

Chapter 1

Introduction to Highway Engineering and Traffic Analysis

1.1 INTRODUCTION

In many industrialized nations today, highways present engineers and governments with formidable challenges relating to safety, sustainability, environmental impacts, congestion mitigation, and deteriorating infrastructure. As a result, highways are often viewed from the perspective of the many challenges they present as opposed to the benefits they provide. Historically, highways have always played a key role in the development and sustainability of human civilization. Today, in the United States and throughout the world, highways continue to dominate the transportation system, by providing critical access for the acquisition of natural resources, industrial production, retail marketing, and population mobility. The influence of highway transportation on the economic, social, and political fabric of nations is far-reaching and, as a consequence, highways have been studied for decades as a cultural, political, and economic phenomenon. While industrial needs and economic forces have clearly played an important part in shaping highway networks, societies' fundamental desire for access to activities and affordable land has generated significant highway demand, which has helped define and shape highway networks.

Without doubt, highways have had a dramatic impact on the environment in terms of the consumption of nonrenewable resources, air pollution, and the generation of greenhouse gases. In addition, vehicle crashes result in well over a million deaths worldwide every year and are the leading cause of death among people 15 to 29 years old [World Health Organization 2015]. As with other critical infrastructures (such as electrical power generation and distributions systems, water distribution systems, and storm-water and sewage systems), highway systems are costly to build, manage, and maintain, and inadequate management and maintenance can result in additional costs with regard to congestion, safety, and a variety of adverse economic impacts.

Given the above, the focus of highway engineering has gone from one of network expansion to one that addresses issues relating to infrastructure maintenance and rehabilitation, improvements in operational efficiency, various traffic-congestion relief measures, energy conservation, improved safety, and environmental mitigation. This shift has forced a new emphasis in highway engineering and traffic analysis and is one that requires a new skill set and a

deeper understanding of the impact of highway decisions than has historically been the case.

1.2 HIGHWAYS AND THE ECONOMY

It is difficult to overstate the influence that highway transportation has on the world economy. Highway systems have a direct effect on industries that supply vehicles and equipment to support highway transportation and the industries that are involved in highway construction and maintenance. Highway systems are also vital to manufacturing and retail supply chains and distribution systems and serve as regional, national, and international economic engines.

1.2.1 The Highway Economy

In the United States, more than 15% of average household income is spent on highway vehicle purchases, maintenance, and other vehicle expenditures. As a consequence, the industries providing vehicles and vehicle services for highway transportation have an enormous economic influence. In the United States alone, in the light-vehicle market (cars, vans, pickup trucks, and so on), as many as 17 million or more new vehicles can be sold annually (depending on economic conditions), which translates to roughly a half a trillion dollars in sales and more than a million jobs in manufacturing and manufacturing-supplier industries. Add to this the additional employment associated with vehicle maintenance and servicing, and more than seven million U.S. jobs can be tied directly to highway vehicles. The influence of the highway economy extends further to the heavy-vehicle sector as well, with more than 1.3 million jobs and trucking industry revenue of roughly three-quarters of a trillion dollars annually in the United States.

The direct influence that highways have also includes the construction and maintenance of highways, with over 100 billion dollars in annual expenditures in the United States alone. This too has an enormous impact on employment and other aspects of the economy.

1.2.2 Supply Chains

The survival of modern economies is predicated on efficient, reliable, and resilient supply chains. Industries have become increasingly dependent on their supply chains to reduce costs and remain competitive. As an example, most manufacturing industries today rely on just-in-time delivery to reduce inventory-related costs, which can be a substantial percentage of total costs in many industries. The idea of just-in-time delivery is that the materials required for production are supplied just before they are needed. While such a strategy significantly reduces inventory costs, it requires a very high degree of certainty that the required materials will be delivered on time. If not, the entire production process could be adversely affected and costs could rise dramatically.

In retail applications, effective supply chains can significantly reduce consumer costs and ensure that a sufficient quantity of goods is available to satisfy consumer demand. The ability of highways to provide reliable service for just-in-time inventory control and other supply chain-related industrial and retail applications has made highways critical to the function of modern economies.

1.2.3 Economic Development

It has long been recognized that highway construction and improvements to the highway network can positively influence economic development. Such improvements can increase accessibility and thus attract new industries and spur local economies. To be sure, measuring the economic development impacts of specific highway projects is not an easy task because such measurements must be made in the context of regional and national economic trends. Still, the effect that highways can have on economic development is yet another example of the far-reaching economic influences of highway transportation.

1.3 HIGHWAYS, ENERGY, THE ENVIRONMENT, AND CLIMATE CHANGE

As energy demands fluctuate and supplies vary, and nations become increasingly concerned about environmental impacts, the role that highway transportation plays has come under close scrutiny. As a primary consumer of fossil fuels and a major contributor to air-borne pollution and greenhouse gas emissions, highway transportation is an obvious target for energy conservation and environmental impact mitigation efforts.

In the United States, highway transportation is responsible for roughly 60% of all petroleum consumption. This translates into about 12 million barrels of oil a day. In light of the limitations of oil reserves, this is an astonishing rate of consumption. Highway transportation's contribution to other pollutants is also substantial. Highway travel is responsible for about 35% of all nitrous oxide emissions and 25% of volatile organic compound emissions, both major contributors to the formation of ozone. Highway travel also contributes more than 50% of all carbon monoxide emissions in the United States and is a major source of fine particulate matter (2.5 microns or smaller), which is a known carcinogen.

The effect of highways on climate change is also formidable. Highway transportation is responsible for roughly 25% of U.S. greenhouse gas emissions (including over 30% of carbon dioxide emissions). While highways affect climate change, the effect that climate change will ultimately have on highways is an issue that has just begun to be addressed [National Cooperative Research Program 2014]. The effect of climate change on extreme weather events, geographic shifts in temperature and moisture, and rising sea levels present highway engineers with extraordinary challenges with regard to highway design, infrastructure maintenance, highway operations, and highway safety.

1.4 HIGHWAYS AS PART OF THE TRANSPORTATION SYSTEM

It is important to keep in mind that highway transportation is part of a larger transportation system that includes air, rail, water, and pipeline transportation. In this system, highways are the dominant mode of most passenger and freight movements. For passenger travel, highways account for about 90% of all passenger-miles. On the freight side, commercial trucks account for about 37% of the freight ton-miles and, because commercial trucks transport higher-valued goods than other modes of transportation (with the exception of air

transportation), nearly 80% of the dollar value of all goods is transported by commercial trucks.

While highways play a dominant role in both passenger and freight movement, in many applications there are critical interfaces among the various transportation modes. For example, many air, rail, water, and pipeline freight movements involve highway transportation at some point for their initial collection and final distribution. Interfaces between modes, such as those at water ports, airports, and rail terminals, create interesting transportation problems but, if handled correctly, can greatly improve the efficiency of the overall transportation system. However, inter-modal coordination can be problematic because of institutional, regulatory, and other barriers.

1.5 HIGHWAY TRANSPORTATION AND THE HUMAN ELEMENT

Within the highway transportation system, traveler options include single-occupant private vehicles, multi-occupant private vehicles, and public transportation modes (such as bus). It is critical to develop a basic understanding of the effect that highway-related projects and policies may have on the individual highway modes of travel (single-occupant private vehicles, bus, and so on) because the distribution of travel among modes will strongly influence overall highway-system performance. In addition, highway safety and the changing demographics of highway users are important considerations.

1.5.1 Passenger Transportation Modes and Traffic Congestion

Of the available urban transportation modes (bus, commuter train, subway, private vehicle, and others), private vehicles, and single-occupant private vehicles in particular, offer an unequaled level of mobility. The single-occupant private vehicle has been such a dominant choice that travelers have been willing to pay substantial capital and operating costs, confront high levels of congestion, and struggle with parking-related problems just to have the flexibility in travel departure time and destination choices that is uniquely provided by private vehicles. In the last 50 years, the percentage of trips taken in private vehicles has risen from slightly less than 70% to over 90% (public transit and other modes make up the balance). Over this same period, the average private-vehicle occupancy has dropped from 1.22 to 1.09 persons per vehicle, reflecting the fact that the single-occupant vehicle has become an increasingly dominant mode of travel.

Traffic congestion that has arisen as a result of extensive private-vehicle use and low-vehicle occupancy presents a perplexing problem. The high cost of new highway construction (including monetary, environmental, and social costs) often makes building new highways or adding additional highway capacity an unattractive option. Trying to manage the demand for highways also has its problems. For example, programs aimed at reducing congestion by encouraging travelers to take alternate modes of transportation (bus-fare incentives, increases in private-vehicle parking fees, tolls and traffic-congestion pricing, rail- and bus-transit incentives) or increasing vehicle occupancy (high-occupancy vehicle lanes and employer-based ridesharing programs) can be considered as viable options.

However, such programs have the adverse effect of directing people toward travel modes that inherently provide lower levels of mobility because no other mode offers the departure-time and destination-choice flexibility provided by private, single-occupant vehicles. Managing traffic congestion is an extremely complex problem with significant economic, social, environmental, and political implications.

1.5.2 Highway Safety

The mobility and opportunities that highway infrastructure provides also have a human cost. Although safety has always been a primary consideration in highway design and operation, highways continue to exact a terrible toll in loss of life, injuries, property damage, and reduced productivity as a result of vehicle accidents. Highway safety involves technical and behavioral components and the complexities of the human/machine interface. Because of the high costs of highway accidents, efforts to improve highway safety have been intensified dramatically in recent decades. This has resulted in the implementation of new highway design guidelines and countermeasures (some technical and some behavioral) aimed at reducing the frequency and severity of highway accidents. Fortunately, efforts to improve highway design (such as more stringent design guidelines, breakaway signs, and so on), vehicle occupant protection (safety belts, padded dashboards, collapsible steering columns, driver- and passenger-side airbags, improved bumper design), as well as advances in vehicle technologies (antilock braking, traction control systems, electronic stability control) and new accident countermeasures (campaigns to reduce drunk driving), have managed to gradually reduce the fatality rate (the number of fatalities per mile driven). However, in spite of continuing efforts and unprecedented advancements in vehicle safety technologies, the total number of fatalities per year has remained unacceptably high worldwide (in the United States, the fatality rate has remained at more than 30,000 per year).

To understand why highway fatality numbers have not dramatically decreased or why fatality rates (fatalities per distance driven) have not dropped more than they have as a result of all the safety efforts, a number of possible explanations arise including: an increase in the overall level of aggressive driving; increasing levels of disrespect for traffic control devices (red light and stop-sign running being two of the more notable examples); in-vehicle driving distractions (such as cell phones); and poor driving skills in the younger and older driving populations. Two other phenomena are being observed that may be contributing to the persistently stable number of fatalities. One is that some people drive more aggressively (speeding, following too closely, frequent lane changing) in vehicles with advanced safety features, thus offsetting some or all of the benefits of new safety technologies [Winston et al., 2006]. Another possibility is that many people are more influenced by style and function than safety features when making vehicle purchase decisions. This is evidenced by the growing popularity of vehicles such as sport utility vehicles, mini-vans, and pickup trucks, despite their consistently overall lower rankings in certain safety categories, such as roll-over probability, relative to traditional passenger cars. These issues underscore the

overall complexity of the highway safety problem and the trade-offs that must be made with regard to cost, safety, and mobility (speed).

1.5.3 Demographic Trends

Travelers' commuting patterns (which lead to traffic congestion) are inextricably intertwined with socioeconomic characteristics such as age, income, household size, education, and job type, as well as the distribution of residential, commercial, and industrial developments within the region. Many American metropolitan areas have experienced population declines in central cities accompanied by a growth in suburban areas. One could argue that the population shift from the central cities to the suburbs has been made possible by the increased mobility provided by the major highway projects undertaken during the 1960s and 1970s. This mobility enabled people to improve their quality of life by gaining access to affordable housing and land, while still being able to get to jobs in the central city with acceptable travel times. Conventional wisdom suggested that as overall metropolitan traffic congestion grew (making the suburb-to-city commuting pattern much less attractive), commuters would seek to avoid traffic congestion by reverting back to public transport modes and/or once again choosing to reside in the central city. This has certainly happened to some extent, but a different trend has also emerged. Employment centers have developed in the suburbs and now provide a viable alternative to the suburb-to-city commute (the suburb-to-suburb commute). The result is a continuing tendency toward low-density, private vehicle-based development as people seek to retain the high quality of life associated with such development.

Ongoing demographic trends also present engineers with an ever-moving target that further complicates the problem of providing mobility and safety. An example is the rising average age of the U.S. population that has resulted from population cohorts and advances in medical technology that prolong life. Because older people tend to have slower reaction times, taking longer to respond to driving situations that require action, engineers must confront the possibility of changing highway design guidelines and practices to accommodate slower reaction times and the potentially higher variance of reaction times among highway users.

1.6 HIGHWAYS AND EVOLVING TECHNOLOGIES

As in all fields, technological advances at least offer the promise of solving complex problems. For highways, technologies can be classified into those impacting infrastructure, vehicles, and traffic control.

1.6.1 Infrastructure Technologies

Investments in highway infrastructure have been made continuously throughout the twentieth and twenty-first centuries. Such investments have understandably varied over the years in response to need and political and national priorities. For example, in the United States, an extraordinary capital investment in highways during the 1960s and 1970s was undertaken by constructing the interstate highway system and upgrading and constructing many other

highways. The economic and political climate that permitted such an ambitious construction program has not been replicated before or since. It is difficult to imagine, in today's economic and political environment, that a project of the magnitude of the interstate highway system would ever be seriously considered. This is because of the prohibitive costs associated with land acquisition and construction and the community and environmental impacts that would result.

It is also important to realize that highways are long-lasting investments that require maintenance and rehabilitation at regular intervals. The legacy of a major capital investment in highway infrastructure is the proportionate maintenance and rehabilitation schedules that will follow. Although there are sometimes compelling reasons to defer maintenance and rehabilitation (including the associated construction costs and the impact of the reconstruction on traffic), such deferral can result in unacceptable losses in mobility and safety as well as more costly rehabilitation later.

As a consequence of past capital investments in highway infrastructure and the current high cost of highway construction and rehabilitation, there is a strong emphasis on developing and applying new technologies to more economically construct and extend the life of new facilities and to effectively combat an aging highway infrastructure. Included in this effort are the extensive development and application of new sensing technologies in the emerging field of structural health monitoring. There are also opportunities to extend the life expectancy of new infrastructure with the ongoing advances in material science. Such technological advances are essential elements in the future of highway infrastructure.

1.6.2 Traffic Control Technologies

Traffic signals at highway intersections are a familiar traffic control technology. At signalized intersections, the trade-off between mobility and safety is brought into sharp focus. Procedures for developing traffic-signal control plans (allocating green time to conflicting traffic movements) have made significant advances over the years. Today, signals at critical intersections can be designed to respond quickly to prevailing traffic flows, groups of signals can be coordinated to provide a smooth through-flow of traffic, and, in some cases, computers control entire networks of signals. Still, at some level, the effectiveness of improvements in signal control is fundamentally limited by the reaction times and the driving behavior of the motoring public as well as the braking and acceleration performance of the vehicles they drive. This presents highway engineers with a formidable barrier.

In addition to traffic signal controls, numerous safety, navigational, and congestion-mitigation technologies are reaching the market under the broad heading of Intelligent Transportation Systems (ITS). Such technological efforts offer the potential to reduce traffic congestion and improve safety on highways by providing an unprecedented level of traffic control. There are, however, many obstacles associated with ITS implementation, including system reliability, human response, and the human/machine interface. Numerous traffic control technologies offer the potential for considerable improvement in the efficient use of the highway infrastructure, but there remain limits defined by vehicle performance characteristics and their human operators.

1.6.3 Vehicle and Autonomous Vehicle Technologies

Until the 1970s, vehicle technologies evolved slowly and often in response to mild trends in the vehicle market as opposed to an underlying trend toward technological development. Beginning in the 1970s, however, three factors began a cycle of unparalleled advances in vehicle technology that continues to this day: (1) government regulations on air quality, fuel efficiency, and vehicle-occupant safety; (2) energy shortages and fuel-price increases; and (3) intense competition among vehicle manufacturers (foreign and domestic). The aggregate effect of these factors has resulted in vehicle consumers that demand new technology at highly competitive prices. Vehicle manufacturers have found it necessary to reallocate resources and to restructure manufacturing and inventory control processes to meet this demand. In recent years, consumer demand and competition among vehicle manufacturers has resulted in the widespread implementation of new technologies including supplemental restraint systems, antilock brake systems, traction control systems, electronic stability control, and a host of other applications of new technologies to improve the safety and comfort in highway vehicles. There is little doubt that the combination of consumer demand and intense competition in the vehicle industry will continue to spur vehicle technological innovations.

As vehicle technologies have progressed, the highway engineering profession is approaching a potential breakthrough in how traffic can be managed and how future highways may be designed. Specifically, the prospect of connected vehicles (being able to receive and send information to other vehicles and central controls and potentially from infrastructure sensors that may transmit pavement conditions and other factors relevant to vehicle operation) and fully automated vehicles has the potential to reshape the landscape of highway engineering. With connected and fully automated vehicle operation, one can imagine immense changes in highway design because the need to account for variation in human abilities (reaction times, sight distances, detection of changing road conditions with regard to weather, ability to predict the actions of other drivers, etc.) and human behavior (choice of car-following distances, speed choice, route choice, lane choice on multilane highways, choices at traffic signals, etc.) would now be replaced simply by the need to assess and account for variation in vehicle characteristics (vehicle dimensions, acceleration, deceleration, etc.), system operating software, and possible component and system failures, all of which are much more “predictable” than the human-related factors that currently dominate highway design. The eventual result is that, with connected and autonomous vehicles, there could be substantial increases in highway capacity for some situations, vast improvements in safety, and essentially a complete change in how highway transportation affects the economy, energy consumption, the environment, the spatial structure of cities, the impact on human activities, and so on.

As autonomous vehicles begin to enter the highway traffic mix, presumably in the coming decade, there will be enormous challenges. While operating a completely connected and autonomous vehicle fleet would be relatively easy because of the complete control available, having autonomous vehicles mixed with human drivers creates a serious challenge because sensor systems must be

able to detect, and software systems must be able to quickly respond to the incredible range of human-driver behaviors.

To better understand the range of vehicle technologies that are likely to be present in highway traffic of the future, the U.S. Department of Transportation's National Highway Traffic Safety Administration has chosen to define levels of vehicle automation as follows (NHTSA, 2018):

No-Automation (Level 0): The driver is in complete and sole control of the primary vehicle controls (brake, steering, throttle, and motive power) at all times.

Driver Assistance (Level 1): Automation at this level involves the driver with driver assistance features in the design of the vehicle.

Partial Automation (Level 2): This level involves engagement from the driver, but the vehicle has combined automated functions controlling both the steering and acceleration/deceleration capabilities.

Conditional Automation (Level 3): Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time.

High Automation (Level 4): The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. The driver has the option to control the vehicle.

Full Automation (Level 5): The vehicle functions under all conditions without a driver and does not require a steering wheel, throttle, or brake pedals. Level 5 vehicles have the most advanced environment detection system.

In today's vehicle fleet, the vast majority of vehicles are at Levels 0 and 1. Many newer cars can be purchased at automation Level 2, and it is quite likely that within the coming decade, that substantial numbers of Level 3 and Level 4 vehicles will be on highways worldwide. While the presence of these vehicles will inevitably change highway design, the fundamental principles covered in this text will still apply with appropriate modification.

1.7 SCOPE OF STUDY

Highway engineering and traffic analysis involves an extremely complex interaction of economic, behavioral, social, political, environmental, and technological factors. This complexity makes highway engineering and traffic analysis far more challenging than many typical engineering disciplines that tend to have an overriding focus on only the technical aspects of the problem. To be sure, the technical challenges encountered in highway engineering and traffic analysis easily rival the most complex technical problems encountered in any other engineering discipline (and this will be even more pronounced with the

potential introduction of autonomous vehicles). However, it is the economic, behavioral, social, political, and environmental elements that introduce a level of complexity unequalled in any other engineering discipline.

The remaining chapters in this book do not intend to provide a comprehensive assessment of the many factors that influence highway engineering and traffic analysis. Instead, Chapters 2 through 8 seek to provide readers with the fundamental elements and methodological approaches that are used to design and maintain highways and assess their operating performance. This material constitutes the fundamental principles of highway engineering and traffic analysis that are needed to begin to grasp the many complex elements and considerations that come into play (now and in the future) during the design, construction, maintenance, and operation of highways.

REFERENCES

- National Cooperative Research Program. *Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report*. Strategic Issues Facing Transportation, Volume 2, NCHRP Report 750, Transportation Research Board, Washington, D.C., 2014.
- National Highway Traffic Safety Administration (NHTSA). <https://www.nhtsa.gov/technology-innovation/automated-vehicles-safety>
- Winston, C., V. Maheshri, and F. Mannering. An exploration of the offset hypothesis using disaggregate data: The case of airbags and antilock brakes. *Journal of Risk and Uncertainty*, vol. 32, no. 2, 2006.
- World Health Organization. *Global Status Report on Road Safety 2015*. Geneva, Switzerland, 2015.