

An Overview of System Design Issues Related to Safety Aspects of Bicycle Infrastructure



MTI Report WP 12-05



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AN OVERVIEW OF SYSTEM DESIGN ISSUES RELATED TO SAFETY ASPECTS OF BICYCLE INFRASTRUCTURE

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EXECUTIVE SUMMARY

The major goal of this report is to discuss some of the bicycle infrastructure design issues related to safety. Because this was a seed project with limited funding, the review could not be comprehensive. The intent was to create a framework within which the major shortcomings in the approach to the system-level design of bicycle-related infrastructure could be identified and discussed. The author hopes that the identified problems will be further researched and considered in future designs. This is a critical review of existing practice. However, to improve transportation safety for all travelers, the shortcomings of existing practice must be identified before optimal improvements can be made. It should be noted that the review went beyond bicycle infrastructure. The connection to and interaction with the other modes of transportation were also considered. In addition, the role that bicycle transportation plays in the functioning of the transportation system was also considered. The latter issue is important because increased bicycling could not only increase the frequency of bicycle accidents/crashes but also possibly lead to an overall increase in transportation injuries and death.

It should be noted that the review is principally conducted from the start of a transportation system plan through the implementation and operational stages. These latter stages are characterized by the fact that a change is finally implemented, whether it is constructed or the operation is changed and the debate about the implementation is finally over. The discussion also includes the importance of evaluating any changes in terms of the function (or central service delivery) of the transportation system and its components. In the case of the transportation system, the basic function is to transport people or goods from point A to point B. In the author's opinion, one of the problematic issues related to the benefits of implementing bicycle-related infrastructure is that part of the bicycle community wishes to define the functionality of the transportation system at least partly in terms of the trip being an end in itself, such as exercise, and not moving from point A to point B. Scarce road space could then be taken away from other modes or uses directed at getting from point A to point B. This leads to a lot of debate that is, in the author's opinion, focused or biased in favor of bicycling without a clear assessment of the performance of bicycling as a mode of transportation. The author hopes that this critical review will shed some light upon the implications of this very important issue.

The focus of the discussion in this report is on the design of infrastructure for bicycling. Cycling is not restricted to bicycling; it can include tricycles and other configurations of pedalcycles. But most of the discussion in this report pertains to bicycling and the infrastructure comprising the way (bike paths, etc.) and traffic intersections. The infrastructure is discussed in terms of individual elements and also from a system perspective. These elements do not exist in a vacuum, but they are a part of the overall transportation system, land use, and other environmental components. In contrast, based on the author's observation, a large portion of the existing literature related to bicycling focuses on bicycling alone without putting it in the context of the overall transportation system and the principal function of the system—i.e., moving from point A to point B. Comment is also made on the promotion of bicycling and the accompanying provision of infrastructure, which often occurs without giving adequate consideration or notice of the risk of injury and death when bicycling. Much has been written about the design of individual components of bicycling infrastructure, but the focus in this report is on the larger issues that affect design.

The wide range of bicyclists' physical characteristics (such as size, power, skill, response to road and traffic conditions, etc.) makes it challenging for the designer to design bicycle facilities with the same sophistication and safety as facilities for motor vehicles. While there are some design features that can be incorporated that will increase safety for bicyclists, there are also behaviors and factors inherent in bicycling that are impossible to design for. Having bicyclists and motor vehicles on the same street would mean that the different human and vehicular characteristics related to bicycles and motor vehicles respectively would be close to impossible to accomplish. An attempt should at least be made to integrate the design standards for motor vehicles and bicycles into common design manuals. Incompatibility of the standards may make it clear when separate facilities for bicyclists should be considered and when bicyclists should not be allowed on a road.

Differences in speeds lead to an exponential increase in the frequency of crashes. Bicyclists commonly travel at speeds that are generally lower than motor vehicle speeds, which can then lead to an increase in crashes between motor vehicles and bicyclists. The solution would be to separate the motor vehicles and bicyclists, which has been common practice. However, this solution is costly, and there is a lack of space in which to accomplish it. A similar effect may be had by not allowing bicyclists on roads and streets with higher average speeds and by designating alternative routes through neighborhood streets.

Unfortunately, of late, providing more bike lanes and bike paths has been motivated in part by statements that bicycling leads to an increase in health benefits and a decrease in the carbon footprint from travel. These kinds of statements are sometimes misleading and are not always accompanied by the facts. When more people bicycle, more people are exposed to higher risk than they would have been had they used a personal vehicle or public transportation to travel. A study³ showed that on a per trip basis, a bicyclist is 2.3 times more likely to be killed than a person using a personal motor vehicle. Another study showed that funds are more efficiently spent on improving traffic flow and public transportation to decrease pollution than on spending it to create a bike path, for example.⁴ More than 50% of bicycling is for exercise and recreation, which do not substitute for a motor vehicle trip and therefore do not decrease pollution. A study⁵ of the risk of injuries in sports showed that bicycling has a higher injury rate per 100,000 people than, for example, basketball or soccer.

Planning and designing infrastructure for bicycling, such as bike paths, could lead to the increased safety for existing bicyclists. But creating more and better bicycle infrastructure could possibly attract people to bicycling and lead to an increase in overall risk of injury and death. Moreover, the dilemma is that there may never be adequate funds to create enough facilities to separate bicyclists from motor vehicles in the U.S. Additionally, bicyclists would still have to navigate the streets, without separation of bicycles from motor vehicles, to reach the bike paths. Bike paths may not aid in low-volume conditions at night, when lack of visibility creates relatively unsafe conditions.

“Safety in numbers” is a commonly held belief. It essentially comes down to the possibility that the presence of more bicyclists will make motorists more aware of bicyclists, but it also exposes more bicyclists to risk when they are in areas where large numbers of bicyclists are not present. Additionally, having more bicyclists increases the likelihood of crashing in the absence of motor vehicles.

A study in Orlando, Fla. showed that 64% of bicycle-vehicle crashes involved an unsafe choice by bicyclists.⁶ These collisions cannot be eliminated by design. Additionally, the bicyclist’s choice not to wear a helmet and consequently being exposed to more serious injury in a crash cannot be solved by designing better facilities. The aging of the population in the US is an important factor in design of roads and traffic control systems. This factor has led to changes in design and control standards used in design of roads and streets for motor vehicles and pedestrians. This factor will impact the overall risk of bicycling. Older people have comparatively lower balancing skills, and riding a bicycle may lead to an increase in falls. Better road and traffic control will probably have a negligible effect on reducing such falls.

The false belief that bicycling is always healthful and decreases environmental impact could lead to an overinvestment in bicycling infrastructure while not placing enough emphasis on enforcement to affect bicyclists’ and drivers’ dangerous behavior and on laws that would require bicyclists of all ages to wear helmets.

Much has been accomplished in the last few years to establish and improve standards for the design of individual bicycle facilities. However, because separate bike paths and even sufficient space for bicycle lanes were not incorporated into the design of arterial streets in typical major U.S. cities and metropolitan areas, it is very difficult to establish separate lanes and separate paths for bicycles. Because of urban sprawl, the average commute distances could preclude commuting by bicycle for many people. Implementation of “complete streets,” in which emphasis is given to all modes, may lead to a breakdown in the functioning of the hierarchical structure of the street system, wherein arterial streets are intended to fulfill the function of mobility. If lanes were taken away from general use and designated for the exclusive use of bicyclists, motor vehicles may deviate to streets that are not suited to accommodating large volumes of motor vehicle traffic, and those streets may experience less safe conditions.

Conditions on the “complete streets” may also become less safe for all users. In some cities in Europe, it is difficult to use a personal motor vehicle because of inadequate road space. These cities, such as the center of Barcelona, generally have a very high population density and relatively good public transportation systems. It is not convenient to use personal motor vehicles under these circumstances. Separate bike lanes are provided on sidewalks, and bicycles are also extensively used in areas where motor vehicles are not allowed. Most U.S. cities do not have such a high population density, and people working in the central business districts of U.S. cities must rely on personal motor vehicle transportation to access workplaces, at least in the absence of good public transportation. When scarce road space is allocated for exclusive use of bicycles, then poor mobility and poor travel safety may result.

More research into and development of standards are necessary. Designing better individual facilities probably cannot, by itself, significantly improve the safety of bicycling. More research is necessary, especially regarding the impact of re-allocating traffic lanes and road space on arterials for the exclusive use of bicyclists. Additional research is also needed for dealing with bicyclists when they are concentrated in intersections by having bike lanes entering those intersections. Increased enforcement and regulation, as well as education on the risks of bicycling, could make significant contributions to improving bicycling safety.

The design of individual streets, lanes, and other transportation system components is dictated primarily during the planning stage. Moreover, the allocation of road space and resources is made during the planning stage. To make the allocation of resources effective and efficient, benefit-cost analysis should be utilized as much as possible. It is already extensively used in allocating funds for road safety improvements. The selection of possible projects for implementation is based on the reduction of crashes (benefits) and the cost of implementation.

In the event that benefit-cost analysis is used for the selection of projects for implementation—and even when it is not used for allocating funds—the same benefit and cost categories must be considered for all modes, and the function of the system or project should be clearly defined. The principal function of road space is for traveling from point A to point B and is not intended for exercise and recreation. People may use it for the latter purpose, but it is very much a secondary purpose and should not detract from the principal function. Bicycle facilities such as trails designed for exercise and recreation should be considered separately to serve these functions. One of the major problems with considering dissimilar benefits for selecting projects for implementation is that the project alternatives cannot be prioritized on the same basis. This would lead to a misallocation of resources.

It would appear prudent for transportation agencies to refrain from promoting bicycling, especially in the absence of a clear assessment of the risk and the possible significant cost to society resulting from increased injury and death. These agencies certainly should not promote bicycling based on health benefits and reduced environmental impact without making the risk of injury and death clear.

It is probably unlikely that the percentage of all trips undertaken by bicycling will constitute a significant percentage of trip-miles in the foreseeable future because the base from which it has to grow is so low. There is also the danger that this assumption could result in planning and increased implementation of bicycle-related facilities instead of making improvements to infrastructure for other transportation modes—which would be more efficient in fulfilling the principal function of transportation. Until a clear determination is made of the role that bicycling could reasonably play in the future transportation system, the focus should be on the safety of short-distance bicycle trips and not on bicycle networks for which the function is unclear—i.e., serving the health and recreation function versus traveling from point A to point B. Attention should be given to the needs of the captive riders, and pressure from bicycle advocacy groups should be resisted. A planning and decision-making system should be established that trades off the needs of all modes when allocating resources. This would be in contrast with a decision-making system that includes a bicycle committee, which may not be inclined to focus on the needs of all modes of transportation.

The rapid aging of the population will result in different demands on the transportation system. Increased automation of motor vehicles could benefit older drivers. Bicycling will, in all probability, not benefit as much from improved technology, thereby rendering bicycling a less desirable personal mode of transportation for the elderly than motor vehicles. This factor should be considered when envisioning the future of transportation.

Bike lanes are often considered along an arterial street in a neighborhood in which changes in the transportation situation are made to adjust to the development. The goal may be to make the street more “bikeable” and walkable. To achieve this end, general-use travel lanes may be reduced (“road diet”), and the street could be made more “complete” in the process. However, these types of actions should not be taken before ensuring that the motor vehicles displaced by these actions are not going to cause problems elsewhere without explicitly taking action to accommodate those displaced motor vehicles.

Similarly, bike lanes and bike paths could be considered where changes to transportation systems are made in downtown areas of cities to make the downtown more livable. In this case, bypass streets to the downtown area should be established before committing to the “livable” downtown. In the absence of an effective public transportation system, such a downtown design should not be undertaken without proper provision of access and parking for motor vehicles. In the author’s opinion, the idea that a large percentage of people will commute long distances with a bicycle and forsake their personal vehicles in most U.S. cities is probably folly.

Some college towns in the United States may present an opportunity in which the environment can be structured to allow extensive bicycling. This is in part due to the fact that housing and the campus can be close together and that a great number of students may not have cars. However, due diligence still must be paid to ensure that the mixing of motor vehicles and bicycles is minimized.

It is the author’s view that the way in which safety improvements for bicyclists is approached should be fundamentally changed. Decreasing fatalities and injuries should be considered for the transportation system as a whole instead of trying to decrease the fatalities and injuries to bicyclists alone by implementing countermeasures, or for that matter looking at individual statistics for other modes. Even better, assessing the overall performance of the transportation system when making improvements should be based on the decrease in the overall cost of transportation. The cost should include the infrastructure cost, travel time cost, vehicle operating cost, and accident/crash cost, taking the explicit function of the system into account. Environmental impacts should also be assessed by taking into account vehicle impacts as a whole and not assuming that improving bicycle facilities decreases environmental impacts or is emissions-neutral under all circumstances. This kind of approach will also shed light on the extent to which bicycling should be promoted or whether scarce resources for transportation should be allocated elsewhere, including transportation services for the rapidly-expanding elderly population.

I. INTRODUCTION

The major goal of this report is to discuss some of the bicycle infrastructure design issues related to safety. Because this was a seed project with limited funding, the review could not be comprehensive. The intent was to create a framework within which the major shortcomings in the approach to the system-level design of bicycle-related infrastructure could be identified and discussed. The author hopes that the identified problems will be further researched and considered in future designs. This report is a critical review of existing practice and policy. However, to improve transportation safety for all travelers, the shortcomings of existing practice must be identified before optimal improvements can be made. It should be noted that the review went beyond bicycle infrastructure. The connection to and the interaction with other modes of transportation were also considered. In addition, the role that bicycle transportation plays in the functioning of the transportation system was considered. The latter issue is important because increased bicycling could not only increase the frequency of bicycle accidents/crashes, but also possibly lead to an overall increase in transportation injuries and death.

It should be noted that the review is principally conducted from the start of a transportation system plan through the implementation and operational stages. These latter stages are characterized by the fact that a change is finally implemented, whether it is constructed or the operation is changed and the debate about the implementation is finally over. The discussion also includes the importance of evaluating any changes in terms of the function (or central service delivery) of the transportation system and its components. In the case of the transportation system, the basic function is to transport people or goods from point A to point B. In the author's opinion, one of the problematic issues related to the benefits of implementing bicycle-related infrastructure is that part of the bicycle community wishes to define the functionality of the transportation system at least partly in terms of the trip being an end in itself, such as exercise, and not moving from point A to point B. Scarce road space could then be taken away from other modes or uses directed at getting from point A to point B. This leads to a lot of debate that is, in the author's opinion, focused or biased in favor of bicycling without a clear assessment of the performance of bicycling as a mode of transportation. The author hopes that this critical review will shed some light upon the implications of this very important issue.

The focus of the discussion in this report is on the design of infrastructure for bicycling. Cycling is not restricted to bicycling, but most of the discussion in this report pertains to bicycling and the infrastructure comprising the way (bike paths, etc.) and traffic intersections. The infrastructure is discussed in terms of individual elements and also from a system perspective. These elements do not exist in a vacuum, but they are a part of the overall transportation system, land use, and other environmental components. In contrast, based on the author's observation, a large portion of the existing literature related to bicycling focuses on bicycling alone without putting it in the context of the overall transportation system and the principal function of the system—i.e., moving from point A to point B. Comment is also made on the promotion of bicycling and the accompanying provision of infrastructure, which often occurs without giving adequate consideration or notice of the risk of injury and death when bicycling. Much has been written about the design of individual components of bicycling infrastructure, but the focus in this report is on the larger issues that affect design.

There is an important debate about the unsafe behavior of bicyclists or drivers. The author hopes that this critical review will shed some light upon this very important issue. Most of the discussion will be on the behavior of bicyclists, but this should not be interpreted that the unsafe behavior of drivers in collisions is not important or is not a significant contributing factor.

Broadly speaking, all pedal cycles should be included in the discussion. For simplicity, the term “bicycles” will be used because most pedal cycles are bicycles. Most of the discussion is about the ways (or paths) and traffic intersections. Other important elements of the infrastructure, such as bicycle storage and the finer details of bicycle way and intersections design, will not be discussed. Bicycle infrastructure design manuals, which address these kinds of details, are available from national, state, and local agencies. Considerable resources have been and still are being committed to refining standards for the design of individual facilities, such as a bike path (separate facility used only for bicycles), bike lanes, and other designated bicycle ways.

In parts of the industrialized world, such as in Europe, bicycles have been and still are a major means of transportation. One study showed that the bicycle mode share of total trips ranges from 9% in Germany to 27% in the Netherlands.⁷ In the case of trips with a distance of less than 2.5 km (1.6 miles), these percentages change to 41% and 44%, respectively. By comparison, the corresponding mode shares for the U.S. are 1% and 2%, respectively. In the Netherlands 32% of bicycle trips are made to school or work and 27% for recreational purposes. The corresponding numbers for the U.S. are 11% and 75%. Not only is the proportion of trips by bicycle in the U.S. very small, but also a disproportionate number of trips are made for recreational purposes. The objective of the latter trips is therefore not for reasons of getting from point A to point B, which is usually the objective of transportation. This is very different from most trips in which the objective may be to travel to work or school, go shopping, etc. This aspect of trip making by bicycle poses a challenge for designers and will be discussed in the report.

According a US DOT Policy Statement on Bicycle and Pedestrian Accommodation Regulations and Recommendations published in 2010, “Increased commitment to and investment in bicycle facilities and walking networks can help meet goals for cleaner, healthier air; less congested roadways; and more livable, safe, cost-efficient communities. Walking and bicycling provide low-cost mobility options that place fewer demands on local roads and highways.”⁸

Numerous cities have followed similar directions. Some have developed extensive bicycle plans and set ambitious goals for bicycle use. The City of San Jose, Calif. has a goal to increase the share of bike mode from 1% to 5% in 2020 and to 15% in 2040.⁹ It is unclear whether such goals can be met. Ogilvie, et al. conducted an overview of 22 studies directed at determining whether intervention succeeded in walking and cycling as an alternative to cars. They found that although some interventions produced mode shifts, interventions such as publicity campaigns and engineering measures have not been effective.¹⁰

Promoting bicycling may result in more travel-related deaths and injury while not improving mobility significantly. On the average, the likelihood of death when cycling is higher than

the likelihood of dying when using an automobile for the same trip. Beck, et al. found that “relative to passenger vehicle occupants, motorcyclists, bicyclists, and pedestrians are 58.3, 2.3, and 1.5 times, respectively, more likely to be fatally injured on a given trip.”¹¹

Promoting health is one of the major benefits cited for the provision of bicycle facilities. However, the idea that bicycling is healthful may not be true for everyone. Riding long distances each day will lead to chronic injuries for some. In a survey conducted by Schweltnus and Derman in South Africa among 294 male and 224 female recreational bicyclists, it was found that 85% experienced chronic or overuse injuries, of which 36% of these warranted medical attention.¹² Injuries to the neck, knee, groin/buttock, hands, and lower back were reported. The researchers concluded that training errors and bicycle-cyclist “fit” were usually the cause of these chronic injuries. Because the majority of bicycling in the US is conducted for recreational purposes, this is an important consideration when evaluating whether bicycling is in fact as healthful as some may say. It may be better to promote another way of exercising.

There is also some doubt as to whether there would be a significant reduction in air pollution. Grant, et al.¹³ also concluded that bicycle and pedestrian projects generally have modest emissions reduction effects. They studied the changes in reduction of several pollutants and calculated the cost-effectiveness of each project. For example, it costs \$453,217 to reduce emissions by one ton of CO by building a bike path. By comparison, it costs only \$2,030 to reduce emissions by one ton of CO by improving traffic flow through freeway traffic management, and it costs between \$621 and \$115,766 by providing transit service upgrades. They wrote: “Bicycle and pedestrian generally have modest effects on emissions,” and “Bicycle and pedestrian trips may be more effective when designed to enhance access to transit, so that longer trips lengths may be reduced.”

Traditionally, road and highway design standards and traffic control systems have included provisions for providing infrastructure (ways, intersections, and traffic control) specifically for pedestrians and motorized vehicles, but not for bicycles. Efforts have recently been made to improve bicycle facilities, but these have consisted mainly of striping bicycle lanes without increasing available road space and without providing for exclusive traffic control for bicyclists. More recently, separate bike paths and trails, which are sometimes shared with pedestrians, have been provided to this end. Lack of available space in urban and some rural areas makes the ubiquitous provision of exclusive bikeways expensive, if not impossible, to implement. Some cities are trying to provide better bicycle facilities by converting motor vehicle lanes to exclusive bikeways, which the City of San Jose, Calif. recently implemented. Some of these actions are directed to improving the safety of bicyclists, but they could possibly also have the effect of increasing the probability of death and injury, as will be discussed in this report. Considerable attention has been given to designing interconnected bicycle systems in some cities. This strategy will also be discussed in this report.

New concepts for transportation systems, which include bicycling, have moved to the forefront. Two such new concepts are “Complete Streets” and “Road Diets.” According to the National Complete Streets Coalition,¹⁴ “Complete Streets are streets for everyone. They are designed and operated to enable safe access for all users. Pedestrians, bicyclists, motorists and transit riders of all ages and abilities must be able to safely move along

and across a complete street. Complete Streets make it easy to cross the street, walk to shops, and bicycle to work. They allow buses to run on time and make it safe for people to walk to and from train stations.”

Separating different modes of travel and/or providing different modes of travel in the right of way have been done for a long time. Unfortunately these types of designs have now become ends in themselves instead of determining how well these designs, which are essentially only alternatives to several possible design configurations, carry out the main function of the transportation system, i.e., traveling from point A to point B. Because the demand for transportation is mainly a derived demand, the central objective is to minimize the cost of transportation (for people and goods), which includes the cost of infrastructure, and user costs consisting of delay (or travel time), vehicle operating costs, and accident costs. Merely having a “Complete Street” does not mean that the central objective is optimized. Having empty buses in bus lanes and little-utilized bicycle lanes may not result in a good use of resources.

Politics play a role in the promotion of bicycling through the involvement of advocacy groups. In California, for instance, the California Bicycle Coalition, the AARP California and other similar organizations sponsored the California Complete Streets Act of 2008.¹⁵ In the Oakland, California, Bicycle Plan of 2007,¹⁶ the City had a goal to become a bicycle friendly community by 2012, as recognized by the League of American Bicyclists. Having such a goal may not necessarily ensure optimal allocation of resources for transportation facilities for all modes, because it may be unlikely that an organization focused on bicycling would stop wanting more infrastructure or benefits for bicyclists.

It is incumbent upon designers to improve road safety for all concerned, including bicyclists. Given the misconceptions whereupon bicycling is promoted, the designer is faced with solving traffic safety problems that are directly caused by promoting bicycling. Creating more clarity and objectivity about the issues that must be addressed in design will lead to better and safer transportation.

Because the point of departure or context influences the design issues significantly, various contexts used to provide structure to the report will be discussed in the next section, followed by discussion of the design issues within each of these contexts. Finally, a summary of major conclusions and suggestions for further study will be presented.

Because the range of subject matter was larger than just a focus on bicycling, it was not possible to present an extensive literature review on all the issues. The subject matter ranges from bicycle-related items to road design and traffic engineering. Moreover, some theory related to travel forecasting, benefit-cost analysis, system design, and the relationship of traffic to land use patterns was applied to illustrate the effect of adding bicycle lanes and paths. The literature that was cited consisted of those that illustrate the shortcomings related to the policy and practice regarding bicycle infrastructure. It was impossible within the scope of this project to provide the background to some of the theory. Some readers may have to review these theories. A thorough understanding of the principles of road design and related standards, as well as some fundamental traffic engineering theory of and the operational effects of geometric design, is also required to understand some of the concepts utilized in this report.

II. THE CONTEXTS USED FOR THE DISCUSSION OF THE DESIGN OF BICYCLE FACILITIES

Transportation facilities have traditionally been designed within a context that may vary from place to place. This process was first formalized with the National Environmental Policy Act (NEPA) of 1970.¹⁷ This process has further evolved into a process called “Context-Sensitive Solutions” (CSS), which takes into account the physical and historical aspects of the environment during project development as well as the values and needs of other affected stakeholders, including the community wherein the project is located.¹⁸ It is this author’s opinion that this process will continue to evolve and ultimately will require more structure than it currently has in order to ensure that projects are carried out efficiently.

While the CSS process is a broad-based approach to implementing transportation facilities, there are more specific contexts and associated procedures that must be considered to gain understanding of the issues related to the design aspects of bicycle facilities. Some of these contexts and procedures have been established for a long time but have not necessarily been implemented in a consistent basis, even as part of the CSS process. It should be pointed out that the use of the word “context” here is somewhat different from the use of the word in CSS and is more specific to the point of departure of the design approach. The meaning of the word “context” will be articulated in each of the ensuing discussions. The choice of the contexts is based on the author’s decision, and they are used primarily to provide structure to the report. It is not implied that these are standard contexts. These contexts or points of departure will be discussed in the order of the more specific to the more general.

The first context is the “operator-equipment-environment,” in which the word “environment” primarily indicates the infrastructure, e.g., bike lanes, intersections, etc. From the safety point of view, the temporal aspect can also be considered, i.e., whether the condition is before, during, or after the crash. Haddon developed this concept.¹⁹

The second context is the place of engineering in the context of the “four Es” traditionally implemented to improve road safety, which was an approach followed by some transportation agencies in the 1990s to serve as a basis for the development of road safety management systems. They are:

- Engineering,
- Education,
- Enforcement, and
- Emergency response.

The maximum benefit in terms of safety improvement can be had when all elements are present in a transportation system and it stands to reason that the improvement will be maximized when synergy is attained among the four Es. “Encouragement” is sometimes used in this context, but this term could be confusing. If it were meant to encourage

bicyclists to wear helmets and obey traffic laws, then it would be advisable. If it were intended merely to encourage bicycling, it could lead to increased risk of injury and death.

The third context is the place of design within the life cycle of a project: planning, design, construction, maintenance, and operation. It should be noted that design takes place not only in the traditional “design” stage of the cycle, but also during the planning phase, in which the system is “designed” or “planned,” and the function, objectives, and constraints for the detailed design is defined. In addition, improvements can also be made after the system has been in operation. Very often, these improvements are for the purpose of improving safety.

The fourth context is the land-use context. The term “land use” is used here in the broad context. There are different aspects that can be considered. There is the land-use/transportation interaction. Without appropriate transportation infrastructure, a development, such as a shopping center, cannot be successful. Transportation infrastructure developed in a vacuum, such as the proverbial “bridge to nowhere,” is a waste of resources.

Other land-use-related aspects can be considered, such as the design of the streetscape, particularly those that are related to the inclusion of bicyclists. A good example of the latter is the concept of “complete streets,” wherein the idea is to provide facilities for multiple modes of transportation, including bicycles. It could be argued that this is merely a term for an old concept because bicycles have not been prohibited from using most roads, with limited-access roads (such as freeways) generally being the exception.

The contexts discussed above are not exhaustive, but they represent the major traditional points of departure for transportation safety design, in particular road safety design, which is highly relevant for bicycle infrastructure design. It is quite important to consider these various contexts within which design takes place to understand the extent to which improved design can lead to improved safety and also the limitations placed upon the designer. Even though it could be argued that the safety aspects of the design of infrastructure components (versus system design) are the most prominent of the design aspects, there are still other aspects (such as mobility) to consider. Multiple actors are involved in the process: planners, politicians, regulators, and others.

The safety design for bicycle infrastructure will be discussed within these contexts in the following sections of this report. Considerable overlap exists among the contexts. All the factors that may be considered within a context are not discussed under each context to minimize duplication.

III. DESIGN WITHIN THE CONTEXT OF THE OPERATOR-EQUIPMENT-ENVIRONMENT

THE BASIC FRAMEWORK

The concept developed by William Haddon²⁰ developed a matrix of the different aspects of the “operator-equipment-environment.” It can be depicted in the following way:

	Before Crash	During Crash	After Crash
Operator			
Vehicle and Equipment			
Environment (infrastructure)			

Much of the environment is the road or path infrastructure. From the safety point of view, the objective is to provide an environment, before a crash, that will ensure that the bicyclist can operate the bicycle safely within the environment. If the same approach for the design of roadways for motor vehicles would be followed for designing bicycle lanes, then the operator characteristics, the equipment capabilities (design vehicle), and the design speed would have to be specified. Then the roadway would be designed based on these factors.

During a crash, the objective is to make it as safe for the operator as possible. For example, signs or any other appurtenances should be placed as far away as possible from the traveled way so they do not contribute to injury of a bicyclist.

After a crash, there should be an opportunity for the bicyclist to recover. In the case of motor vehicles, an example would be to provide a flat roadside where the driver of a vehicle that has run off the road can recover control.

Notwithstanding the fact that the designer works primarily in the design of the environment, improved road safety results from combining safety improvements that involve the operator, vehicle/equipment, and the environment, along with the synergy among these elements.

The issues, challenges and problems associated with the operator, equipment, and environment, relevant for bicycle transportation, will be discussed in the following sub-sections of the report. Parallels will be drawn with design for bicycles and motor vehicles, for which design policies are relatively more mature. The discussion is not meant to be exhaustive, but it is intended to provide a perspective on the challenges faced in designing and operating roads and paths for bicycles.

THE OPERATOR CHARACTERISTICS

For the purpose of this discussion, operator characteristics will be considered in the following categories:

- The ability of the operator (bicyclist) to control the vehicle/equipment,
- The ability to respond to the way (roadway or bike path) conditions,

- The ability to respond to traffic conditions,
- The ability to respond to traffic control, and
- The characteristics that influence the ability of other vehicle operators to respond to bicyclists.

The ability of a bicyclist to control a bicycle includes the capability to power (accelerate and maintain a certain speed) a bicycle, steer the bicycle, and decelerate or bring the bicycle to a stop. Drivers must pass licensing tests for operating different classes of vehicles, and there is a narrower and relatively higher level of vehicle operating skills that the designer can count on, as compared with bicyclist characteristics. Physical capabilities play, relatively speaking, significantly less of a role in the operation of motor vehicles than in the operation of bicycles. For instance, the ability for a motorist to accelerate, maintain a sustained speed over a long distance, or negotiate a horizontal curve is more a function of the vehicle than the physical capability of the driver. In contrast, bicyclists must provide the power for accelerating through an intersection or up an incline and the skill to negotiate a sharp turn. A young child or older person would be expected to have much lower ability to accelerate than a young adult and may be less capable of balancing the bicycle and riding in a straight line.

Besides the obvious problems with having relatively unskilled bicyclists that can injure themselves and others, the relatively broad range of operating and physical dimensions, such as height, present the designer with some very difficult challenges. As will be discussed in a later section of this report, eye height plays an important role in the design of a roadway. It determines the ability of a vehicle operator to observe an object and take evasive action. Roadway elements such as vertical curves are designed accordingly. It appears reasonable to use standard eye heights for motorized vehicles because people are permitted to drive a vehicle when they are adults or approaching adulthood. However, the same is not true for bicyclists.

Another complicating factor in the provision of efficient and safe bicycle facilities is the lack of knowledge about bicyclists' responses to emergency situations. For example, much is known about the ability of a motor vehicle driver to perceive, react, and brake to a stop when necessary. Road facilities are designed to make provision for these parameters. Comparatively, very little is known of the same characteristics for bicyclists because of the great variation in the age, physical capability, and skill level.

The way in which motor vehicle operators respond to traffic conditions has been studied extensively. Much is known about perception-reaction time, gap acceptance, car following, etc., and the effects that these kinds of factors have on traffic flow and road safety. Not only is much less known about bicyclist behavior, but the range of their behavior will be greater because bicyclists are not licensed and there is a greater range in their maturity.

Another operator-related issue is the complexity created by mixing motor vehicle traffic and bicyclists at intersections. The perception-reaction time taken into account to provide

stopping sight distance in the design of a section of roadway is normally based upon one bit of information (such as one object on the road or one other vehicle). However, in complex situations, such as would be experienced at an urban intersection, decision sight distance should ideally be taken into account because drivers must process more bits of information. Decision sight distance for a stop in an urban situation is considerably longer than the stopping sight distance considered for one section of roadway. Decision sight distance is a parameter that has been considered only in the last few decades and only in relatively few intersection designs. This is because of the high cost associated with this type of design and the limitations that undulating topography places on accommodating a design based on decision sight distance. Most intersections had existed before the consideration of decision sight distance, and therefore a relatively small percentage of intersections account for decision sight distance. Adding bicyclists to the mix of traffic at intersections requires drivers to consider more bits of information. Similarly, bicyclists must pay increased attention to a complicated environment.

The ageing of the general population and the concomitant increase in the age of drivers are increasingly presenting a challenge for road designers. Whereas vehicles are increasingly outfitted with warning devices and a degree of automation to offset some of the problems accompanying the ageing drivers, it is hard to imagine that the same effects can be achieved for bicyclists. In the author's opinion, this would probably not make bicycling the choice for a personal travel mode by an elderly person.

Motor vehicles are generally much more visible than bicyclists because of their size and requirements for lights. In dense traffic, bicyclists may not be as visible as motor vehicles; consequently motorists may focus more on other motor vehicles and less on bicyclists. The result is that bicyclists may have to be relatively more defensive and make themselves more visible to ensure their safety. Jacobsen²¹ reported that there is safety in having more bicyclists on the road, which leads to more awareness of bicyclists. In cities such as Amsterdam, there are also fewer vehicles on the road, leading to a lower probability of collisions between motor vehicles and bicyclists.

As mentioned before, most bicycle trips in the United States are undertaken for recreation and exercise. The Pedestrian and Bicycle Information Center²² reported on data about the purpose of bicycle trips, which was contained in the 2002 National Survey of Pedestrian and Bicyclist Attitudes and Behaviors as well as in the 2003 Omnibus Survey by the Bureau of Transportation Statistics (BTS). According to the first survey, recreation accounted for 26% of trips and exercise/health for 23.6% of trips. Commuting to work or school comprised only 5% of trips. According to the BTS data, the majority of trips were undertaken for exercise/health (41%) and recreation (37%), with only 5% for commuting. If some of the bicycle trips undertaken for recreation and exercise could be taken off the roads and streets (away from motor vehicles) and transferred to trails, a safer situation for all travelers could result.

THE EQUIPMENT

Cars are configured in ways that alleviate the effects of collisions. Safety features such as crumple zones, same-level bumpers, and air bags, as well as mandatory use of seats belts and child seats, all contribute to improving safety of motorists during the crash.

Improvements in brakes (anti-lock brake systems, or ABS), improved steering, and similar features help in controlling the vehicle. Motor vehicles are increasingly becoming better equipped to prevent collisions with the aid of equipment that can detect nearby objects, including other vehicles. The objective of research into some modern equipment is to eliminate human factors, such as having to react to an emergency situation, and thereby prevent collisions. Police officers regularly enforce regulations for road-worthiness of motor vehicles, such as having working taillights and headlights.

Conversely, ill-maintained bicycles are often seen. Unlike the majority of motor vehicles, bicycles are not necessarily equipped with rear-view mirrors, reflectors, and other equipment, such as warning devices that would make them visible and improve safe operation. Some bicycles have better brakes than others, but the sophistication is not comparable to motor vehicle equipment. Additionally, bicycles cannot be configured with the same safety features, such as seat belts, that motor vehicles have.

Bicycle helmets generally are not mandated for adults in the U.S., although helmet use plays a critical part in bicycling safety. Omweg²³ notes in a discussion of bicycle safety data that 62% to 90% of all bicycle crash fatalities involve head injuries and that properly-fitted and approved-design helmets can reduce head and brain injuries by 70% to 85%. Moreover, small children are exposed to injury when they are placed on carriers mounted on bicycles or towed behind a bicycle. These differences between bicycles and motor vehicles make bicycles inherently less safe than motor vehicles.

Facilities for motor vehicles are designed for specific driver characteristics and for a specific chosen design vehicle. Upon choosing the appropriate design vehicle, the roads must be designed at least for the characteristics of that design vehicle. For instance, it is customary to design state roads for all legal vehicles in a given state, but residential streets are not required to be designed for all legal design vehicles. Further, drivers must be licensed for a particular type of motor vehicle class. Although some attempts have been made to classify bicyclists according to their characteristics and the trip objective—for example, recreation versus commuting—it is very difficult to apply one set of characteristics for a specific facility because bicyclists of all ages and abilities are permitted to use almost all roads, with the exception of freeways (or more appropriately stated, access-controlled roads). For example, the California Highway Design Manual²⁴ specifies only one eye height for all bicyclists, i.e., 4.5 feet (1.4 meters). It specifies the eye height of automobile drivers at 3.5 feet (1.07 meters). The American Association of Highway and Transportation Officials²⁵ specifies 8 feet (2.4 meters) as the eye height for a truck driver.

An often-overlooked fact is that bicycles are inherently unstable, and consequently they are relatively more prone to a crash caused by instability. Except for improving the quality of the pavement, better design of bicycle facilities will not solve this problem.

THE ENVIRONMENT

The environment for bicyclists includes the way (road or dedicated facility) and associated infrastructure (road signs, etc.), other traffic traveling in the same direction, intersecting traffic, intersection infrastructure, and the wayside (or roadside). A major objective of the

design and control of this environment is to maximize safety for all modes. The discussion in this section will be primarily about the infrastructure components. Attention will be given in a later section to safety issues relevant for designing the transportation system that incorporates the network of roads and control systems.

It is extremely important to note that the environment for bicyclists is very rarely disconnected from the environment for other modes. Trails and bike paths made exclusively for bicycling would be an exception. This issue is important because standards for the design of bicycle facilities often fail to recognize this point. In other words, the design standards for bike lanes and the design standards for motor vehicles are different, but the two types of vehicles and operators must be accommodated on the same road or street.

A review of studies on pedestrian and bicyclist safety by Karsch, et al.²⁶ reported that in 2009 (from data obtained from the Centers for Disease Control), 200,748 people were treated for bicycle-related injuries occurring in traffic, representing a rate of 66 per 100,000 population. However, 518,750 people were transferred to hospital emergency rooms or hospitalized for bicycle-related injuries occurring in public and non-public roadways, which represents a rate of 175 injuries per 100,000 people. Czerwinsky²⁷ analyzed bicycle-involved accident data and found that 62% of the accidents involved a fall, 15% involved a motor vehicle, while 4% involved both a fall and a motor vehicle. The remainder also could have been related to a fall or a vehicle. Czerwinsky also found only 22% of bicycle accidents that required visits to emergency rooms occurred on streets. It can therefore be seen that cycling in traffic is not the only significant source of bicycle-related injuries.

Notwithstanding the fact that a large proportion of bicyclist crashes do not involve a motor vehicle, it is useful to note the specific effects that the mix of traffic has on crashes. According to research conducted by Solomon,²⁸ the probability of being involved in a crash increases exponentially with differences in speed. Having bicycles mixed with motor vehicles on roads, where the speeds between the two modes are significantly different, leads to higher frequencies of crashes. The severity of crashes is proportional to the mass and the squared value of the speed, with the result that a collision between a motor vehicle traveling at high speed and a bicyclist often leads to death or serious injury for the bicyclist. The same factors play a role in collisions when bicyclists mix with pedestrians on sidewalks. One obvious solution is to provide separate bikeways, but this is not a simple matter, as will be discussed later in this report. It also should be noted that in a city, such as Amsterdam, where there are a large number of bicyclists traveling at the same speed, that the absence of differences in speed makes it safer for the bicyclists. Conversely, putting well-trained bicyclists, racing at high speeds in bikeways, which are separated from motor vehicles and pedestrians, together with slower bicyclists can still lead to collisions with bad outcomes. It should be noted that separate bikeways should be accessible by emergency responders for treating injuries after a crash.

The characteristics of the environment of a specific component (bike lane, bikeway, etc.) include the quality of the road surface, the geometric design of the facility (vertical alignment, horizontal alignment, and cross section), the control systems, the roadside (or wayside) design, and the nature of the component, i.e., whether it is a separate bikeway or not. The roadside influences some of the outcomes when a bicyclist loses control and departs the

traveled way. A forgiving wayside will reduce the severity of injury, but if a bicyclist were to fall in a roadway, where motor vehicles were present, there could be dire consequences.

Most urban traffic accidents occur at intersections. Much is known about the response of drivers to signals, their response time to traffic interval changes, lost time, etc. Relatively less is known about bicyclist behavior. Whereas motor vehicles and pedestrians are channeled through the intersection in traffic lanes and pedestrian crossings or governed by specific laws, such as a driver having to yield to pedestrians, bicyclists' responses are not specified to the same degree. For example, bicycles could turn with motor vehicles from the left lane from different positions relative to the motor vehicles, or bicyclists could use the crosswalk to first cross the street and then use the next crosswalk to complete the left-turn maneuver. The latter movement is probably the safest, but it is not required.

Adding bicyclists to the traffic stream causes an additional set of conflicts at intersections. Motor vehicles turning left at an intersection will have conflicts with motor vehicles and pedestrians. Conflicting movements, such as merging and diverging as well as crossing movements, can cause collisions. These conflicts for the motor vehicle population are often eliminated through channelization and providing separate turning phases for signalized intersections. Bicycle lanes may attract more bicyclists to the bicycle lane from other streets (or, as discussed elsewhere in the report, generated because of an improved supply function) because their perception is that the bicycle lane may provide safer travel conditions. The bicycle lane may provide safer conditions resulting from separation from automobiles and mitigating the effect of the differences and speed. However, the intersection may present an increased risk. When more bicycles pass through the intersection, the turning vehicles and bicyclists will encounter more conflicts. Taking the right-turn vehicles as an example, the crossing conflicts with bicycles will be akin to vehicles turning right from the second lane from the left across the vehicles going straight through the intersection. This situation is exacerbated by the left-turning vehicles because the bicyclists may be obscured by the oncoming vehicles. Because data on accidents as related to combinations of road and intersection treatments could not be found, this topic may be worthwhile to research. It should be noted that bike lanes would not necessarily be safer for bicyclists under nighttime conditions, when bicyclists will be relatively less visible.

At a broader level, societal attitudes about transportation are part of the environment wherein transportation takes place. As will be discussed in more detail later in this report, land use and the urban form can have a major influence on the environment, which, in turn, can be more or less conducive to bicycling. Cultural differences among countries make a difference in the attitudes toward bicycling. In some European cities, such as Amsterdam, a relatively large proportion of people use bicycles. One could speculate that cultural differences between the Dutch and Americans could account for, in this author's opinion, the greater tolerance in the Netherlands toward bicyclists, or perhaps bicyclists are better behaved in the Netherlands. In addition, a city such as Amsterdam is relatively compact, with a high residential density and with living spaces relatively close to workplaces. Consequently, trips are relatively shorter than they would be in a modern city in the United States, where residential density is relatively lower. In addition, public transportation availability is relatively high in Amsterdam, and road space for automobiles is limited, which are factors that make it more difficult for people to use automobiles.

Because space is so limited, it makes bicycling relatively more attractive as a means of personal transportation. Added to these factors is the relatively higher price of fuel in the Netherlands. This creates an environment that is conducive to bicycle use.

PERSPECTIVE ON THE OPERATOR-EQUIPMENT-ENVIRONMENT CONTEXT

While it may be possible to incorporate some features into roadways and traffic control systems that could mitigate the number and severity of bicycle collisions, there are other actions that would have significant affects in mitigating the severity of injuries and reduce fatalities. One would be to mandate wearing helmets and require some level of training for bicyclists before allowing them to ride without supervision on streets. A culture of safer behavior on the bicyclists' part could be established through more education and enforcement of traffic laws. Bicyclists could be required to use crosswalks and to cross with pedestrians during pedestrian phases of the signal to complete turning or crossing maneuvers. It should be noted that this type of operation may be seen in some European cities, where bicyclists have their own signal phases.

Additional bike paths and trails could be established to separate bicyclists horizontally and vertically (grade separation) from motor vehicle traffic and increase safety, but there would never be adequate funds available to achieve this on a large scale. Bicyclists would mix with some motor vehicles at some point. Additionally, any such action would not eliminate the danger of falling off a bicycle without involvement from other road users.

Some advancement in design standards could be made by more integration of bicycle facility design standards into design standards and manuals for motor vehicles. This could shed more light on the resolution of conflicting requirements for bicyclists and motor vehicles.

IV. DESIGN WITHIN THE ENGINEERING-EDUCATION-ENFORCEMENT-EMERGENCY RESPONSE CONTEXT

The context of engineering, education, enforcement, and emergency response is directed primarily toward the safety of the transportation system. This topic has been well documented for motor vehicles and to a lesser extent for bicycling. The discussion in this chapter will focus on the broad aspects of these topics.

ENGINEERING

The design of any type of transportation infrastructure is a very complex issue regarding both the design of the system and the individual components of the system. Because the major portion transportation system is mostly already in place, current and future projects consist mostly of improvements. The task of adding onto or improving the system is becoming increasingly difficult because major construction must occur while minimizing traffic delay. Retrofitting roads with bicycle lanes or paths is especially complex because traditionally very few roads were designed specifically for bicycles.

Some issues pertaining to the design of bicycle travel facilities were discussed in the previous chapter, and some overlap with this discussion is unavoidable. However, the issues will be approached from a different perspective in this chapter. Additionally, some of the system design issues will be addressed. As before, some parallels will be drawn between the design principles appropriate for motor vehicles and those appropriate for bicycles.

Some Basic Aspects of Design of Roads for Motor Vehicles

Road design for motorized vehicles is focused on mobility (throughput) and safety. Mobility is a function of traffic, control, and roadway conditions. Because the central topic of this report is the safety aspect of design, design with respect to safety will be the focus of discussion in this section. However, as will be pointed out, mobility affects safety directly (on the road itself) and indirectly (when traffic is diverted to other roads). It should be noted that the access function of the majority of streets is also important and will be addressed.

Modern roadway design procedures and standards have been evolving over the last century, since the advent of motor vehicles. It is quite complex, and it is outside the scope of this report to provide an exhaustive discussion of the topic. However, a comprehensive discussion can be found in the procedures documented in the American Association of State Highway and Transportation Officials' (AASHTO) "A Policy on Geometric Design of Highways and Streets." ²⁹

The aspect of design related to providing sight distance was introduced in the previous chapter. It will be more fully articulated here. Providing adequate sight distance will allow a driver to perceive, react, and take appropriate action. The sight distances include: stopping sight distance, horizontal sight distance, decision sight distance, and passing sight distance. Intersection sight distance is related to stopping, horizontal, and decision sight distance. In large part, the procedures focus on the movement of one vehicle on a specific section of roadway.

Consider the design for stopping sight distance. A large part of the design procedure for safety is based on designing for stopping sight distance, although this is not the only safety “distance” that is used in design. Design for stopping sight distance starts with selecting the design vehicle (the basic vehicular characteristics that the road will be designed for) and the design speed (the minimum speed that the road will be designed for). Then the road is designed in such a way that the driver can see an object of a specified height on the road surface and will have adequate distance to perceive, react, and brake to a stop. The perception-reaction time is based upon one bit of information for unalerted conditions for the 85th percentile of all drivers. The value is 2.5 seconds. The braking distance is a function of the vehicle’s braking system as well as the quality of the road surface. The eye height for a passenger car, when used as the design vehicle, is generally specified as 3.5 feet (1.07 meters). Object heights are not standard across all design standards, but they usually vary between 0.5 foot (0.15 meters) and 2 feet (0.6 meters), although the surface of the road can be the appropriate “object” under certain circumstances.

Selection of the design speed is a significant part of the process. It is usually associated with the type of facility, which is defined by its primary function in the hierarchy of streets or roads. In the case of roadways, the alternative functions consist of:

- Mobility
- Collection and distribution
- Access

The design speed is usually higher for roads that have the primary function of mobility (carrying large volumes of different types of vehicles at relatively high speeds) and roads designed for long-distance travel. These roads include freeways, expressways, and other arterial roads. These types of roads are more costly because they provide more traffic lanes, requiring relatively flatter grades, horizontal curves with longer radii, and longer vertical curves. Added safety features, such as providing clear zones, wherein vehicles that have accidentally left the traveled way can recover without colliding with hazardous objects, contribute to higher cost.

At the other end of the spectrum, access roads, such as local or residential streets, have lower design speeds and associated standards because these facilities function to provide access to a terminal such as a house garage. These roads are not designed for carrying large volumes of traffic. Roads that collect vehicles from access roads and feed them into the arterials are known as collector roads. These roads also have the reverse function of distributing traffic to access roads, and they have standards in between arterials and access roads. Commercial areas have a similar hierarchy of streets.

In the AASHTO Policy,³⁰ there are 20 distinct design vehicles. Choosing the appropriate design vehicle for a road will impact both the safety and cost of the road. For example, designing for a passenger car requires a relatively lower eye height, which requires relatively flatter roads. Designing for a truck necessitates longer radius curves.

An important principle in planning and designing road systems, from both a mobility and safety perspective, is to establish a properly balanced hierarchy of arterial, collector, and access roads. The principle is to have enough capacity and relatively shorter travel times to attract high volumes of traffic to the arterials. If this principle were not maintained, then it could become relatively more attractive for traffic to divert through residential neighborhoods, with resulting lower levels of road safety. This situation can arise when higher-density developments are allowed than were expected when the road system was planned, with consequent increased trip generation. Travel times through neighborhoods can become shorter than on the arterials and also less frustrating for the drivers. Consequently drivers can choose to cut through neighborhoods and cause unsafe conditions with their presence. "Traffic calming" procedures have been developed to mitigate this situation.

Traffic calming methods include prohibiting or slowing down traffic that cuts through residential neighborhoods. These strategies can be successful to a greater or lesser degree, but they point to a failure in planning or system management. In this case, neither the arterials nor the local streets function in the way that they should. The result could be the deterioration of neighborhoods, or, in the case of commercial areas, relocation of businesses. An argument could be made that this lack of adequate capacity on arterial streets could be addressed by providing more and better public transportation, but public transportation often does not provide the accessibility provided by automobiles in the modern U.S. cities characterized by urban sprawl.

An important principle employed in road design is the separation of vehicles travelling at different speeds. Solomon³¹ found that the frequency of involvement in collisions increased exponentially with differences in speed. For this reason, vehicles travelling at different speeds are separated. An example of implementing this principle is the provision of separate right-turning lanes at intersections and interchanges. Another is the requirement of traveling at a minimum speed on a freeway.

Aspects of the Design of Bicycle Facilities

The design of bicycle facilities can be approached in a manner similar to the design of roadways for motor vehicles. The California Department of Transportation defines three types of facilities: bike paths, bike lanes, and bike routes.³² Its specifications for these types of facilities are:

Bike paths provide for bicycle travel separate from motor vehicles and are designated for recreational use or high-speed commuting. Three design speeds are specified: 20 mph/32 kmh (mopeds prohibited), 30 mph/48 kmh (mopeds allowed), and 30 mph/48 kmh (on long downgrades - steeper than 4% and longer than 500 feet, or 152 meters).

Bike lanes are implemented on streets in corridors with significant bicycle demand. Adequate space for bicycles should be provided by narrowing vehicle lanes, removing vehicle lanes, removing parking etc. Merely painting bike lanes without providing adequate space is not considered adequate.

Bike routes are intended to provide continuity to other bicycle facilities. These routes should be maintained for bicycle use. In some cities, bicycle plans have been developed to provide connected networks of bicycle facilities and information on these networks is widely disseminated.

Providing bike paths and lanes could improve bicycling safety because of separating the bicycles from motor vehicles. However, important issues must be considered before thinking that safety would be improved by implementing these facilities. A caveat is that the number of bicyclists would remain the same. As will be discussed more fully in a following section of this report, providing more bicycle facilities can encourage bicycling, which could lead to an increase in injuries and fatalities. Promotion of bicycling could have the same effect.

Another issue to consider is whether the provision of these facilities could endanger other travelers or inherently increase the risk to bicyclists. An example of such a situation can be found in the central area of San Jose, Calif. Recently one of three lanes in a one-way street, which directly connects to an interchange, was converted to a dedicated bicycle lane. The result is that the flow in the remaining two general-use lanes increased substantially, together with an increase in intersection delay. A potentially hazardous condition exists for both bicyclists and motorists. During peak traffic periods, this author frequently observed drivers, wanting to turn right, entering the bicycle lane far in advance of the 200 feet (approximately 61 meters) that the California traffic laws call for.³³ Sometimes motor vehicles would enter the bicycle lane at the intersection preceding the desired right turn, which could be at the next intersection. These vehicles generally traveled at higher speeds than the vehicles in the general-use lanes, which were in some cases stopped. The drivers who waited to enter the bicycle lane at the correct location then had to contend with the unexpected situation wherein the drivers who had entered the bicycle lane further back approached them at high speed. This situation was exacerbated when the vehicles entering the bicycle lane at the appropriate location (200 feet, or approximately 61 meters) did so at a very low speed. In other circumstances, drivers entered the bicycle lane before the 200 feet (approximately 61 meters) mark from a stopped condition, while another vehicle approached at high speed in the bicycle lane. These differences in speed increase the probability of collisions. A contributing factor may be that there are relatively few bicyclists in the bike lane. This situation would become worse if bicyclists were to ride in the wrong direction in the bicycle lane and if skateboarders were to enter the bike lane.

Further problems are created by this change. Drivers wanting to turn right into the street from a driveway must cross the bicycle lane. Because of the increased flow during the peak traffic periods, few acceptable gaps are available and, as happens in such cases, shorter gaps are accepted, leading to some risky situations. Bicyclists, turning into the bike lane from driveways are also faced with an unexpected situation—not expecting cars traveling at high speeds in the bike lane.

Clearly, when creating a bike lane in the situation described above, there is more at stake than just the safety of the bicyclists. Care should therefore be exercised to think not only of bicyclist safety, but to consider the overall safety situation for all. It is not even clear that bicyclist safety is improved, given that bicyclists may not expect motor vehicles using the lane in the way described.

Most traffic congestion occurs during peak periods. Because a relatively small portion of bicycle trips are undertaken for commuting to work, taking away lanes from general traffic use and designating them for exclusive bicycle use could then lead to a very dangerous situation. The street situation in San Jose, described above, illustrates the problems arising from trying to create better conditions for relatively few bicyclists while causing problems for a large number of motorists. On the other hand, bicycling for recreation and exercise, which constitute more than half of all bicycle trips, could likely occur in areas where the roads do not have high standards, such as in rolling and mountainous terrain. It may be cost-prohibitive to re-design these types of roads to make them safer for all to use. These types of roads are currently used for recreation and exercise and may be unsafe to use, but the situation will become less safe if bicycling were to be promoted for reasons of improving health.

Integrating bicycle facilities with motor vehicle facilities is not a simple matter. An additional complicating factor is that classifications for different types of bicycle facilities are not the same as classifications for roads intended for motor vehicles. Whereas the latter is classified in terms of functionality, i.e., mobility versus access, the classification of bicycle facilities could be characterized in terms of the degree of separation from motor vehicles (bike lane versus bike path).

In most urban areas it would be unlikely that an extensive integrated network of bike paths could be created, primarily because of the already-existing development. Bicycling would still occur primarily on streets, without separate bike lanes or paths, with the accompanying risk.

The implementation of “complete streets” (in which provision is made for all modes with “equal” importance) or “road diets” (with bike lanes) could be an improvement in some situations, but it could also lead to a deterioration of mobility and safety in other situations. In densely populated neighborhoods, transit could provide greater mobility in a safe manner if care were taken to make access to train stations and bus stops safe and secure for passengers. Walking and bicycling, in the absence of high automobile flows, could provide access. However, in an area where population density is relatively lower and trip lengths longer, creating a complete street or a road diet could decrease capacity for the longer trips and reduce safety if automobiles were to be diverted through residential neighborhoods. Creating “complete streets” may be easier in densely populated cities with good public transportation, where it is inconvenient to drive a car.

EDUCATION

Education and training are important issues for bicyclists (as well as for drivers and pedestrians). Not only must bicyclists be able to operate an unstable vehicle in traffic, but they also must be aware of the risk of riding a bicycle and more specifically riding in certain circumstances. It means that bicyclists should be educated about bicycling in general, but they also should receive training. Training would encompass handling the bicycle and responding to roadway and traffic conditions as well as how often and how much to ride. Overuse injuries could occur. In addition, the operators are much more diverse than are motor vehicle drivers, making education and training more difficult. Absent mandatory licensing, education becomes even more essential.

Much more can be said about this topic, but the major purpose of this discussion is about how education can have a positive effect on the safety-related design of bicycle facilities. In the broad sense, bicyclists can be educated to ride on certain roads and circumstances and discouraged to ride on other roads and circumstances. Designers can be helpful in designating roads that would fit the two classifications. They will then be able to improve safety for all facilities that lend themselves to bicycling.

Bicyclists should always be clearly informed about the risk of bicycling. This is contrary to the promotion of bicycling that some transportation agencies engage in and the events such as “bike to work days,” when people, who may not have ridden a bicycle for some time are enticed to bicycle in traffic. A study about the risk of injuries in sports showed that bicycling has a higher injury rate per 100,000 people than do sports such as basketball or soccer,³⁴ for example. A different form of exercise may be more appropriate. Designers cannot solve the problems arising out of such circumstances.

ENFORCEMENT

Pete Faeth³⁵ wrote an informative report on the behavior of bicyclists and their adherence or non-adherence to traffic laws in Davis, California. In a study conducted in Orlando,³⁶ it was found that 64% of all bicycle-vehicle crashes involved an unsafe choice on the part of the bicycle riders.

Enforcement for bicyclists and pedestrians is very different from enforcement for motor vehicle drivers because only the latter group is required to be licensed. Additional safety-related regulations could be promulgated to improve safety. A safer bicycle culture could be achieved by making the wearing of helmets mandatory; prohibiting towing children in a cart or carrying children on a seat on a bike; prohibiting engaging in distracting behavior, such as cell phone use while bicycling; and prohibiting bicyclists from racing to beat the lowest recorded travel times on travel routes. A change in culture would also make designing for safety more effective because the road operation would be more in sync with the intent of road designs.

Collisions occurring from unsafe choices and unlawful behavior cannot be mitigated through design solutions, but education and enforcement could help to improve safety. One could say that because bicycling has been part of community activities for so long and has largely been unregulated, there may be resistance to increased regulation and enforcement. However, given that bicycling is promoted by some transportation agencies and general-use road space is dedicated to bicycling, the safety of all road users must be given increased attention.

EMERGENCY RESPONSE

Emergency response to road accidents has many facets. Accidents must be detected first, followed by an assessment of what kind of emergency response is required, and then the emergency services must be rendered. The design of roads and streets to facilitate emergency response requires a great deal of coordination with entities tasked with emergency response. Not only must physical access be considered during design

to allow emergency response, but traffic control can also provide priority for emergency response vehicles. Because access to accident sites will not change on most roads and streets, the emergency response to bicyclist-involved accidents will not be affected. In the case of separate bicycle facilities, attention must be given to providing ready access for emergency vehicles and personnel.

PERSPECTIVE ON THE ENGINEERING-EDUCATION-ENFORCEMENT-EMERGENCY RESPONSE CONTEXT

Much has been accomplished in the last few years to establish and improve standards for the design of individual bicycle facilities. More research into and development of standards are necessary. Separate bike paths and even enough space for bike lanes were not incorporated in typical U.S. cities. As a result, it is difficult to retrofit the streets to incorporate separate lanes and separate paths for them because of urban sprawl and lack of good public transportation.

Designing better individual facilities probably cannot, by itself, significantly improve the safety of bicycling. Increased enforcement and regulation, as well as education on the risks of bicycling, could make significant contributions to improving bicycling safety. In addition, campaigns to make drivers more aware of bicyclist safety could improve the situation.

V. DESIGN WITHIN THE PLANNING-DESIGN-CONSTRUCTION-OPERATION-MAINTENANCE CONTEXT

The development and implementation of the design aspects of bicycle facilities cannot be discussed without putting it in the context of the life cycle of a project. In this regard, that life cycle can be divided into the following phases:

- Planning
- Design
- Construction
- Maintenance and operation

The planning phase dictates not only where the facility will be located, but also the functionality and design “level” of the facility. The term design “level” can be interpreted as the degree of mobility or safety aspects implicit in the design standards. The latter could include the number of lanes as well as the design speed.

It is during the planning phase that the evaluation (for feasibility) and prioritization of projects, accompanied by the allocation of funds take place. To ensure that the evaluation and prioritization of projects are efficient in terms of using scarce resources, it is imperative that the objectives and constraints for the candidate (alternative) projects be clearly defined and articulated. As discussed in the introduction to this report, a very important emerging trend is the promotion of bicycling. If bicycling were promoted, it may follow that more attractive bicycle facilities will be created. Creating more bicycle facilities for politically or other expedient reasons, which are not tested against sound principles, could actually lead to an overall condition that is less safe than without promotion, regardless of the degree of safety incorporated in the design of specific bicycle facilities. Specific attention will be given to this issue in this section of the report.

The planning outcome will dictate the design, the characteristics of the final constructed project, and what occurs during the operational and maintenance phase of a project. It should be noted that civil engineers are tasked with providing safe and efficient transportation infrastructure, but very often problems are created at the planning stage that cannot be solved at the design stage. It is especially difficult to solve problems that surface after a project has been constructed.

Because the safety aspects of the design phase were discussed in a prior section, and for the sake of simplifying the ensuing discussion, the focus of this chapter will be on the planning phase and the re-design issues emanating from the facilities operation phase and specifically the crash history during the latter phase. The process of selecting the projects to mitigate safety-related problems will also be discussed. The objectives and criteria used for mitigation will then be contrasted with the objectives and criteria commonly used for deciding on the improvements to be made for bicycling during the planning stage.

THE PLANNING STAGE

The transportation planning process is quite complex and is closely tied to land use planning. The transportation system is designed primarily to provide a connection between a source of trip production (home, etc.) and various attractions such as places of work, education, recreation, etc. With very few exceptions, the demand for transportation is a derived demand, meaning it is undertaken for the purpose of traveling to work, shopping, etc. and not for the trip itself. This is an important point relevant for planning bicycle facilities because more than one-half of bicycle trips are undertaken for the purpose of recreation and exercise. In other words, the trip is an end in itself.

It should be noted that very few major roads and streets are constructed in the U.S. Most often, existing roads and streets are improved, and the problem at hand is to decide which and what improvements to make. The discussion in this section will focus on a part of the planning process, i.e., the principles of benefit-cost analysis as applied to the project selection process and specifically how this affects the evaluation of bicycle-related projects. Some of the benefits and costs of transportation projects, including bicycle-related projects, will be included in the discussion. Additional benefits claimed for bicycling, such as the improvement of health and reduction of air pollution, and the complications of taking them into account will also be considered.

Reference will be made to the systems approach or systems engineering aspects of this process. As part of this discussion, the network aspects of the bicycle infrastructure and the relationship with the overall road network will be discussed, including the effects of the diversion of traffic resulting from dedicating existing road space to bicycling. A brief discussion of some political aspects of the decision-making process will be presented. Finally, reference will be made to some constraints to bicycling, which limits the efficacy of bicycling as a general mode of transportation and the effects that this has on the overall transportation system.

Some Aspects of Benefit-Cost Analysis

Using a benefit-cost approach for selecting projects requires that the marginal monetary values of the benefits should offset the marginal costs of providing the facilities over the useful life of the project. That is, the benefit-cost ratio must be greater or equal to one. Traditionally, the following types of benefits would be accounted for:

- The reduction of collision costs
- The decrease in vehicle operating costs
- The decrease in travel time costs

It should be pointed out that although the term “costs” is used, the benefits lie in reducing costs. The costs in the benefit-cost ratio are those accruing to the transportation agency:

- Planning

- Design
- Construction
- Maintenance
- Operation

Environmental impacts, such as reducing air pollution, are sometimes quantified, but usually not for individual, small projects. There are also multiplier effects, but these are often small and not calculated for relatively small projects.

Benefit-cost analysis, utilizing the categories of benefits and costs listed above, has been used for a long time. This procedure is not always abided by because projects may be too small to warrant the effort, or sometimes the people responsible for the implementation of the project do not know how to carry out the procedures. Of course, there are projects, such as the creation of a park, for which benefits are hard to convert to monetary values, but this is not true for most transportation projects. It is also true that there are transportation projects, such as those implemented for the mitigation of noise, in which the benefits are also hard to convert to monetary values. However, in the case of most transportation projects, the bulk of the benefits and costs can be calculated in monetary terms.

Once it has been established that a project has a benefit-cost ratio of greater than one, then the priorities for implementation of the various projects competing for scarce resources must be established. Because there are invariably more projects that have a benefit-cost ratio of greater than one, having a benefit-cost ratio of greater than one is a necessary criterion for implementation, but it is not a sufficient one. Projects must be prioritized to determine which projects have the highest priority for implementation. Needless to say, the projects must be compared or prioritized on the same basis, i.e., using the same benefits and costs categories.

When prioritizing projects, it is important to realize that there are two types of projects— independent projects and mutually exclusive projects. Independent projects (alternatives) can be implemented at the same time, while only one project (alternative) out of a set of mutually exclusive projects (alternatives) can be implemented. Deciding on whether to build a road in one state versus a road in another state is an example of having to choose between two independent alternatives—they could exist at the same time. Having stop control and signal control at the same intersection is mutually exclusive. Another example of mutually exclusive alternative projects would be if a lane on a street were to be designated for exclusive use, such as for buses only or bicycles only.

Prioritizing independent projects is relatively simple; projects are ranked based upon the benefit-cost ratio. The prioritization of mutually exclusive projects is more complicated. It must be based on incremental analysis, such as incremental benefit-cost analysis. Prioritizing a combination of both independent and mutually exclusive alternative projects should be approached in the same way as an incremental analysis. It should be noted that the budget constraint could play a role in the prioritization because it takes into account some aspects of the magnitudes of projects and could lead to a change in the rank order of the alternatives.

It should be pointed out that whether benefit-cost analysis is performed or not, the decision to implement a project implies implicitly that both criteria—that the benefit-cost ratio is greater than one and that the projects have been appropriately prioritized—have been met. It is therefore important that the implementation of a large-scale strategy, such as providing an extensive bike path network and promoting bicycling, should be required to meet both these two criteria. In addition, a benefit-cost analysis should be performed to ensure a basis of departure that will lead to effective and efficient allocation of resources. Once such a basis is established, political and other issues come into play, but absent such an analysis, the decision-making can lead to extremely bad outcomes in terms of the distributive and allocation effects. If a benefit-analysis—or an analysis based on similar principles—were not used, then the question would be: What is the basis of the analysis, or, worse, what is the bias introduced?

People normally do not question a structural engineer's decision about the soundness of a structural design. However, in the case of transportation systems, drivers, politicians, news writers, or just about any road user feel free to offer expert opinions. This is also true for bicycle transportation. The acceptance of unfettered offering of "expert" opinions underlines the importance of having a sound basis for resource allocation as a starting point.

Crash Cost Reduction

Planning and design for bicycle facilities were not explicitly carried out during the early years of creating modern transportation facilities, and bicyclists were expected to be cautious when using roadways or sidewalks. One could argue that bicycle use was primarily considered apt for those who could not or did not own a car and who did not have access to convenient public transportation, or who used bicycles for recreation.

The need to plan for and design safer bicycle facilities is an easy concept to understand, although the creation of appropriate design standards and the implementation thereof is a complex matter. One of the clear benefits would be the reduction of bicycle-related accidents or crashes. What is more difficult to rationalize is the motivation for promoting bicycling, given the increased risk involved.

Beck, et al. found that relative to passenger vehicle occupants, bicyclists are 2.3 times more likely to die on a given trip and 1.8 times as likely to be injured.³⁶ Another estimate of the relative risk involved in bicycling can be found in a publication by Teschke, et al.³⁷ They estimated fatality and non-fatal injury rates for different modes of travel in British Columbia per 100 million kilometers of travel. Based on their estimates, bicyclists are 1.44 times as likely to die as compared with passenger vehicle occupants and 3.67 times as likely to be injured.

Blincoe, et al. estimated that the lifetime economic cost (in 2010 dollars) to society of each fatality incurred in motor vehicle crashes was \$1.4 million. According to the National Highway Safety Administration,³⁹ 726 pedal cyclists were killed in the U.S. in 2012 in motor vehicle related traffic collisions. The costs of the fatalities alone would amount to more than \$1 billion in 2010 dollars. Besides the tragic loss of life and the cost to society, there would be increased psychological trauma for motor vehicle occupants, especially the

drivers, who may escape injury, regardless of whether they are the cause of the collision. Direct costs, such as legal defense costs and expenses for psychological treatment, also could be incurred for drivers.

Because the likelihood of being killed or injured is higher for a bicyclist than for a motor vehicle occupant, the costs of accidents would increase if car occupants would shift to bicycling.

It is also worthwhile to consider the problem created by measuring the performance of a system using efficiency measures for different aspects of that performance. These types of approaches can be found in the literature on transportation system evaluation and in strategic plans for public institutions. Typically, these types of measurements for transportation systems could consist of the measurement of delay, level of service of different parts of the system, number of accidents, etc. at the same time. A safety evaluation or planning system could measure the performance of the system in terms of bicyclist fatalities, pedestrian fatalities, motor vehicle-related fatalities, and so forth. C. West Churchman discussed the problem with this approach in his work "The Systems Approach."⁴⁰ Essentially, it boils down to the fact that, while implementing strategies and tactics to improve the system's performance in terms of individual measurements, the opportunity to improve the central objective may be overlooked. That central objective should be to minimize the overall cost of accidents/crashes, regardless of the mode. For example, the most cost-effective way to decrease that cost may be to allocate all the resources to pedestrian safety improvements and none to bicycle or motor vehicle related safety improvements if that were to maximize the reduction of the overall costs of crashes, which would include the cost of the mitigation measures.

Vehicle Operating Cost Reduction

The operating costs for a bicycle trip should be less than that of a comparable trip using a motor vehicle because the costs associated with motor vehicles are higher than that of the bicyclists' equipment. This is an incentive for bicycling, but it is unclear what the extent of the impact on overall transportation costs will be, given that bicycle trips are relatively short. Krizek, et al.⁴¹ considered the saving of energy to be relatively small from the creation of bike lanes, although they proposed a methodology to calculate the benefits from the reduction of auto use. This benefit should be taken into consideration when conducting an analysis, especially when conducting a benefit-cost analysis for alternative transportation systems when the trips are projected to be relatively short.

Travel Time Reduction

Examination of the travel time differences between bicyclists and people using other modes, such as public transportation, brings up some interesting issues. When motor vehicle drivers experience congestion, bicyclists could experience shorter travel times than the motorists do, especially if they are using bicycle lanes or paths. This would apply primarily in cities such as Amsterdam, but it could also occur on a smaller scale in any city under conditions of relatively significant traffic congestion. However, under the later conditions, the impact on overall congestion costs would probably be relatively small, given that bicycle trips are relatively short.

In the study conducted for the Federal Highway Administration to “evaluate and assess the direct and indirect impacts of a representative sample of Congestion Mitigation and Air Quality (CMAG)-funded projects on air quality and congestion levels,” Grant, et al.⁴² studied projects that included one bikeway, a bike path, a transit bike depot, and a cyclistNET marketing program. They concluded that congestion reduction effects are usually limited because of the relatively short trip lengths and the seasonal limitations on bicycling in some areas. They commented that reducing vehicle-miles of travel by shifting to bicycling and walking occurs more often in the case of short trips to local shopping areas, schools, or commercial districts.

When bicycles use general-use lanes and share the lanes with motor vehicles, the overall effect could be an increase in total travel time for all road users. This effect will be magnified if existing general-use lanes were restricted to bicycle use only.

Reduced Environmental Impact

In the absence of congestion, riding a bicycle to work instead of using a personal motor vehicle would reduce environmental impact. Bicycle trips taken for exercise do not reduce air pollution because they do not substitute for motor vehicle trips.

Grant, et al.⁴³ also concluded that bicycle and pedestrian projects generally have modest emissions reduction effects. They studied the changes in reduction of several pollutants and calculated the cost-effectiveness of each project. For example, it cost \$453,217 to reduce emissions by one ton of CO by building the bike path. By comparison, it cost only \$2,030 to reduce emissions by one ton of CO by improving traffic flow through freeway traffic management, and it cost between \$621 and \$115,766 when upgrading transit service was evaluated.

Promotion of bicycling could also lead to additional environmental impact. If motor vehicle traffic were to be significantly slowed down by the presence of bicyclists in shared lanes, then some air pollutants may increase. When general-use lanes in San Jose were converted for bicycle use only, motor vehicles were slowed down significantly during peak traffic periods to the point where vehicles were delayed for more than one signal cycle. Because there were very few bicyclists using the bicycle lane, the net effect was surely an increase in air pollution.

Complications Related to Health and Other Benefits Claimed for Bicycling

Benefits, other than those traditionally considered for transportation projects, are claimed for bicycling. As an example, in proposing guidelines for the analysis of investments in bicycle facilities, Krizek, et al.⁴⁴ considered improved mobility, health, and recreation as well as reduced auto use as benefits in a benefit-cost analysis. The mobility benefit appears to consist primarily of being able to bicycle, while the health benefit is based on improving a person’s overall health in terms of chronic diseases, such as cardiovascular disease and obesity. However, it does not account for the increased costs due to of death and injury resulting from crashes or musculoskeletal injuries due to overuse. The recreation benefit is related to enjoyment of the trip. The benefits from reduced auto use include reduced congestion and air pollution as well as user cost savings.

Alternative transportation projects must be compared on the same basis, i.e., considering the same benefits and costs. The benefits are dictated by the facility's function, which is for transportation—moving from point A to point B. Therefore, the benefits should be related to reduced crash, vehicle operating, and travel time costs. Reduced air pollution costs could be considered as well. In allocating road space to a mode or modes, these benefits should be calculated and used to determine the benefit costs ratios as well as the relative priority of an alternative use. Introducing health benefits is contrary to the function of the road space. The function is not for exercise. If such benefits were to be introduced in the benefit-cost analysis, then some calculations should be made for the benefit of listening to music in a car or being able to perform work tasks on a bus.

The argument could be made that the way in which Krizek, et al.⁴⁵ approached investment in bicycle facilities is well suited for evaluating trails for recreational biking but is not suited for evaluating bicycling as an alternative mode of transportation for commuting, shopping, etc. when competing for alternative uses of road space. Bicycling for these purposes should be evaluated in exactly the same way as other transportation modes. Funds for trails or bike lanes should ideally come from sources other than those intended for transportation.

The reality, however, is that recreational bicycling takes place on roads, and transportation authorities probably will continue to make safety-related improvements for bicyclists because of a desire to improve safety or because of political pressure. However, the problem with funding bicycle-related improvements is exacerbated by promoting bicycling for health/recreation benefits. Given the large proportion of trips undertaken for the latter purpose, more trips will be added in this category than for the purpose of commuting, shopping, etc., with a concomitant increase in collisions. In the author's opinion, it is regrettable that more of the focus is not on people who do not have access to personal motor vehicles and are captive to public transportation, walking, and bicycling.

It would seem unwise to encourage people to ride a bicycle in traffic if they don't have to, especially for exercise/recreational purposes. The cost of one death (\$1.4 million) resulting from the promotion of bicycling is equivalent to the cost of 5,600 stationary bicycles at \$250 apiece. Based on the 2012 record (726 bicyclist deaths), an increase of 73 deaths a year (10% of the total cyclist deaths caused by crashes with motor vehicles) resulting from promoting bicycling would be equivalent to the cost of 408,800 stationary bikes. It would seem that the better strategy would be to advise people to buy a stationary bike to exercise, exercise in another way, or buy a stationary bike instead of using a road bike to exercise.

The System Design and Network Aspects

Higher-level bicycle facilities should not be considered in isolation but also in the context of the network effects associated with them. Maps showing bicycle lane networks and bicycle-friendly roads on a regional basis are becoming more common. Cities such as San Jose, Calif. and Portland, Ore. have maps showing bicycle facilities on their websites. The emphasis of the maps appears to be on the benefits to bicyclists of having continuous networks and providing connectivity to some major destinations. However, given that more than one-half of bicycle trips have the purpose of recreation or exercise, it is unclear what the real reasons are for designing these networks.

Traffic Diversion and Mode Shift

The proper functioning of the street system is predicated upon having adequate arterial capacity and to provide the lowest travel times between origins and destinations. Then it will not be more attractive for traffic to cut through residential neighborhoods using local streets and thereby endangering pedestrians, especially children and pets. Cut-through traffic could endanger bicyclists as well.

Various actions may cause dysfunction of the hierarchical street system. The most obvious is improper design of the street system. Another may be additional land development that generates more traffic than the arterials can accommodate. Then the cities may not be able to add additional capacity to accommodate the newly generated traffic. Dedicating existing general-use lanes for specific modes, such as designating them as bus lanes or bike lanes, can have a similar effect, although the underlying reasons and consequences may be different.

While the issues discussed above are not new, the conversion of existing general-use lanes to bike lanes is relatively new. This could also be the consequence of implementing road diets and complete streets. If dedicating road space to a specific use were properly analyzed and the overall outcome in terms of mobility, safety, vehicle operating costs and the environmental impact were favorable, then such changes would be warranted. However, it is essential to understand that the dedication of more road space to bicycles—especially dedicating existing street lanes to bicycle traffic—may be unwarranted and detrimental to overall traffic movement. To understand in general terms the effects that changes to the street system and the socio-economic behavior of the population may have on traffic flow and the resulting travel-related costs, a discussion based on demand-supply theory will be presented. This theory and its application to travel forecasting have existed for decades.

From a theoretical standpoint, the traffic behavior can be described from the demand-supply interaction as shown in Figure 1. In the figure, typical demand and supply functions for a roadway are shown, where “P” is the average perceived cost of using the facility, and “Q” is the quantity or traffic flow on the road, usually measured in vehicles per hour or equivalent passenger car units per hour. The average perceived cost could contain a number of perceived cost items taken into account by a user. However, for the sake of discussion here, first assume only the perceived cost associated with the average travel time. The resulting traffic flow on a street will be at the intersection of the demand and supply functions, resulting in a flow of q_1 and an average cost of p_1 .

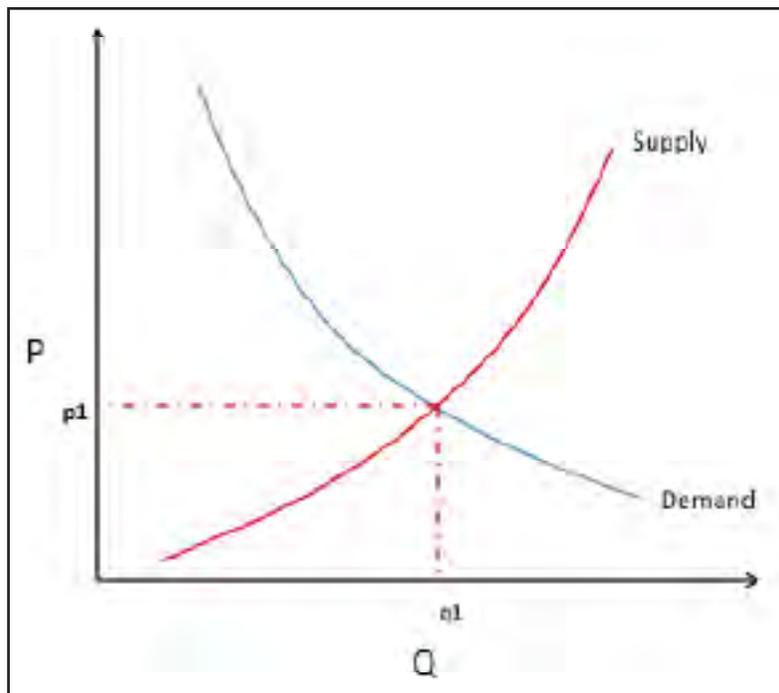


Figure 1. The Interaction of Demand and Supply

If a traffic lane were to be removed from general use on an arterial street (such as in a road diet), then the supply function on the general-use lanes would change as shown in Figure 2. (The exact shape change will depend upon a number of factors such as the original number of available lanes.) The flow will decrease from q_1 to q_2 , accompanied by an increase in average cost from p_1 to p_2 , resulting in fewer vehicles on the arterial street. It should be noted that a change in the demand function is also possible, but, generally, if the overall characteristics of the arterial street do not change, the demand function will remain the same. In an extreme situation, in which the road characteristics are substantially altered, or if there were a significant shift of trips away from motor vehicles to other modes, the demand function may also change. Some issues related to simultaneous changes in the demand and supply functions will be discussed later, but for the sake of simplifying the discussion, assume for the moment that the demand function will remain the same. It should be noted that the amount of change in the flow and price would depend upon the relative slopes of the demand and supply functions.

The extent to which the supply function will shift upward for the general-use lanes will be a function of the proportion of lanes designated for other use, such as for bicycle use only. Designating one of out two lanes in one direction will generally result in a greater reduction of flow than if one out of three lanes in one direction were taken out of general use. The reduction in flow could have surprising consequences for the street where the “road diet” takes place. Businesses on the street could experience reduced revenue, resulting from the loss of drive-by traffic.

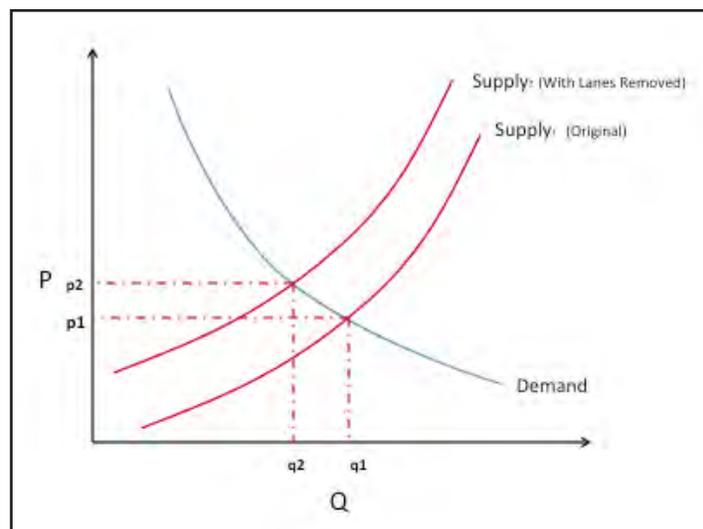


Figure 2. The Effects of Reducing General-Use Lanes on Major Streets

While some of the trips may change from the automobile mode to other modes, some trips may divert to other routes. If the supply function on an alternative route does not change (unless changes such as lane additions or traffic control were made) the situation as depicted in Figure 3 will arise, in which the traffic flow will increase on alternative routes, which could be a neighborhood street. The increases in flow (from q_3 to q_4) and average cost (from p_3 to p_4) occur because of the increased demand. It should be noted that traffic would not divert in cases in which the perceived average travel cost on the major street remains lower than the perceived average travel cost on the alternative route.

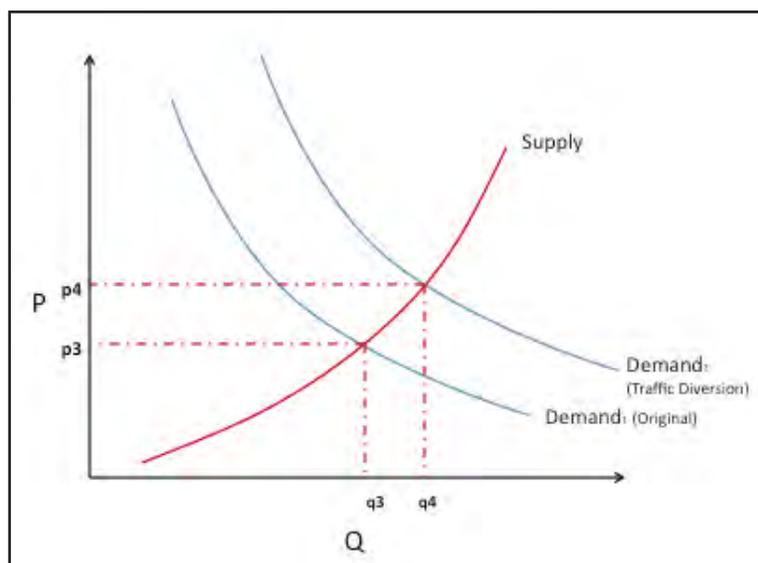


Figure 3. Traffic Diversion to Alternative Routes

The effect of the diverted traffic can be very detrimental with respect to road safety in residential neighborhoods. In general, the expectation on a neighborhood street is not to have high volumes of motor vehicle traffic, and people are generally not as alert to traffic in

residential neighborhoods. Speeding is often associated with commuters who cut through neighborhoods. Adherence to speed limits is generally difficult to enforce in residential neighborhoods because of scarce enforcement resources. It is interesting to note that when “traffic calming” was first introduced, barriers to cut-through traffic were installed in the residential streets to keep the traffic on the arterial streets. It seems that “road diets” applied to arterial streets is a reverse of this concept.

To avoid a shift of motor vehicles to routes where the effects could be detrimental, the traffic could be diverted to a more desirable location by improving a specific route. The improvement could consist of adding a lane or improving the traffic flow through better control. The resulting situation would then be as shown in Figure 4. There will be an increase in flow (q_5 to q_6) and, for the situation seen here, an increase in perceived average cost (p_5 to p_6). However, depending on the exact shapes of the demand and supply functions, there could be a decrease in average perceived cost. Improving an alternative route(s) or an alternative mode of transportation, such as transit, at the same time as designating existing lanes for specific use on the original route, could lead to better network functioning if there would be a significant mode shift. However, it should be kept in mind that Ogilvie et al. found that mode shifts are not easy to effect.⁴⁶

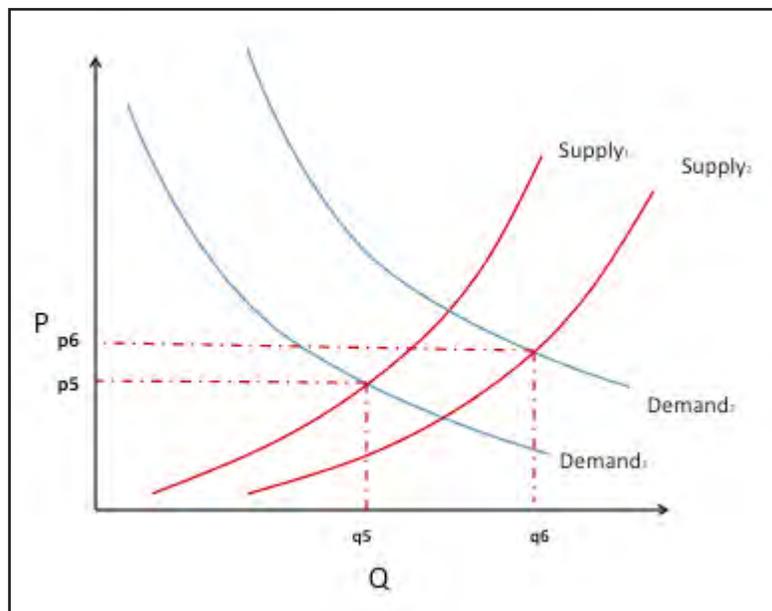


Figure 4. Traffic Diversion to Improved Route

Further to this discussion, the question may be posed: What would be the effect of dedicating increased road space to bicycling, thereby changing the supply function for bicycles? The effect can be seen in Figure 5.

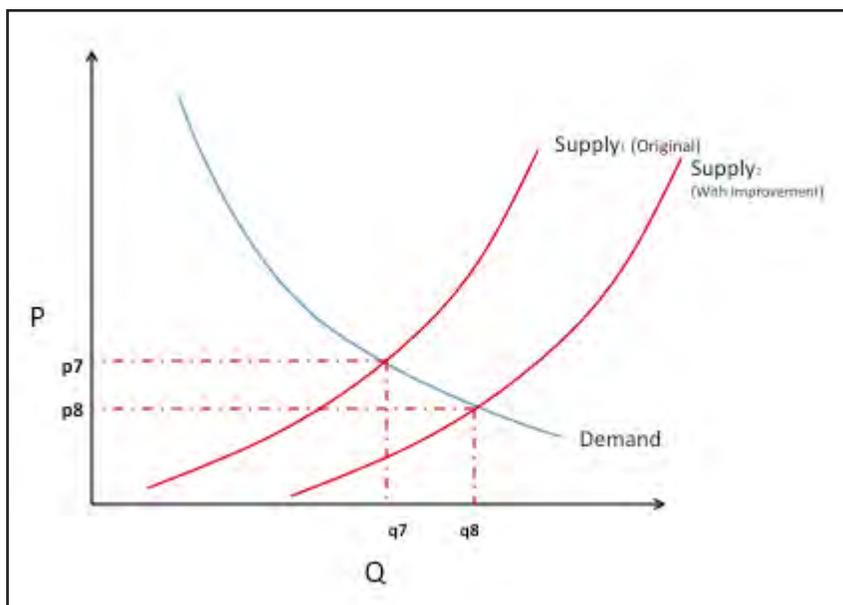


Figure 5. The Effect of Improving Bicycle Infrastructure Substantially

Although this is theoretically possible, such a shift would probably not be very large because there are relatively few bicyclists and the demand may be relatively inelastic. This situation is shown in Figure 6.

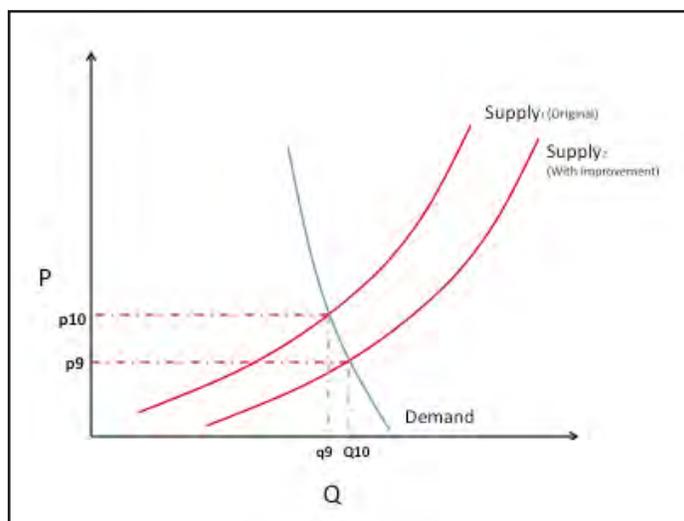


Figure 6. The Effect of Inelastic Demand

A shift to bicycling could theoretically also be effected by promoting bicycling, such as encouraging people to bicycle to work on a given day. This situation is shown in Figure 7.

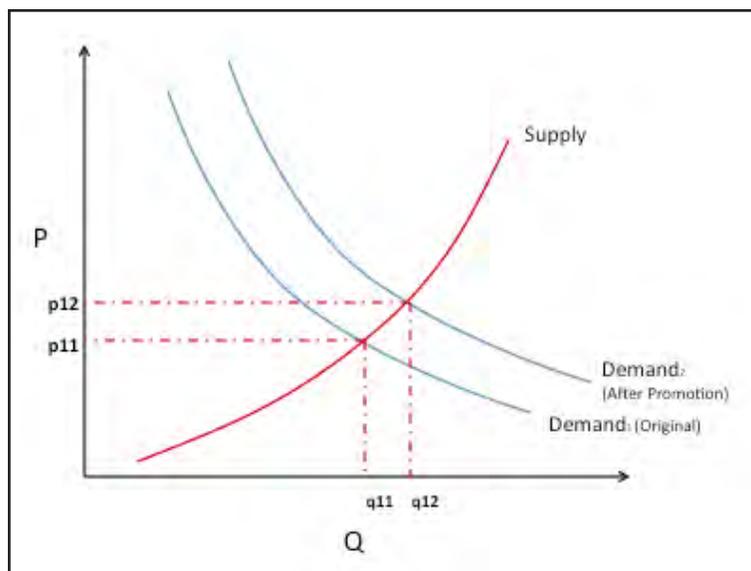


Figure 7. The Effect of Promoting Bicycling

A significant change in the number of people bicycling is more likely to result from large-scale changes in facilities, such as creating a substantial dedicated bicycle network for which there is a demonstrated demand. A shift in the demand function could occur if the bicyclists' perception were that the travel conditions, such as the safety of the route, were significantly changed, or if bicycling were to be extensively promoted. The result would be as shown in Figure 8. Such changes could also occur if general-use lanes were converted to bike lanes.

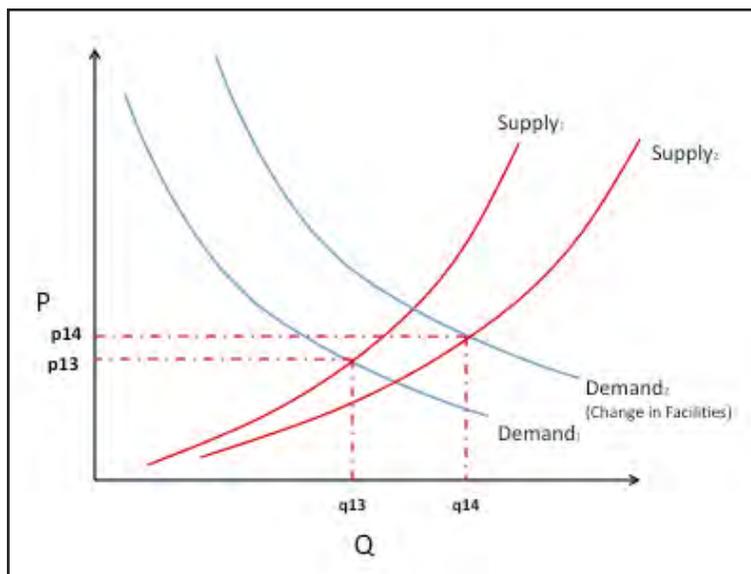


Figure 8. Change in Facilities and Promotion

For this to happen, however, the addition of bike lanes and paths must occur on a large scale, and the demand must be relatively elastic. It is unclear whether this type of change is feasible in view of the study conducted by Ogilvie, et al.⁴⁷ They found that although some interventions

produced mode shifts, interventions such as publicity campaigns and engineering measures have not been effective. The shift to bicycling resulting from engineering measures was relatively small. Improving cycle networks resulted in a 3% increase in bike trips in Delft, Netherlands after three years. After five years there was a negative shift of 5% of all trips in Detmold, Germany and a zero shift in Rosenheim, Germany.

Increased demand for bicycling can also occur if the average travel times for other modes were to increase as a result of an upward shift in the demand function (similar to the situation in Figure 7) for them, which could be the result of increased population, more land development, etc. This could be one of the reasons bicycling became so popular in cities such as Amsterdam. With no opportunity to expand the street system for cars and with travel demand increasing, others modes such as public transportation and bicycling must be utilized. These changes occurred over a long period of time and are not the equivalent of suddenly converting existing general-use lanes in a downtown area without giving the community and the land use time to change. It should also be pointed out that creating congestion by changing the use of existing lanes to force people to change modes is not the same as congestion pricing, in which pricing can be gradually changed, allowing development and trip-making to adjust without immediate disruption. With gradual changes, people can change working and living locations that work for them. Business and adjustments to goods movement can change efficiently.

It should be stressed that the travel behavior discussed above is based on society's perception of supply and demand. When making the decision to travel, people focus more on the directly perceived costs, such as travel time and perhaps fuel costs. Other costs, such as motor vehicle insurance, the cost of the road (except for tolls), and safety are often not considered.

The safety issue could be factored into the selection of mode in two ways. If conditions were perceived as unsafe, then this could be included as a perceived cost, and the effect would be the same as shifting the supply function upward. Warning against the danger of bicycling could shift the demand function lower. Both of these effects would result in reduced bicycle flows.

Note that proponents of bicycling point to the relatively high mode share of bicycling in Europe and use this as a basis for promoting bicycling in the U.S. However, they often fail to realize or point out that the part of Europe where the cycling share is relatively high has a long history of bicycling. It will take a long time, if at all, to reach relatively high levels in the U.S. because its growth must occur from such a low base. The percentage of all trips made by bicycle is about 0.9% of all trips, according to the Pedestrian and Bicycle Information Center.⁴⁸ In some cities in the U.S., bicycling constitutes a higher percentage of all trips. However, it still would require a very high growth rate to attain significantly high percentages to warrant a major focus on bicycle transportation and to change the overall transportation and land use system significantly. In the author's opinion, it is unlikely that U.S. cities soon will change into cities such as those in Europe, with high population density. In the meantime, it may be prudent to focus on short-distance trips and the needs of people who may ride a bicycle because they do not have access to a personal motor vehicle.

Political and Institutional Issues

Political and institutional factors can play significant roles in decision making for allocating resources for transportation facilities. The behavior and structure of political institutions can lead to success, but also to some failures.

One type of institutional failure is related to the life cycle of a project. During the planning phase, very broad issues are considered, and planning can occur within the Context-Sensitive Solutions (CSS), where all stakeholders have a say. The issue of safety may not be as prominent as it should be. At the local level of government, the explicit safety of bicyclists may not be considered as much as the demands of vocal bicyclist advocates are. This could be speculation, but it could be asked why these governments promote bicycling when the risks are known and why they focus their promotion primarily on selected health and environmental impacts. While the argument could be made that these governments are in fact trying to make it safer for bicyclists, the promotion aspects would not make it safer.

Another type of institutional failure is the creation of bicycle committees. This could lead to a situation in which the bicyclists' positions are promoted through such a committee, whereas the best allocation of resources would probably happen in the absence of such a committee. This would require a structure for decision-making in which all modes of transportation and the overall safety of transportation are explicitly considered.

Involving advocacy groups—for any mode of transportation—too deeply in the decision making process may lead to problems later when crash statistics may necessitate undoing some changes to transportation systems. This could be true for some of the “bike-friendly” strategies. The advocacy groups may not willingly relinquish their positions of influence. Making showpieces out of bicycle-related projects and becoming too wedded to such projects should be avoided. A showpiece may very well become folly. Moreover, if it were someone's showpiece, that person or institution may hold onto it for too long, thereby exposing people to unnecessary risk.

It should be the goal of transportation agencies to educate the public about the risks involved in bicycling while at the same time improving the safety for bicyclists. By law, licensed professional engineers involved in planning and designing bicycling venues have the duty to maintain the public's safety and to warn the public of unsafe conditions. In some cases, this may extend to warning the public of the risk involved in bicycling and not to promote bicycling per se.

DURING THE OPERATION STAGE: LOOKING BACK AFTER A CRASH

To gain further perspective on the role that planning and design (including design standards and procedures) play in bicycling safety, it is informative to examine the possible outcomes after a crash—especially a serious crash causing significant injuries and possibly death. There are consequences for all parties directly involved in the crash—those found guilty of causing the crash as well as those found not guilty. The consequences may be property damage, physical injury or death, punitive measures (monetary fines as well as incarceration), or psychological trauma. In addition, the transportation agency that was

responsible for the design, construction, and maintenance of the facilities where the crash occurred may be held liable. The evidence examined for assessing liability usually includes the participants' actions, the vehicles' conditions, the roadway design and condition, as well as the adherence to accepted standards.

Many transportation agencies have a road safety management system. The basis of such a system is to periodically identify sites (intersections or sections of roadways) with histories of high crash frequencies as possible opportunities for reducing crashes and, consequently, systematic safety improvements. The process of identifying these sites and selecting the improvement projects vary widely in terms of sophistication. The simplest way of identifying the sites for possible improvements is to compare the number of crashes over a period of time for all the sites and to rank order them based on the frequency. A more sophisticated way would be to divide the number of crashes by the exposure to traffic, i.e., the number of vehicle-miles traveled. More sophistication can be incorporated in this process by considering the severity of the crashes. This can be accomplished by placing a dollar value on the type of crash. Crashes can be classified as fatal, injury (different types of severity can be considered), and property-damage-only crashes. Various statistical methods and projections can be incorporated.

After identifying and prioritizing sites based on crashes, alternative projects are then identified to address the cause of the crashes. The projects are evaluated for feasibility by carrying out a benefit-cost analysis. Usually the benefits comprise the reduction in crash costs that could result from implementing an improvement, while the costs are the agency-related expenditure for the planning, design, construction, maintenance, and operation of the projects. These projects are then prioritized, as discussed in a previous section on benefit-cost analysis. An extensive discussion of both identifying the sites that warrant attention, as well as the evaluation and prioritization process, can be found in the Highway Safety Manual.⁴⁹ Layton wrote a document that should be read together with the Highway Safety Manual to enable the correct implementation of safety project evaluation and prioritization.^{50,51}

The reasons for implementing a road safety management system are twofold. It ensures that the available resources are allocated in an efficient and effective manner, thereby maximizing the safety benefits. Secondly, it aids in preventing and defending lawsuits. Early identification and ranking of potentially hazardous locations and allocating funds based on benefit-cost analysis make optimal use of scarce funds to prevent crashes and, thereby, provide the best means to defend against lawsuits.

It is essential to understand the implications of the process discussed in this section on planning and allocating funds for improving bicycle facilities. In this process, all safety-related projects must be evaluated on the same basis, and the benefits of exercise and recreation do not fit into this analysis. Projects proposed for improving safety for bicyclists must be evaluated in terms of their safety improvement and not in terms of health and recreation benefits. It is the author's opinion that the arguments in a court case related to a crash would be argued on the safety issues and not on the health and recreational issues.

Note that the cost of crashes is the most significant cost factor related to motor vehicle travel. In a report prepared by Cambridge Systematics for the AAA,⁵² it was found that the cost of crashes in the US in 2009 totaled \$300 billion versus total congestion costs of \$97.7 billion. This translates into a per capita of cost \$1,522 and \$590 respectively in the U.S. This result shows how the cost of crashes is significant. It is thus important to work toward decreasing this significant cost to society.

Krizek, et al.⁵³ discussed the issues of implementing improvements that will make bicyclists feel safe, and thus encourage bicycling, as opposed to making improvements that actually improve safety. They did not endorse either approach. It is the author's opinion that improvements that actually make it safer for bicyclists should be implemented. Giving bicyclists a false sense of security to entice them to travel by bicycle should be avoided. Krizek, et al. also noted that bicycle safety and trip data are difficult to analyze because the data are difficult to uncover.⁵⁴ The author of this report agrees that trip data are scarce and that the crash data are hard to analyze. Moreover, crashes are relatively rare events in a selected area, such as a city or county, and are therefore difficult to analyze statistically. Bicycle crashes are comparatively even more rare because of the low incidence of bicycling. Therefore, they are even more difficult to analyze in a systematic way, as required to identify problem locations and prioritize along with other safety-related projects. However, given that bicyclists are more likely to be killed than motor vehicle occupants, it would appear logical not to promote shifting from motor vehicles to bicycling before gathering more data and conducting research to quantify the actual safety benefits of bicycle-related projects. Then it must be determined whether the likely rise in accidents resulting from the possibly increased bicycling could be offset by implementing projects to improve bicycle safety. Moreover, the bicycle-related projects should be prioritized along with non-bicycle projects. If this approach were not followed, cities and other jurisdictions could be increasingly subject to lawsuits emanating from crashes because of the misallocation of resources.

IMPLICATIONS FOR THE DESIGN OF BICYCLE FACILITIES

Important conclusions can be made regarding the design of bicycle facilities from the discussion above—and the implications for design are significant. The design of individual streets, lanes, and other transportation system components is primarily dictated during the planning stage. Moreover, the allocation of road space and resources is made during the planning stage. To make the resource allocation effective and efficient, benefit-cost analysis should be utilized as much as possible. It is already extensively used in allocating funds for safety improvements. The selection of possible projects for implementation should be based on the reduction of crashes (benefits) and the cost of implementation.

In the event that benefit-cost analysis is not used for allocating funds, the same benefit and cost categories must be considered for all modes, and the function of the system or project should be clearly defined. The principal function of road space is primarily for moving from point A to point B and is not intended for exercise. Bicycle facilities for exercise and recreation should be considered separately from those provided to serve the principal transportation function.

It would appear prudent for transportation agencies to refrain from promoting bicycling in the absence of a clear assessment of risk and possible significant cost to society resulting from increased injury and death. It is unlikely that the percentage of all bicycle trips will increase significantly in the foreseeable future because the base from which it must grow is so low. There is also the danger of assuming that bicycling's contribution to trip making will be significant. This could result in planning and implementing bicycle-related facilities instead of making improvements to infrastructure for other transportation modes. Until a clear determination can be made of the role that bicycling could reasonably play in the future transportation system, the focus should be on short distance trips and not on bicycle networks. Attention should be given to the needs of the captive riders and pressure from bicycle advocacy groups should be resisted. A planning and decision-making system should be established that take all modes into account—not only bicycle plans, but rather trading off the needs of all modes of transportation.

VI. DESIGN WITHIN THE LAND-USE CONTEXT

The discussion in this section will focus upon the effects of different land-use concepts on transportation options and how it affects the design of transportation systems and specifically bicycle transportation infrastructure.

Before the age of mechanized transportation, cities depended mostly upon walking and animals for transportation. In some cities, canals were also used. Land-based trips had to be relatively short because of the limitations of foot and animal transportation. With the advent of mechanized transportation systems, railroads provided efficient transportation of passengers and freight. Rail-based systems also played a major role in urban transportation. The resulting cities were still dense because access to the rail systems still depended upon walking or using animals. With the advent of the automobile and trucks, together with changes in socioeconomic factors, urban sprawl developed in the US and other countries. When the cost of automobiles decreased significantly as a result of mass production, ownership of personal motor vehicles increased significantly and was one of the major factors enabling urban sprawl. Families with children favored houses with yards, furthering urban sprawl, which in turn increased dependency upon cars for personal travel. In addition, the increase in two-worker families in turn increased dependence on the automobile for commuting because spouses may not be able to find employment in the same city in a metropolitan area. Coupled with the increased emphasis on ensuring the safety of children, parents are more apt to drive their children to school and other activities. All of this points not only to a symbiotic relationship between land use and personal motor vehicle transportation, but also to an evolution of urban form and transportation. It is of course possible that the urban form could be changed to facilitate the use of public transportation and bicycles. However, this could take a long time. Meanwhile, demographic changes (a proportional increase in elderly people) and technological innovation may lead to changes that are different from those required to make bicycling relatively more desirable and safer.

It is outside the scope of this project to discuss all the aspects of the interactions and relationships between land use and transportation. However, it is necessary to discuss some of the key issues related to land use that affect the design of transportation networks and individual transportation facilities that involve bicycling. Before discussing some of these key issues, it will be useful to reference some basic principles and issues related to the interaction between land use and transportation to provide context to this discussion. The following basic issues will be discussed:

- The evolution of street and highway systems in small towns
- The effects of changes in land use and transportation systems on the remainder of the urban area

These discussions will be followed by a discussion of the effects on the design of bicycle facilities within the structure of land use and other transportation modes and facilities.

THE EVOLUTION OF STREET AND HIGHWAY SYSTEMS IN SMALL TOWNS

Small towns can evolve in different ways. They could be fulfilling a function such as being a market center, a major stop on long journeys, etc. For the purpose of the following discussion, the example of a town growing out of general merchants in an isolated area will be used.

The first stage in the development is to establish, perhaps, a general store next to a highway. Another similar or complementary store may be established because of economic opportunity. This stage is shown in Figure 9.

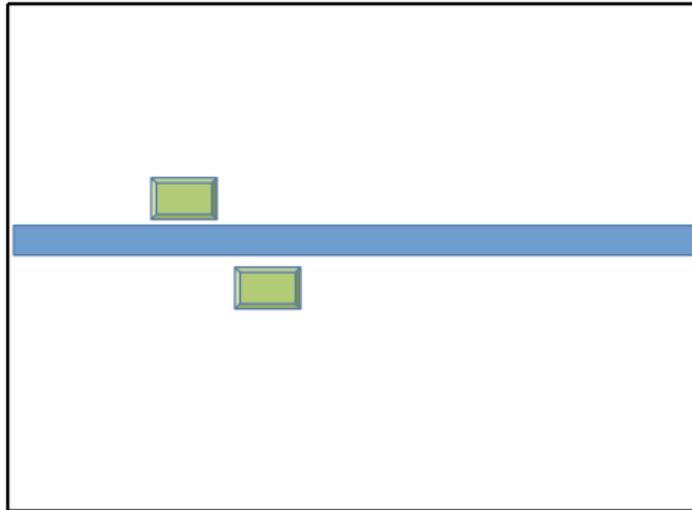


Figure 9. General Stores Next to a Rural Highway

Next, residential buildings may be constructed for workers, with perhaps additional commercial buildings, as shown in Figure 10.

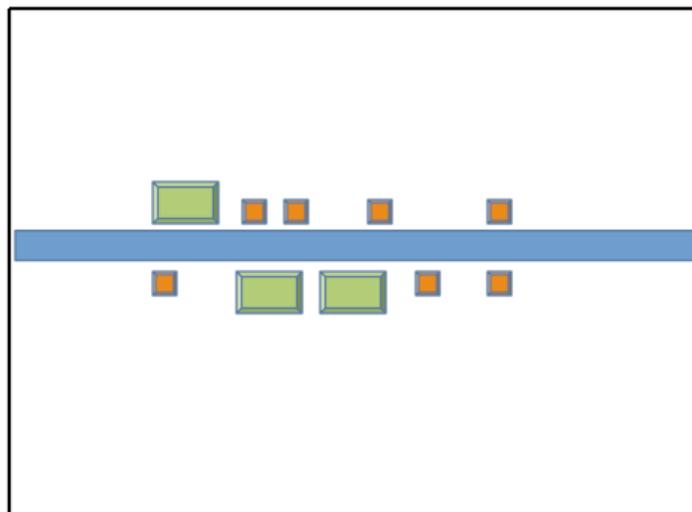


Figure 10. Further Development Next to Highway

The next development stage could be the creation of streets serving the expanded development. This type of development would result in shorter average trip lengths than further extension of the linear development next to the highway. This possible layout is shown in Figure 11.

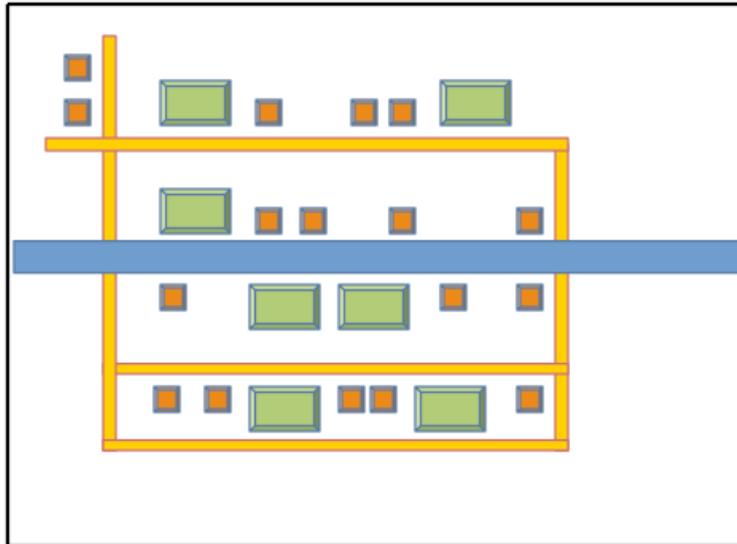


Figure 11. Development of Supporting Street System

This small town development can be supported by installing additional traffic controls, such as stop signs or signal controls, at street intersections. This would lead to delays for long-distance traffic, which is contrary to what a highway is designed to accomplish. Moreover, vehicle parking and pedestrian traffic could further degrade the highway's operation. The latter types of activities are shown schematically as a strip next to the highway in Figure 12.

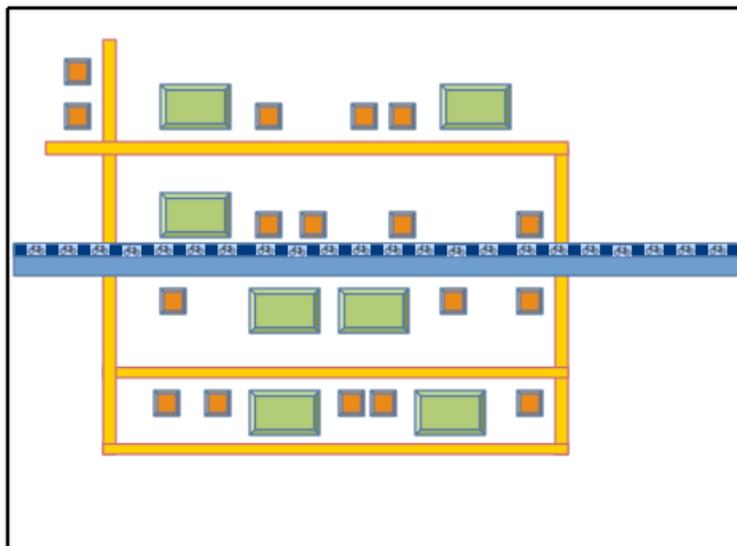


Figure 12. Additional Activity Next to Highway

Adding traffic controls and additional activity adjacent to the highway—and the increase in delay (and mobility) as well as an increase in crashes/accidents—could necessitate constructing a bypass road. This situation is shown schematically in Figure 13. Constructing the bypass road creates a hierarchy of roads or streets to fulfill the access and collection-distribution function in the overall street system. The bypass road restores the highway's mobility function, while the remainder of the streets and the original portion of the highway, which traversed the core of the town, can fulfill the collection-distribution and access functions.

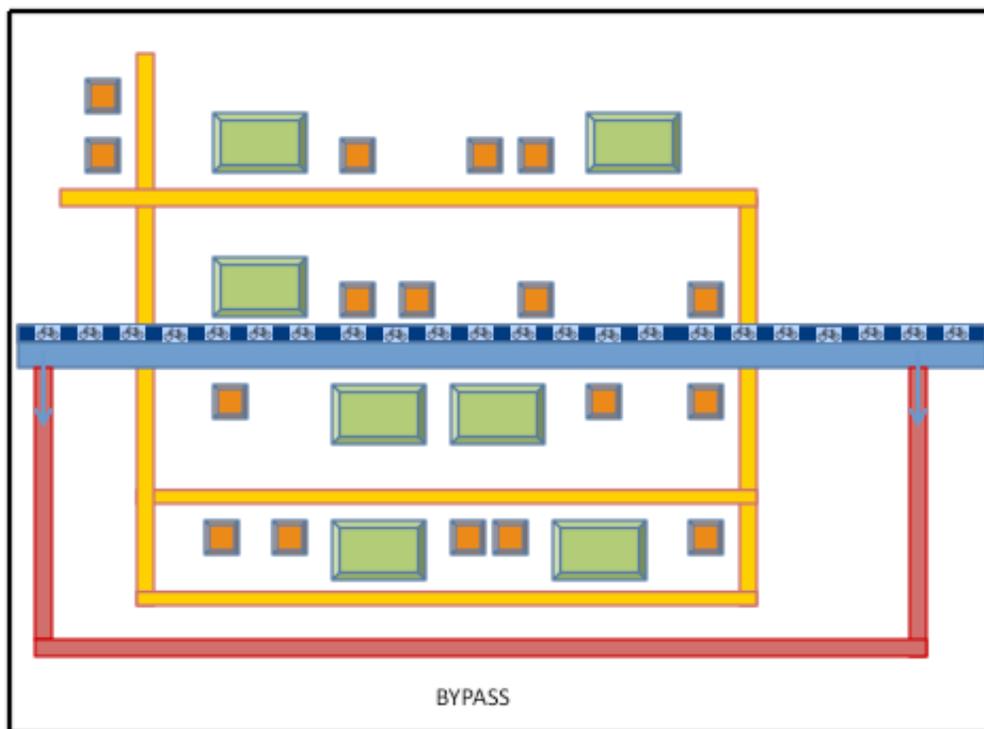


Figure 13. Construction of a Bypass Road

Ideally the layout of the street system should be designed to form a clear hierarchy of streets. Arterial streets should be spaced at appropriate distances to provide the mobility function, and collector and access street networks should be laid out in an orderly fashion to fulfill their functions. A “haphazard” development of street systems invariably leads to problems with safety and mobility.

The situation described above is also relevant for a small town that has been incorporated into a metropolitan area or a former “Main Street” type of development. This type of development can also be seen in small towns that are absorbed within a metropolitan area. The important point is that all functions of the street system must be maintained to ensure cost-efficient transportation. Failure to provide a bypass road or street would mean delay on the original highway or the main street through the town and probably deterioration in the safety of motor vehicle, pedestrian, and bicycle transportation. A “road diet” may partially solve the problem in the main street, but it does not solve the problem for the through traffic. This may cause a problem elsewhere unless something similar to a bypass route could be established by improving another route or providing another mode of transportation that people would use.

The layout of street systems in the relatively more modern cities in the US were intended to prevent the type of development discussed above. Urban street systems were designed with arterials and collector streets at distance intervals that would provide the necessary capacity (and mobility) to accommodate the traffic generated by the land use, which these major streets were serving, in an efficient and effective manner.

EFFECTS OF CHANGES IN LAND USE AND TRANSPORTATION SYSTEMS

Two situations will be discussed in this section. One consists of increased development along an arterial street in a neighborhood where changes in the transportation situation are made to adjust to the development. The other is where changes to transportation system are made in downtown areas of cities to make the downtown more livable. Both of these situations are often accompanied by attempts to make it easier to walk and bicycle. A parallel can be drawn between these situations and the development of the small town.

Sometimes city officials, residents, and businesses engage in so-called “visioning” plans for a street (often an arterial street) in a neighborhood where development consists of restaurants and small shops, and where people come for recreation. Because of increased foot traffic, the number of general traffic lanes is reduced (road diet) to decrease the number and speed of motor vehicles. Failure to provide a “bypass” street, which would serve motor vehicles, could result in delay and deterioration of safety in the neighborhood. Sometimes the answer to these types of problems is sought in traffic calming, but that could cause traffic to move into other areas, with the possible accompanying detrimental effects.

Focusing on one neighborhood, and responding primarily to the concerns of the residents or local merchants of that neighborhood, could lead not only to street safety problems in that neighborhood, but also to result in traffic-related safety problems in neighboring areas—in which the residents and merchants are not consulted in the visioning plan. Some of the traffic that used the now narrowed neighborhood arterial street could be using the arterial street in an adjacent neighborhood. It could be equated to “kicking the can down the road” or perhaps into the next neighborhood. Comparable effects could result from tinkering with the streetscape in any way that could divert traffic to another route or mode. This tinkering could include implementing bicycle lanes or creating a “complete street.”

It is necessary to pay attention to the overall network transportation system and the related safety effects of such changes in transportation systems and land use. It also is paramount to make explicit consideration of a possible bypass street before making changes to an arterial street or allowing additional development there.

Similar issues arise when cities attempt to make their downtown areas more livable, accompanied by making the area more bike and walk friendly. In this case, the means to reach these downtown areas should be considered, together with ensuring that there are bypass streets to the areas where general-use travel lanes are reduced. In the absence of effective public transportation systems, it still should be possible to effectively reach the downtown area and to park personal motor vehicles. It may be wishful thinking that effective public transportation systems would be possible in cities with urban sprawl or that a significant number of people may ride bicycles long distances in these cities to access

the downtown areas. The development of large office campuses, such as those found in Silicon Valley, further complicates the concepts of creating walkable and bikable areas. The campuses themselves may be walkable and bikeable, but reaching them would be difficult by foot or by bike.

It is the author's opinion that all people do not necessarily equate "more bikeability and walkability with livability." Better transportation or less congestion could make their lives better and easier. Moreover, almost all trips require some walking, but relatively few people bicycle.

IMPLICATIONS FOR DESIGN

"Road diets" and "complete streets" should not be undertaken before ensuring that the motor vehicles displaced by these actions are not going to cause problems elsewhere. Developing arterial streets and determining land use should not be undertaken without explicitly accommodating the displaced motor vehicles. The alternative would be to prohibit bicycles on these arterials and to designate paths for them through the neighborhoods, where they would be separated from high motor vehicle flows.

Similarly, bike lanes, bike paths, and vehicle-free zones could be considered where changes to transportation systems are made in urban downtown areas to make those areas more "livable." In this case, bypass streets to the downtown area should be established before committing to the "livable" downtown. In the absence of an effective public transportation system, such a downtown design should not be undertaken without proper provision of access and parking for motor vehicles. In the opinion of the author, the idea that a large percentage of people will commute long distances with a bicycle and forsake their personal vehicles in large U.S. cities is probably folly.

When implementing drastic changes in the transportation systems in local areas, it may be good practice to do it gradually to allow business and residential patterns to adjust. Moreover, the amount of sprawl and the type of land use in the area should determine the suitability for a transportation system.

College towns in the United States may present an opportunity in which the environment can be structured to approach the functioning as do the European cities described above. This is in part due to the fact that housing and the campus can be close together and that a great number of students may not have cars. However, due diligence still must be paid to ensure that mixing motor vehicles and bicycles is minimized.

VII. CONCLUSIONS AND RECOMMENDATIONS

The wide range of bicyclists' physical characteristics (such as size, power, skill, ability to respond to road and traffic conditions, etc.) makes it challenging for the designer to design bicycle facilities with the same sophistication and safety as facilities for motor vehicles. While some design features can be incorporated that will make it safer for bicyclists, there are also behaviors and factors inherent in bicycling that are impossible to design for. Having bicyclists and motor vehicles on the same street would mean that the different human and vehicular characteristics related to bicycles and motor vehicles, respectively, would be nearly impossible to accomplish. At the very least, an attempt should be made to integrate the design standards for motor vehicles and bicycles into common design manuals. Incompatibility of the standards may make it clear when separate facilities for bicyclists should be considered and also when bicyclists should not be allowed on a road.

Differences in speeds lead to an exponential increase in the frequency of crashes. Bicyclists commonly travel at speeds that are generally lower than motor vehicle speeds, which can then lead to an increase in crashes between motor vehicles and bicyclists. The solution to this problem would be to separate the motor vehicles and bicyclists, which has been common practice. However, this solution is costly and there is also a lack of space to accomplish it. A similar effect may be had by not allowing bicyclists on roads and streets with higher average speeds and by designating alternative routes through neighborhood streets.

Unfortunately, of late, providing more bike lanes and bike paths has been motivated in part by statements that bicycling leads to an increase in health and a decrease in the carbon footprint from travel. These kinds of statements are sometimes misleading and are not always accompanied by all the facts. When more people bicycle, more people are exposed to higher risk than they would have been had they used a personal vehicle or public transportation to travel. A study⁵⁶ showed that on a per trip basis, a bicyclist is 2.3 times as likely to be killed than a person using a personal motor vehicle. Another study showed that funds are more efficiently spent on improving traffic flow and public transportation to decrease pollution than on spending it to create a bike path, for example.⁵⁷ More than 50% of bicycling is for exercise and recreation, which do not substitute for a motor vehicle trip and, therefore, do not decrease pollution. A study about the risk of injuries in sports showed that bicycling has a higher injury rate per 100,000 people than do sports such as basketball or soccer,⁵⁸ for example.

Creating more and better bicycle infrastructure could possibly attract people to bicycling and lead to an increase in overall risk of injury and death. Planning, designing, and implementing infrastructure for bicycling, such as bike paths, could help to increase safety for existing bicyclists. But creating more and better bicycle infrastructure could possibly attract people to bicycling and lead to an increase in overall risk of injury and death. Moreover, the dilemma is that there may never be adequate funds to create enough facilities to separate bicyclists from motor vehicles in the U.S. Bicyclists would still have to navigate the streets—without separation of bicycles from motor vehicles—to reach the bike paths. Bike lanes and paths may not aid under low-volume conditions at night, when lack of visibility creates relatively unsafe conditions.

Conceptually, there is safety in numbers for bicyclists. It essentially comes down to possibility that the presence of more bicyclists will make motorists more aware of bicyclists, but it also exposes more bicyclists to risk when they are in areas where large numbers of bicyclists are not present. Additionally, having more bicyclists increases the likelihood of crashing even in the absence of motor vehicles.

A study in Orlando, Fla. showed that 64% of bicycle-vehicle crashes involved an unsafe choice by bicyclists.⁵⁹ These collisions cannot be eliminated by design. Additionally, the bicyclist's choice not to wear a helmet and consequently being exposed to more serious injury in a crash cannot be solved by designing better facilities. The aging of the population in the US is an important factor in designing roads and traffic control systems. This factor has led to changes in design and control standards used in designing roads and streets for motor vehicles and pedestrians. This factor will impact the overall risk of bicycling. Older people have comparatively lower balancing skills, and riding a bicycle may lead to an increase in falls. Better road and traffic control will probably have a negligible effect on reducing such falls. Additionally, improvements in the safety of motor vehicles in crashes, preventing crashes through warning devices, and vehicle-road automation are not available for bicyclists.

From an overall point of view, as seen in this context, common beliefs about health and environmental benefits due to bicycling are not always true. These beliefs could lead to an overinvestment in bicycling infrastructure while not placing enough emphasis on enforcement to affect bicyclists' dangerous behavior and on laws that would require bicyclists of all ages to wear helmets.

Much has been accomplished in the last few years to establish and improve standards for designing individual bicycle facilities. However, it is difficult to incorporate separate lanes and paths for bicycles because these separate paths and even sufficient space for bike lanes were not incorporated into designing arterial streets in typical major U.S. cities and metropolitan areas. Because of urban sprawl, the average commute distances could preclude commuting by bicycle for many people. Implementation of "complete streets," in which emphasis is given to all modes, may lead to a breakdown in the functioning of the hierarchical structure of the street system, wherein arterial streets are intended to fulfill the function of mobility. If lanes were removed from general use and designated for the exclusive use of bicyclists, motor vehicles may deviate to streets that are not suited to accommodating large volumes of motor vehicle traffic, and those streets may experience less safe conditions.

Conditions on the "complete streets" may also become less safe for all users. In some cities in Europe it is difficult to use a personal motor vehicle because of insufficient road space. These cities, such as the center of Barcelona, generally have a very high population density and relatively good public transportation systems. It is not convenient to use personal motor vehicles under these circumstances. Separate bike lanes are provided on sidewalks, and bicycles are also extensively used in areas in which motor vehicles are not allowed. Most U.S. cities do not have such a high population density, and people working in the central business districts of U.S. cities must rely on personal motor vehicle transportation to access workplaces in the absence of good public transportation. When scarce road space is allocated for exclusive use of bicycles, then poor mobility and poor travel safety may result.

More research into and development of standards are necessary. Designing better individual facilities probably cannot, by itself, significantly improve bicycling safety. More research is needed, especially regarding the impact of re-allocating traffic lanes and road space on arterials for the exclusive use of bicyclists. Additional research is also needed for addressing bicyclists in intersections when they are concentrated because of bike lanes entering those intersections. Increased enforcement and regulation, as well as education on the risks of bicycling, could make significant contributions to improving bicycling safety.

The design of individual streets, lanes, and other transportation system components is dictated primarily during the planning stage. Moreover, allocation of road space and resources is made during the planning stage. To make this allocation of resources effective and efficient, benefit-cost analysis should be utilized as much as possible. It is already extensively used in allocating funds for road safety improvements. The selection of possible projects for implementation is based on the reduction of crashes (benefits) and the cost of implementation.

In the event that benefit-cost analysis is used for selecting projects for implementation—and even when it is not used for allocating funds—the same benefit and cost categories must be considered for all modes, and the function of the system or project should be clearly defined. The principal function of road space is for traveling from point A to point B and is not intended for exercise and recreation. People may use it for the latter purpose, but it is very much a secondary purpose and should not detract from the principal function. Bicycle facilities, such as trails designed for exercise and recreation, should be considered separately to serve these functions. A major problem with considering dissimilar benefits for selecting projects is that the project alternatives cannot be prioritized on the same basis. This would lead to a misallocation of resources.

It would appear prudent for transportation agencies to refrain from promoting bicycling in the absence of a clear assessment of the risk and the possible significant cost to society resulting from increased injury and death. They certainly should not promote bicycling based on health benefits and reduced environmental impact without making clear the risk of injury and death.

It is probably unlikely that the percentage of all trips undertaken by bicycling will constitute a significant percentage of trip-miles in the foreseeable future because the base from which it must grow is so low. There is also danger in assuming that bicycling's contribution to trip making will be significant. This could result in planning and implementation of bicycle-related facilities instead of making improvements to infrastructure for other transportation modes—which would be more efficient in fulfilling the principal function of transportation. Until a clear determination is made about the role that bicycling could reasonably play in the future transportation system, the focus should be on the safety of short-distance bicycle trips and not on bicycle networks, for which the function is unclear—that is, serving the health and recreation function versus traveling from point A to point B. Attention should be given to the needs of captive riders, and pressure from bicycle advocacy groups should be resisted. A planning and decision-making system should be established that trades off the needs of all modes when allocating resources. This would be in contrast with a decision-making system that includes a bicycle committee, which may not be inclined to focus on the needs of all transportation modes.

The rapid aging of the population will result in different demands on the transportation system. Increased automation of motor vehicles could benefit older drivers. Bicycling will not, in all probability, benefit as much from improved technology, thereby rendering bicycling a less desirable personal mode of transportation than motor vehicles for elderly people. This factor should be considered when envisioning the future of transportation.

Bike lanes are often considered along an arterial street in a neighborhood in which changes in the transportation situation are made to adjust to the development. The goal may be to make the street more bikeable and walkable. To achieve this end, general-use travel lanes may be reduced (“road diet,” and the street could be made more “complete” in the process. However, these types of actions should not be taken before ensuring that the displaced motor vehicles will not cause problems elsewhere. Rather, explicit accommodations must be made for the displaced motor vehicles.

Similarly, bike lanes and bike paths could be considered where changes to transportation systems are made in urban downtown areas to make the area more livable. In this case, bypass streets to the downtown area should be established before committing to the “livable” downtown. In the absence of an effective public transportation system, such a downtown design should not be undertaken without proper provision of access and parking for motor vehicles. The idea that a large percentage of people will commute long distances with a bicycle and forsake their personal vehicles in most U.S. cities is probably folly.

Some college towns in the United States may present an opportunity in which the environment can be structured to allow extensive bicycling. This is in part due to the fact that housing and the campus can be close together and that a great number of students may not have cars. However, due diligence still must be paid to ensure that mixing motor vehicles and bicycles is minimized.

It is the author’s view that the way in which safety improvements for bicyclists are approached should be fundamentally changed. Decreasing fatalities and injuries should be considered for the transportation system as a whole instead of trying to decrease the fatalities and injuries to bicyclists alone by implementing countermeasures—or for that matter, looking at individual statistics for other modes. Even better, assessing the overall performance of the transportation system when making improvements should be based on the decrease in the overall cost of transportation. The cost should include the infrastructure cost, travel time cost, vehicle operating cost, and accident/crash cost, taking the explicit function of the system into account. Environmental impacts should also be assessed by taking into account vehicle impacts as a whole and not assuming that improving bicycle facilities decreases environmental impacts or is emissions-neutral under all circumstances. This kind of approach will also shed light on the extent to which bicycling should be promoted or whether scarce resources for transportation should be allocated elsewhere, including transportation services for the rapidly-expanding elderly population.

ENDNOTES

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