane projects do not work well if the right lane provides a rough riding surface because of poor pavement conditions or the presence of grates for drainage inlets. Drivers may avoid the right lane if they believe uncomfortable driving will occur over rough drainage inlets. Thus, projects with narrower lanes may be most satisfactory at sites with curb inlets that do not have grates in the roadway.
- The needs of bicyclists should be considered in implementing projects involving narrower lanes. The literature indicates that curb

lane widths of at least 4.6 m (15 ft) are desirable to accommodate the shared operation of bicycles and motor vehicles (*9,10*); thus, it may not be possible to fully accommodate bicyclists even on many existing streets with 3.6-m (12-ft) curb lanes. Decisions concerning implementation of projects with narrower lanes should be made by taking into consideration the volume of bicyclists using the roadway and the availability of other bicycle facilities in the same corridor.

- When lanes are narrow, operational efficiency at some sites may be reduced because of staggering of traffic in adjacent lanes. The capacity per lane may be reduced because drivers are reluctant to travel side by side. However, drivers in adjacent lanes still travel at shorter headways than they could in a single lane, so the overall through traffic capacity of the street should increase, but not by as much as would be possible if wider lanes could be used.
- Projects that can be implemented by remarking only can be implemented very quickly, often in a single day. However, projects that involve construction, such as median removal, require more time to complete.
- A common problem in remarking projects is that it is difficult to remove the existing pavement markings completely. Current removal methods include grinding, sandblasting, and waterblasting. Because of these problems, some agencies implement almost all remarking projects in conjunction with pavement resurfacing.
- Remarking projects may be confusing to drivers if the new lane lines no longer match the pavement join lines (or the reflections of the pavement joint lines). This potential problem is another indication that implementation of remarking projects in conjunction with pavement resurfacing is very desirable.
- Access control regulations concerning driveway location and design are important on all urban arterial streets, but especially for streets that are not wide enough to install a median or center TWLTL. Driveway design and location measures that have been found to be effective are summarized in NCHRP Report 330 (*7*).

ROLE OF TRAFFIC CONGESTION IN SAFETY

The highway community needs broader knowledge about the relationship between traffic congestion and safety so that we can take better advantage of opportunities to improve safety by reducing traffic congestion. Although the examples of two-lane highway and urban arterial improvements presented above illustrate specific instances in which traffic operational improvements also improve safety, we do not have a complete understanding of the relationship between traffic congestion and safety. For example, it would be extremely valuable to know how safety varies with V-C ratio and what V-C ratios provide minimum accident rates.

It would also be valuable to have a better understanding of the role of oversaturated operating conditions, with V-C ratios greater than 1.0, in producing accidents. Freeways in many urban areas operate under oversaturated stop-and-go conditions during peak hours and under more normal free-flow conditions at other times of day. The stop-and-go operations may lead to high accident rates, particularly involving rear-end and lane-changing accidents, although the lower speeds involved suggest that the severity of such accidents may be relatively low. Oversaturated approaches to signalized intersections develop queues that may extend well back from the intersection. Such queues may also be associated with rear-end accidents. The safety implications of oversaturated intersection operations also need to be studied more fully.

Only limited research has been conducted on the variation of safety with V-C ratio. One recent study was reported by Hall and Pendleton (*11*), who studied roadway accident rates in New Mexico as a function of V-C ratio by comparing the hourly patterns of reported accidents to the hourly patterns of traffic volumes from permanent count stations on the same highways. This study took exactly the right approach to this research, but the applicability of the results was limited by the nature of the roadway system in New Mexico, which includes very few highways with high V-C ratios. Another recent study by Hall and Polanco de Hurtado (*12*) has examined the variations of accident experience with traffic volumes at urban intersections. More research of this type is needed, over a greater range of V-C ratios, to establish valid relationships between safety and traffic congestion to provide a basis for maximizing the safety benefits from operational improvement projects.

SUMMARY AND CONCLUSIONS

Traffic operational conditions have a strong influence on the potential for the occurrence of traffic accidents. Many operational improvement projects provide important safety benefits through reductions in traffic congestion. This paper has presented examples of traffic operational improvements that also have positive impacts on safety, including:

- Installation of passing lanes and short four-lane sections to increase passing opportunities on two-lane highways; and
- Reallocation of street width on urban arterials, through use of narrower through lanes and removal of raised medians, to provide room for operational improvements such as center TWLTLs.

The safety benefits of these types of improvement projects result partly from an increased level of service and partly from smoother traffic operations with fewer vehicle-vehicle conflicts.

It is important that geometric design policies recognize that substantial safety benefits can be obtained from traffic operational improvements and that, in some cases, exceptions to geometric design standards may be necessary to obtain both the operational and safety benefits. Further research is needed to establish relationships between traffic congestion (e.g., V-C ratio) and safety as a basis for using traffic operational improvements as a means for reducing accidents.

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