A SYSTEMATIC APPROACH TO URBAN TRAFFIC SAFETY: THEORY AND APPLICATIONS FOR THE IMPLEMENTATION OF VISION ZERO BOSTON

A Thesis Presented
By
Dustin James Kerksieck

to

The Department of Civil and Environmental Engineering

in partial fulfillment of the requirements
for the degree of

Master of Science

in the field of

Transportation Engineering

Northeastern University
Boston, Massachusetts

August, 2016

ABSTRACT

In 2015, Boston announced that it would pursue a "Vision Zero" policy to eliminate fatal and serious traffic crashes in the City. The Vision Zero goal has been adopted by a growing number of cities in the United States, but these programs are all very recent and actions to achieve that goal vary by jurisdiction. Vision Zero best practices have not yet been established in this country.

The purpose of this thesis is to provide a systematic framework for an effective Vision Zero policy in Boston by borrowing and expanding on concepts from successful programs in Europe. This thesis explores Vision Zero's origins in Sweden and the Netherlands and reviews a number of behavioral models that are relevant to urban traffic safety. Based on these behavioral models, five fundamental principles of safe streets are established to be used as the basis for all planning and design decisions. By applying the five fundamental principles, a list of critical action items for the City is provided, followed by a brief case study illustrating how the five principles can be used to inform concrete design decisions.

STATEMENT OF CONTRIBUTION

Based on a synthesis of traffic safety theory, this thesis improves the connection between fundamental human characteristic and the road design principles enunciated in the Dutch "Vision Zero" traffic safety program known as Sustainable Safety, and tests their applicability to the US urban context.

This thesis expands two of the five principles of the Dutch systematic safety program. To the principle of predictability - which is based on the theory that risk of error increases when drivers have to react to unexpected situations – it adds ***simplicity in decision-making***: the risk of error increases as decisions become more complex, even if the traffic situation is anticipated. Design implications include a recommendation for pedestrian crossing islands; favoring 2-lane, as opposed to multilane, roads; and protected left turns over permitted left turns because of how they simplify crossing decisions for pedestrians and motorists.

To the principle of forgivingness – based on the theory that humans will continue to make mistakes, both intentionally and unintentionally – this thesis add the principle of ***restrictiveness***. While forgivingness aims to lessen the risk of serious injury after a mistake has been made, restrictiveness aims to prevent people from the making the mistakes or they are inclined to make in the first place.

Transferring safety principles from Europe should involve examining whether they are applicable to an American urban context, recognizing differences between European and American street design, law, and culture. To this end, this thesis tests whether Dutch safety principles can explain treatments that, in US practice, have proven to reduce crash risk. For a large sample of treatments with crash modification factors below 1, it finds that they can all be explained in terms of systematic safety principles.

ACKNOWLEDGEMENTS

I would like to thank Professor Peter Furth for his guidance in preparing this paper.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

In March of 2015, Mayor Marty Walsh announced that Boston would be adopting a "Vision Zero" plan (City of Boston - Mayor's Press Office, 2016). Vision Zero is a set of policies and practices intended to eliminate traffic deaths and serious injuries. While that goal sounds ambitious, jurisdictions that have Vision Zero (or Vision Zero-like) programs, such as those in the Netherlands, Sweden, and New York City, have seen significant reductions in traffic deaths (SWOV Institute for Road Safety Research, 2013), (Goodyear, 2016), (New York City Mayor's Office of Operations, 2016).

At the announcement, Mayor Walsh identified five early action items:

1. Improve the Boston Police Department's electronic crash reporting system in order to collect better crash data;
2. Hire a Transportation Safety Data Analyst and a "DDACTS" (Data Driven Approaches to Crime and Traffic Safety) Analyst to analyze crash data;
3. Identify pedestrian crash hot spots and high-crash corridors based on analysis of the data;
4. Pilot test rapid-response improvements at pedestrian crash hot spots, high-crash corridors, and residential slow zones; and
5. Start outreach programs through the Boston Public Health Commission (BPHC) to educate residents on safe road behavior.

The announcement of Vision Zero Boston was followed by a website and 26-page Action Plan in December, 2015 (City of Boston, 2015) (City of Boston Transportation Department, 2015). This Action Plan provided additional details on four main goals and identified numerous concrete tasks that the City plans to accomplish in 2016.

The first goal is to reduce speeds and build safer streets. This step will focus on data collection and engineering solutions aimed at slowing traffic speeds and improving bicycle and pedestrian safety. Improvements will be concentrated at four "Initial Target Areas": the Massachusetts Avenue and Codman Square "Priority Corridors", and the Stoney Brook and Talbot-Norfolk Triangle "Slow Street Pilot Zones" (Figure 1).

Figure 1: Initial Target Area for Infrastructure Improvements, from Boston's Vison Zero Action Plan

The second goal is to reduce distracted and impaired driving. This will be achieved through targeted enforcement; public education and outreach campaigns; and promoting transit, ride-sharing, and taxi services as an alternative to driving while impaired.

The third goal is to engage Bostonians in Vision Zero. The goal is to create a city-wide culture of safety through education and to gather community support for any Vision Zero actions.

The City's fourth and final goal identified thus far is to hold themselves accountable through transparent data collection and data sharing practices.

By adopting these policies, Boston is taking a leading role in bringing the goals of Vision Zero to the US; however, as an early adopter, the City should expect a certain amount of trial and error as they explore different approaches. The purpose of this thesis is to introduce the principles on which successful European programs are based, and offer recommendations on how these principles could be applied here to maximize the benefits of the "trials" and minimize the "errors" as Boston develops a safer road network.

This thesis is organized into six chapters:

Chapter 1 looks at Vision Zero's origins in Europe, its recent spread to the United States, and its effectiveness. Current US practices are also reviewed.

Chapter 2 establishes several fundamental concepts on which Vision Zero should be based: goals, behavioral models, and risk factors.

Chapter 3 outlines five principles for the design of systematically safe roads. A roadway classification hierarchy with accompanying design criteria based on the five principles is offered as the skeleton on which to build a systematically safe roadway network.

Chapter 4 is an action plan: a list of goals for the City of Boston to apply the five principles described in the previous chapter.

Chapter 5 is a short case study of how the five principles can be used to guide real-world design decisions. Gallivan Boulevard in Boston is used as the example.

Chapter 6 concludes this thesis and suggests future steps for implementing Vision Zero that are beyond the scope of this document.

CHAPTER 1: VISION ZERO IN EUROPE AND THE U.S.

1.1 Sweden

The term “Vision Zero” is borrowed from a Swedish initiative that was proposed in 1994. The principle that “any loss of life in traffic is unacceptable” was written into Swedish law in 1997 and now guides Swedish infrastructure design and traffic enforcement.

The Swedish system is based on the idea that **mobility is a civil right, and that providing a transportation network where users must risk death is a violation of that right**. This was a significant shift from the previous, more utilitarian approach:

> ...Political economists have built their whole career on cost-benefit analysis. For them it is very difficult to buy into “zero.” Because in their economic models, you have costs and benefits, and although they might not say it explicitly, the idea is that there is an optimum number of fatalities. A price that you have to pay for transport.
>
> The problem with the whole transport sector is quite influenced by the whole utilitarian mindset. Now we’re bringing in the idea that it’s not acceptable to be killed or seriously injured when you’re traveling. It’s more of a civil-rights outlook that we bring into the policy.
>
> --Matts-Ake Belin, Sweden’s Traffic Safety Strategist (Goodyear, 2016)

Recognizing that human error is inevitable and that crashes will happen, the Swedes shifted their focus from preventing accidents to preventing deaths and serious injuries. If human body can only tolerate a certain amount of physical force, the transportation system must prevent situations that exceed that level. Specific changes included:

- Limiting speeds to 30 km/h (about 20 mph) where unprotected road users (pedestrians and cyclists) are present and using “safety cameras” to enforce speed limits.

- Making roundabouts the preferred intersection treatment because they avoid dangerous angle- and head-on collisions.
- Restriping rural two lane roads with three narrow lanes and a cable median barrier ("2+1" roads), separating opposite directions of traffic while still allowing passing.
- Adding high-visibility features at pedestrian crossings, or avoiding crossings altogether with pedestrian bridges.

Since the adoption of Vision Zero in 1994, Sweden's total miles driven has climbed, but the fatality rate has dropped by half (Goodyear, 2016). Sweden's success is helping spread similar policies to the United States. 25 US cities, including New York City, San Francisco, Washington DC, and Seattle have or are working on plans Vision Zero plans.

1.2 The Netherlands

Even before Sweden had implemented Vision Zero, the Netherlands was developing its own safety program, dubbed "Sustainable Safety". The Dutch and Swedish approaches are similar in many ways, but they differ in some important points of emphasis and practice.

Sustainable Safety represented a paradigm shift for the Netherlands when it was adopted. Recognizing that a significant reduction in traffic deaths could not be achieved through traditional, reactive approaches (e.g. enforcement, targeted safety improvements at accident "hot spots"), Sustainable Safety took an explicitly pro-active stance, sometimes called a "safe system" approach.

Like Sweden's Vision Zero, Sustainable Safety takes human limitation as its axiom, and then strives to create an inherently safe transportation system with built-in fail-safes so that human errors do not result in serious injuries.

> Road traffic should be looked at in the same way as other transport systems… Just as with other transport modes, death and severe injury due to lack of safety is not inevitable or unavoidable like a natural disaster or mystery diseases. The Sustainable Safety vision specifies that safety should be a design requirement in

> road traffic in the same way as in the design of nuclear energy plants, refineries, waste incinerators, and air and rail transport…. In a country like the Netherlands, we would never accept three wide-bodied aircraft crashes a year. (SWOV Institute for Road Safety Research, 2006)

This approach emphasizes the responsibility of the designer and road owner, and removes as much responsibility from the road user as possible. This is done by

- Minimizing exposure to traffic through
  - land-use policies that promote high-density development and, therefore, shorter trips
  - pricing incentives/disincentives aimed at reducing driving
  - promotion of alternative (safer) modes of travel
- Designing roads that simplify the driving task, reducing driver error
- Designing roads that organically produce the desired driving behavior rather than relying on enforcement, and
- Protecting users from serious injury when crashes do occur

Though many elements that would become Sustainable Safety had been practiced in the Netherlands since the ‘70s, the Sustainable Safety vision was formally outlined in 1992 as part of the first *Dutch National Road Safety Outlook*. Because of its large scope, the full Sustainable Safety program was rolled out in two phases. The five-year *Start-Up Programme* began in 1997 and included 24 specific actions that could be implemented in a short period of time. The second Dutch National Road Safety Outlook, titled *Advancing Sustainable Safety* (SWOV Institute for Road Safety Research, 2006)*,* reviewed the results of the Start-Up Programme and recommended next steps for the continuing implementation of the full Sustainable Safety vision.

Both the Swedish and Dutch approaches have produced impressive results. In the Netherlands, it was estimated that Sustainable Safety has reduced deaths by 30% between 1998 and 2007 compared with their pre-existing safety policies (SWOV Institute for Road Safety Research, 2013). As of 2015, there were only 3.6 deaths per 100,000 people in the Netherlands (SWOV Institute for Road Safety Research, 2016). In Sweden, traffic deaths dropped from 7 per 100,000 people in 1997 to fewer than three per 100,000 people today (Goodyear, 2016). For comparison, the rate in the US is approximately 12 deaths per 100,000 nationally (2015 data) and is on the rise (National Center for Statistics and Analysis, 2016). Massachusetts' fatality rate is better than the national average at 5.25 fatalities per 100,000 (2012 data), but is still 50% higher than either Sweden or the Netherlands (Massachusetts Executive Office of Public Safety and Security, 2016)

When it comes to applying these successful European strategies in the US, the Dutch model does offer one advantage over the Swedish: the Dutch policies and design standards are readily available in English. The rest of this paper will focus on the Dutch approach and how it can be applied here in Boston.

1.3 Spread to the US

1.3.1 Current Practice

The traditional approaches to traffic safety in the US have typically been driven by cost-benefit analyses. Inexpensive interventions such as education and enforcement are often promoted while infrastructure improvements are limited to treating "hot spots"--locations with unusually high crash rates. When hot spots are identified, crash data is reviewed in an effort to detect patterns in the types of crashes that are occurring and safety measures are applied to correct the observed crash types. Crash modification factors (CMFs) are often used to determine what safety measures will provide the most benefit. Crash modification factors (sometimes called accident modification factors [AMFs]) distill existing research on a particular design feature into a single number for easy comparison or use in mathematical models.

The major U.S. safety publications, including AASHTO's *Strategic Highway Safety Plan*, *NCHRP Report 500,* and *The Highway Safety Manual* advocate for this approach.

AASHTO's *Strategic Highway Safety Plan* (SHSP) (AASHTO, 2005)*,* written in 1997 and last updated in 2004, is intended to guide states' investments in traffic safety by identifying some twenty "emphasis areas": areas where countermeasures are expected to have the greatest impact. These emphasis areas target specific types of driver behavior (aggressive, distracted, and impaired driving; seatbelt use), vulnerable users (pedestrians, cyclists), highway design features (roadside design, horizontal curves, work zones), and EMS response times.

The SHSP's purpose is to identify problem areas, and while it suggests general strategies for improving safety, it is not meant to be a detailed guide on how to implement them (for example, strategies include "implement comprehensive programs to combat aggressive driving" and "create more effective ways to deal with repeat DUI offenders"). That role falls to NCHRP Report 500 (Transportation Research Board, 2003-2009). NCHRP 500, subtitled *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*, is a 23-volume series containing strategies to how to put the *Strategic Highway Safety Plan* into practice. Each volume focuses on one of the Emphasis Areas identified in the SHSP. NCHRP 500 follows a three-tiered tree-like organizational structure (Figure 2). Within each Emphasis Area, several *objectives* are identified. Several *strategies* are then listed to achieve each objective, resulting in dozens of specific strategies to reduce crashes for each Emphasis Area. Recommended strategies include a variety of approaches, including improvements to education, enforcement, infrastructure, technology, legislation, and emergency medical services.

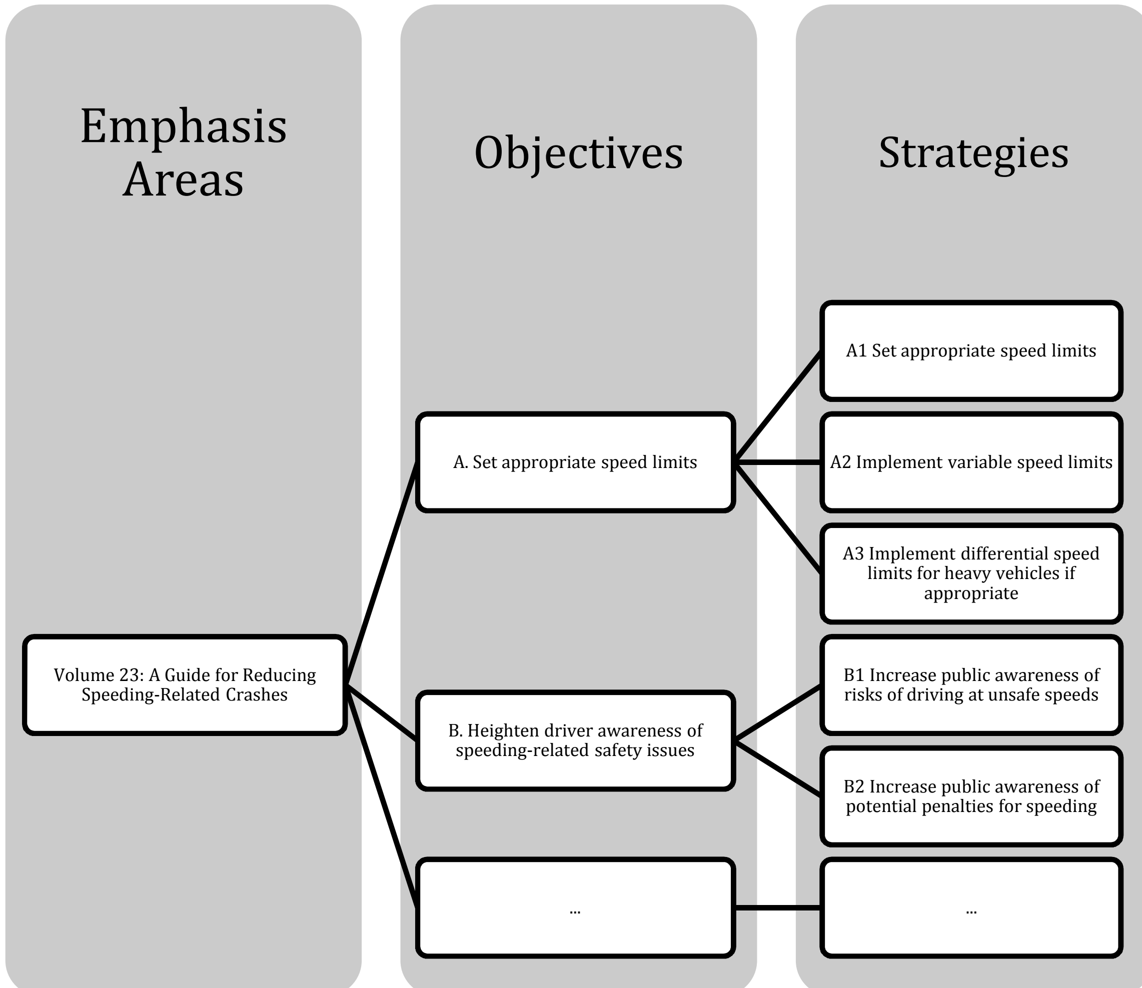


Figure 2: Organizational Structure of NCHRP 500

A perceived shortcoming of the SHSP/NCHRP 500 approach is that it is largely qualitative. The *Highway Safety Manual* (HSM) was prepared to establish a quantitative/predictive approach to traffic safety, making it easier to objectively factor safety into alternatives analyses, much like we do with lifecycle costs, traffic levels-of-service, and environmental impacts.

Published in 2010, the HSM contains a suite of specific methods and mathematical models to:

- Screen for hot spots in the roadway network
- Diagnose problems at identified hot spots

- Perform cost-benefit analyses of potential countermeasures
- Prioritize projects
- Evaluate the effectiveness of countermeasures once installed
- predict crash frequency and severity for a given design

The methods presented in the SHSP, NCHRP 500, and the HSM are not without merit. If resources are limited, it makes sense to pick the low-hanging fruit. But the goal in these publications is to *reduce* fatalities and serious injuries in a cost-effective manner. They are triage for an unsafe system where Vision Zero's approach is to fix the system. The cost-benefit-based methods typify precisely the approaches that the European Vision Zero plans were reacting against.

The traditional US approach differs from Vision Zero in four major ways:

First, crash reduction goals are based on cost-benefit analyses--certain types of crashes are tolerated because it would be expensive to eliminate them.

Second, rather than create an inherently safe system with redundancies and fail-safes—a system that recognizes human limitations—American policies emphasize strategies based on legislation, driver education/outreach, and enforcement. The assumption being that road users wouldn't make mistakes and bad decisions if only they were better trained and better informed about traffic laws.

Third, infrastructure improvements rely on identifying and correcting hot spots, which is a reactive approach that requires data from the very crashes we are trying to prevent. Engineers make changes only after there have been enough crashes to both identify a hot spot and detect patterns in the crash history Even if good data is available, locations with "merely average" crash rates are not addressed.

Finally, the Dutch approach to safety is based on the general application of principles, while the HSM is based on specific engineering solutions determined by CMFs. Any approach based on hot spot analysis and CMFs will have difficulty addressing diffuse crashes that do not follow specific patterns. This is a particular problem in urban areas where most crashes don't occur at localized hot spots. As a result, most of the CMFs that have been studied are primarily applicable to rural and high-speed roads. New designs with undetermined CMFs, low-quality CMFs, or designs with conflicting research also create problems for analysts.

To be sure, treatment of hot spots *is* an important part of a safety strategy. Identifying patterns of crashes is useful for correcting gross design flaws at specific locations. But we do not wait for patterns of meltdowns at nuclear power plants or patterns of passenger jets crashing to emerge before we intervene. To go from fixing high-crash locations to a transportation system that is truly throughout the entire network, new tools are needed.

1.3.2 Adoption of Vision Zero in the US

Recognizing the limitations in the traditional US approaches, several agencies have begun to explore Vision Zero-style policies.

In 2000, the state of Washington committed itself to "Target Zero", the first Vision Zero-like plan in the United States (Washington Traffic Safety Commission, 2013). Washington has identified speeding, impaired driving, and run-off-the-road accidents as three greatest risk factors for deaths and serious injuries and has focused its activities on those three areas. If current trends continue, Washington is on track to largely eliminate traffic deaths by 2030 (Figure 3).

Washington was followed by Minnesota with their "Toward Zero Deaths" program in 2003 and Utah, Nevada, and Iowa joined a program titled "Zero Fatalities", also in 2003. Ten years after it was adopted, Toward Zero Deaths has reduced fatalities by 40% (Figure 4). Minnesota attributes its success to a number of factors including:

- increasing seat belt use,
- reducing impaired driving,
- reducing traffic speeds,
- helping younger drivers,
- preventing run-off-the-road crashes

The Zero Fatalities program has had mixed results: after dropping slightly in the 2000s, fatalities have started to climbed again since around 2010 in both Utah and Nevada (Zero Fatalities, n.d.), (Nevada Department of Public Safety & Transportation, 2016).

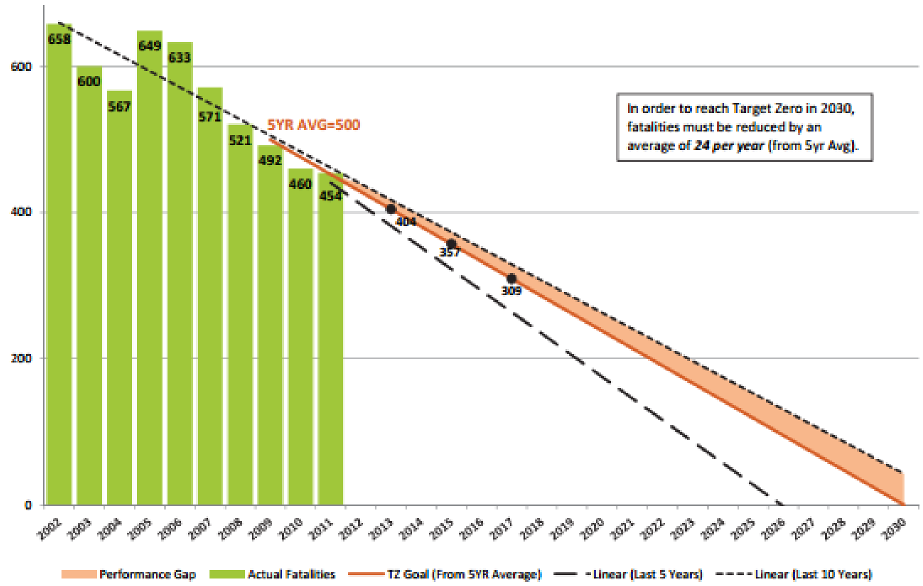


Figure 3: Washington State Fatalities from Traffic Collisions Since adoption of "Target Zero" (Washington Traffic Safety Commission, 2013)

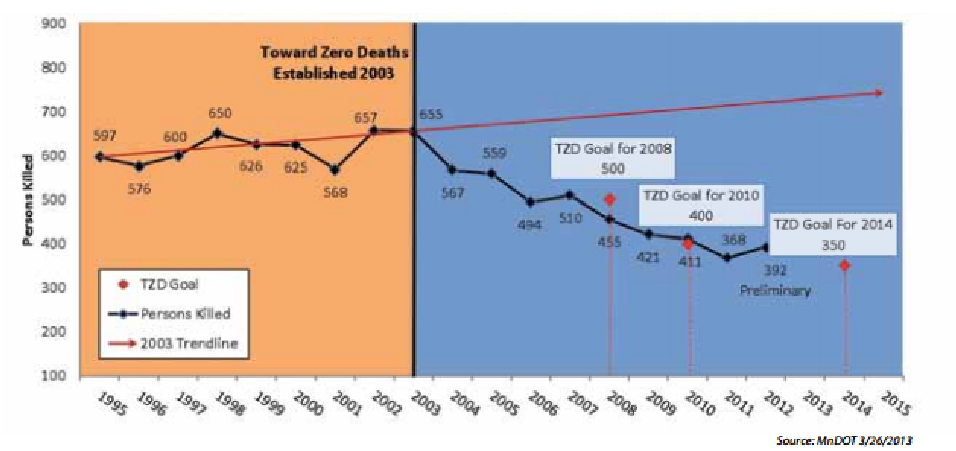


Figure 4: Road Fatalities in Minnesota Before and After "Toward Zero Deaths" (Center for Transportation Studies, 2013)

These state-wide programs tend to focus on rural roads. As a result, Vision Zero was virtually unheard of in American cities until 2014 when New York City released its

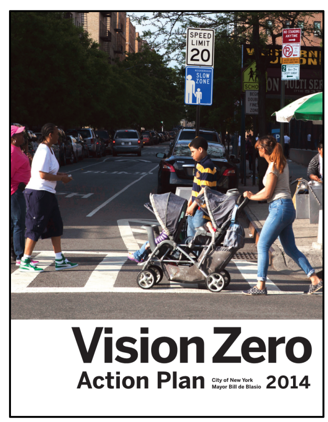
Vision Zero Action Plan. New York was quickly followed by a still-growing list of cities, including Washington D.C., Seattle, Portland, San Francisco, Los Angeles, San Diego, Austin, San Antonio, and now Boston.

As of March 2016, there are 16 "Vision Zero Cities" in the US, and that number is growing rapidly: there are at least 17 additional cities that are considering Vision Zero policies according to the Vision Zero Network, a traffic safety advocacy group (Vision Zero Network, 2016). By their definition, a Vision Zero City is one that has:

1. Set a clear goal of eliminating traffic fatalities and severe injuries,
2. Publicly and officially committed to Vision Zero,
3. A Vision Zero plan in place, and
4. Engagement from key city departments.

Beyond meeting these basic criteria, the various Vision Zero action plans that cities have published have little in common with their European equivalents. A representative sample of US plans are summarized below.

New York's Vision Zero: The cornerstone of New York's plan has been reducing the default speed limit from 30 MPH to 25 MPH and the efforts to improve compliance with that new speed limit, including speed cameras, traffic calming devices, and enforcement. The plan deserves credit for confronting speed as the main predictor of crash severity and for the specificity of its goals. In total, 63 actions organized by City department ("actions for city hall", "actions for NYPD") are identified (City of New York, 2014). A small sample:



- Reduce the citywide speed limit to 25 MPH and increase penalties for dangerous driver behavior.
- Increase enforcement against dangerous moving violations including speeding, failing to yield to pedestrians, signal violations, improper turns/disobeying signage, and phoning/texting while driving.

- Expand Collision Investigation to include all crashes with critical injuries
- Install speed cameras at 20 new locations
- Enhance street lighting at 1,000 intersections
- Explore in-car technology for taxis that limits vehicle speeds, warns drivers of impending collisions, or reduces fare when the driver speeds
- Expand defensive driver training courses for all employees driving City vehicles
- Conduct targeted outreach in 500 schools each year

One notable difference between New York's action plan and the Netherland's Sustainable Safety is its focus on outreach, enforcement, data collection, and organizational changes. Where the Netherlands emphasizes infrastructure improvements, the majority of New York's actions are under the jurisdiction of City Hall, the police department, the Taxi & Limousine Commission, the Department of Citywide Administrative Services, and the Department of Health and Mental Hygiene. As will be argued in later chapters, enforcement and education may reduce the frequency of certain dangerous actions, but as long as the opportunity for unsafe behavior exists, it will occur.

Another difference between New York and the Netherlands is the latter's use of fundamental principles to guide actions, while many of NYC's actions appear somewhat scattered or arbitrary. This is not to say they are not worth trying, but the reasons why some of the actions were included on the list of 63 actions is not obvious, and their efficacy is untested.

Vision Zero New York has only been official policy for two full years so most of its benefits are yet to be realized, but preliminary results are encouraging: fatalities have dropped approximately 10% per year since the beginning of 2014 (Furfaro), (Fitzsimmons), (New York City Mayor's Office of Operations, 2016).

Figure 5: Fatalities in New York City before and after Vision Zero (New York City Mayor's Office of Operations, 2016)

Washington, D.C.: The actions identified in Washington, D.C.'s "Plan of Action" are organized around the themes of Creating Safe Streets, Protecting Vulnerable Users, Preventing Dangerous Driving, and Being Transparent & Responsive. Data analysis is a

strong theme throughout the plan; nearly half of the document's total length is devoted to various heatmaps and charts showing types and locations of crashes, and 42 of the 67 actions identified are focused on improving data collection and/or analysis. With its emphasis on data analysis, one is left without a clear idea of what Vision Zero Washington, D.C. will look like on the ground; most of the proposed actions are one step removed from real-world implementation. Instead of identifying what safety improvements will be installed, actions will "enhance the evaluation of safety improvements and require safety performance goals of roadway improvements." or "determine bus stop locations with the most hazardous conditions, and upgrade at least ten per year"

Seattle, San Francisco, Los Angeles, and Portland: These four west-coast cities' Vision Zero plans – all published in 2015, all very preliminary – are essentially statements of intent at the time of this writing. Most important is the tone they are setting: they start from the idea that traffic deaths are unacceptable and preventable, and commit to safety as their highest priority. All recognize speed as the major predictor of safety.

None of these plans move beyond hot-spot analysis and treatment, though it remains to be seen whether focusing on their "High Injury Networks" is an interim strategy as Vision Zero is rolled out or the core of their long-term approach to safety.

Interestingly, social equity is emphasized in these plans. They each note that a disproportionate number of crashes occur in neighborhoods with large low-income and/or minority populations, and commit to prioritizing projects in these areas.

CHAPTER 2: FUNDAMENTALS OF URBAN TRAFFIC SAFETY

Vision Zero policies can be successful at reducing traffic deaths and serious injuries when implemented correctly, but not every strategy has been equally effective. The following section gives an overview of the critical elements on which the Netherlands' Vision Zero program is founded.

2.1 Statement of purpose

The ultimate goal of Vision Zero can be stated simply: eliminate traffic deaths and serious injuries.

This goal explicitly rejects the idea that risk is an unfortunate but inherent consequence of our modern transportation system. As a society, we would never tolerate jet airliners crashing on a weekly basis or a cruise ship sinking every month, yet this is exactly what happens -- in terms of life lost -- on our streets. Instead, Sustainable Safety says that we should build the types of fail-safe systems you see in other fields into our infrastructure so that traffic becomes inherently safe.

2.2 "Man is the Measure of all things"

While it may seem quaint, this is the most fundamental concept behind a safe transportation system. Unlike commercial air or rail travel, the traffic network puts road users in control of their own vehicles. We do not have highly trained professionals chauffeuring us around; we have kids riding their bikes to school and drivers talking on their cell phones. Knowing this, our system should be designed to take human limitations, vulnerabilities, and proclivities into account. A safe system must explicitly acknowledge that:

- People make mistakes and violate traffic rules, either intentionally or subconsciously. Approximately 90% of crashes are attributed to human error (National Highway Traffic Safety Administration, 2008). No matter how strict our enforcement is or good our training programs are, people are prone to mistakes, lapses in judgement, and willful disregard of traffic laws. Completely eliminating human error, whether through enforcement or education, is an unrealistic objective. Instead, our transportation network must be forgiving enough that errors do not result in fatalities. Our infrastructure should be designed to offer real humans – who characteristically make errors – a safe roadway environment.

- People are physically fragile, especially in relation to the masses and speeds encountered in traffic (Figure 6). Any approach to safety must account for our particular frailties. In-car technology (e.g., air bags, crumple zones) can provide a measure of protection for vehicle occupants, but pedestrians, bicyclists, and motorcyclists will always be vulnerable. Roads should be designed to eliminate the possibility that anyone is exposed to fatal forces.

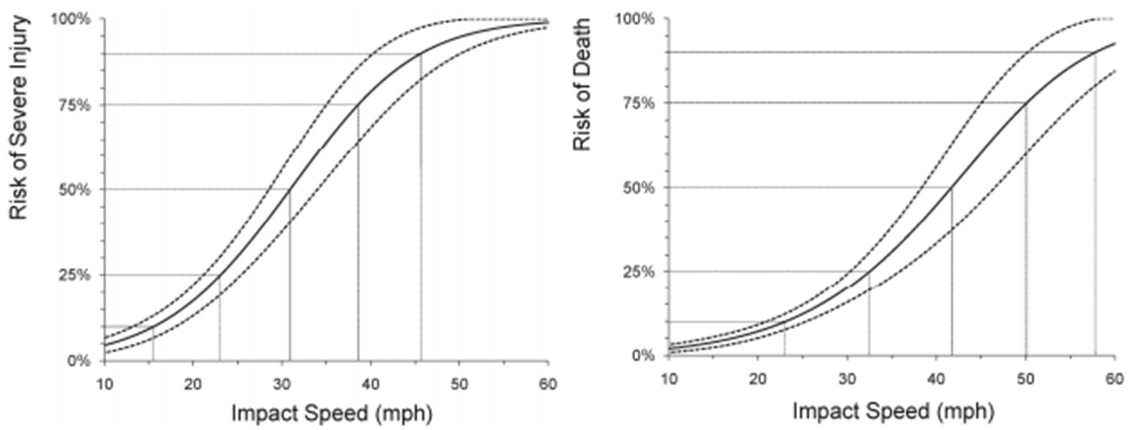


Figure 6: Risk of Pedestrian Injury and Death vs Impact Speed (AAA Foundation for Traffic Safety, 2011)

- Human perception is limited and reaction times can be long. In 50% of crashes, road users reported not seeing the other party (SWOV Institute for Road Safety Research, 2006). Our infrastructure and in-car technology should eliminate literal and figurative blind spots and help drivers anticipate upcoming situations.[1]

---

[1] Human fallibility and physical vulnerability are core elements in the Dutch literature, but limited perception and reaction time is not explored in depth. It is included here to elaborate on another critical human weakness.

Finally, designs and policies must meet users' real-world needs. A design might look good on paper, but if people do not behave as the designer intended, it is unsuccessful.

Once we acknowledge that drivers are fallible, we can rephrase the problem of traffic fatalities. Instead of asking, "Why did that person crash?" the Vision Zero framework would ask, "How did our traffic system allow a situation where serious crashes of this type can occur?" (Vision Zero Network, 2016)

The answer to the first question is often left at "the driver made a mistake". We wring our hands and lament the tragedy, but ultimately blame the driver. Instead, if we recognize that some percentage of drivers eventually *will* make that particular mistake, we are obliged to change our designs, policies, and enforcement practices to take those errors into account and minimize the damage.

2.3 Crash Risk Factors and Driver Behavior models

Any project that attempts to reduce fatalities should first seek to understand what causes crashes, injuries, and fatalities to begin with. Sustainable Safety is grounded in several driver behavior models that attempt to explain the factors that contribute to a crash.

2.3.1 Latent Errors and the "Swiss Cheese" Model

Typically, crashes are the result of several factors, not a single factor. One can usually recover from a single driving mistake or avoid a single design flaw. Many errors have to align in order for a crash to occur.

For example, a slight defect in the road design, which has not been recognized as a problem because drivers normally compensate for it, might cause a crash when a driver becomes distracted at the wrong time. These minor design flaws or bad driving habits that are left uncorrected, either because they are not recognized or are deemed not worth the effort and cost to correct, are known as "latent errors" in the system. When enough latent errors accumulate, it can become difficult to compensate for all of them, and a crash occurs. This is sometimes called the "Swiss Cheese" model due to the figures commonly used to illustrate it (Figure 7). We try to create layers of redundant measures to prevent traffic deaths from occurring (the "cheese"), but latent errors and dangerous actions create "holes" in these layers. If enough holes align, a fatality may occur.

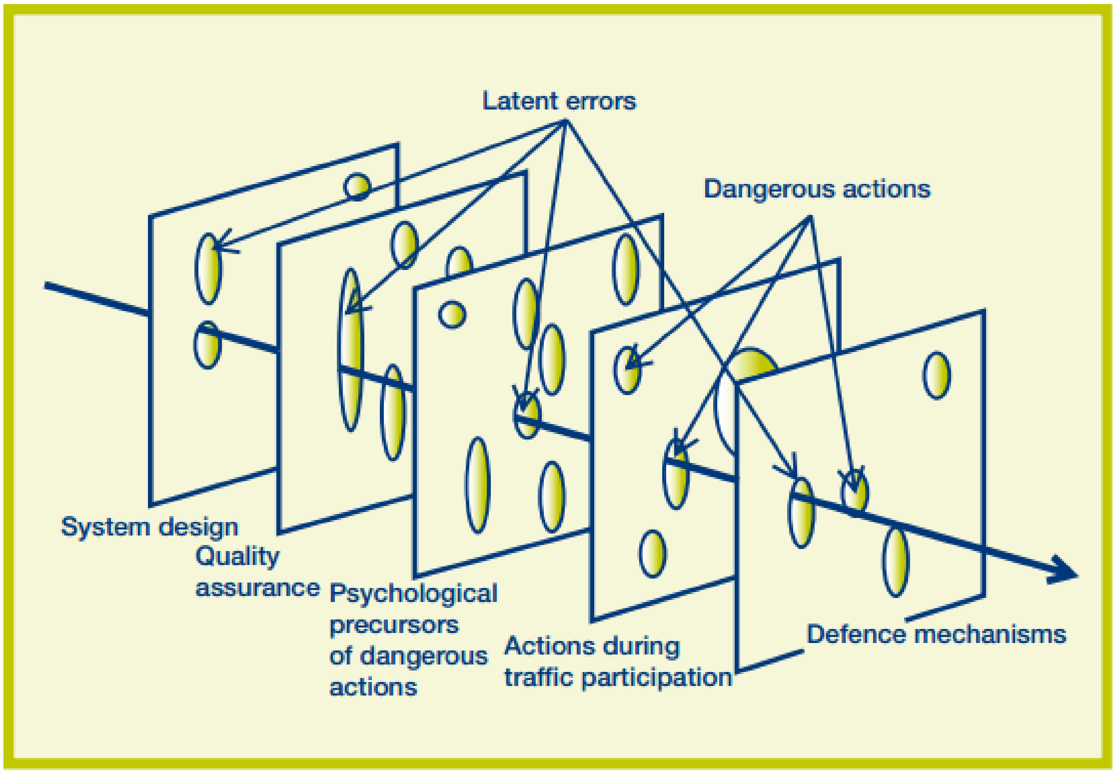


Figure 7: "Swiss Cheese Model" as Schematic Representation of the Development of a Crash. (SWOV Institute for Road Safety Research, 2006)

More attention should be paid to addressing latent errors of all types to make system more forgiving. Eliminating small design flaws and correcting bad driving habits that may not show up in hot spot analysis will help reduce future crashes throughout the entire system.

2.3.2 Levels of Conscious Thinking and Associated Errors

According to categories developed by Rasmussen (SWOV Institute for Road Safety Research, 2006), there are three types of behavior: reasoning-based behavior, rule-based behavior, and subconscious behavior. Each behavior type has a corresponding error that results in dangerous actions.

Reasoning-based behavior (called "knowledge-based" by Rasmussen) includes actions that require acquiring new information, consciously processing that information, and making a deliberate decisions. Examples of reasoning-based actions include navigating in an unfamiliar area, judging gaps while crossing multiple lanes, and reacting to unexpected traffic situations. Reasoning-based decisions require close attention by the road user and may take some time to process. Making a wrong turn when navigating or deciding to make a left turn into oncoming traffic are examples of reasoning-based errors.

Rule-based behavior involves the application of simple rules to the driving situation. When you see brake lights ahead, you slow down. When you need to merge, you look for an appropriate gap. For rule-based behavior, the application of the rules is automatic, but the driver must still pay attention to traffic cues. Misjudging a gap when changing lanes, failing to yield at a crosswalk due to inattention, and rear-ending a stopped car would all be examples of rule-based mistakes.

Subconscious behavior (called "Skill-based" behavior by Rasmussen) is fully automatic and occurs at the subconscious using level using well-practiced skills. Tasks based on muscle memory, such as steering or shifting, or reflexively checking the rearview mirror are subconscious behaviors. Errors in subconscious behavior are classified either as lapses or slips. A lapse is a failure to take an action that should be automatic, such as failing to stop at a stop sign. A slip is occurs when an action is performed incorrectly; missing the brake pedal, for example.

Of the three types of behavior, reasoning-based actions are the most prone to error, and subconscious actions are the most likely to be performed correctly. Also, errors in subconscious behavior can often be quickly corrected before resulting in a crash. Therefore, **as much of the driving task should be made routine and subconscious as possible**. This can be achieved through driver training and through creating a self-explanatory road environment that requires few high-level judgements. The idea of a self-explanatory roadway is the basis for the principles of Functionality and Predictability, which are discussed later.

2.3.3 Intentional Offences and Enforcement

The behavior classification scheme discussed above assumes that drivers are trying to drive according to the rules of the road. But what motivates people to follow traffic laws in the first place and how can we discourage intentional violations?

Theories on rule-following behavior can be classified as either *normative* theories or *instrumental* theories (SWOV Institute for Road Safety Research, 2006). Normative theories posit that people act based on internal motivations that are determined largely by social norms, not external traffic laws. People have a sense of what is and isn't socially acceptable, and will take the most appropriate action as they see it, without regard to reward or punishment. According to normative theories, the "legitimacy" of rules is crucial: to maximize compliance,

- rules should align with most people's concept of correct behavior and
- the relationship between the rule and the rule's objective should be clear.

In other words, compliance will be high when people generally agree that a rule serves a beneficial purpose, but many traffic laws are disregarded by most drivers, perpetuating the norm that compliance is not necessary. To give a tangible example: most people wouldn't knowingly run a stop sign, even if they are sure they won't get a ticket, because traffic is clearly more efficient and safer with right-of-way rules. Speed regulations, on the other hand, are widely ignored. There is a sense that "everybody else is speeding" and the posted speed limit may often seem arbitrary. The benefits of lower traffic speeds may not be immediately obvious until after a crash occurs, especially to a driver running late.

Instrumental theories of behavior say that people perform a type of cost-benefit analyses, at least at a subconscious level, to decide whether to follow a given law. Does the risk of a speeding ticket outweigh the time I could save by speeding? Does the risk of a crash outweigh the time I could save by making this illegal left turn? Combating undesirable behavior, according to instrumental theories, is based on highly visible enforcement. The perceived likelihood of being caught and the penalty for violations must be high enough to tip the cost-benefit analysis in favor of compliance.

To improve safety, enforcement must be a deterrent, not just a punishment; citing a driver *after* a violation has not prevented the unsafe condition from occurring. To be an effective deterrent, there would have to be a sufficient level of police presence throughout the entire, diffuse road network at all times that being caught after a violation becomes a legitimate threat. Due to the associated labor costs, relying on enforcement as a major strategy to reach the level of traffic safety for which Vision Zero strives is not efficient.

Enforcement via technology is also unrealistic. Roadside technologies (red light cameras and speed cameras) can easily increase the coverage of enforcement for certain types of violations, but are currently not allowed in Massachusetts. In-car enforcement technology (e.g., speed governors) is theoretically possible but would also be very expensive and would require a majority of the driving population to accept controlling devices in their personal vehicles. Finally, any type of enforcement, whether traditional or technological, sets up an adversarial relationship between drivers and the City, and creates the potential for abuse.

This leaves self-enforcing infrastructure as the preferred method for ensuring broad compliance with traffic laws. Design strategies that preclude or reduce the benefits of undesired behavior include the following:

- Coordinated traffic signals with short cycle lengths along a corridor result in a “green wave” for drivers traveling at the desired speed, but speeders encounter red lights.
- Speed humps enforce speed limits and discourage cut-through traffic on low-speed residential streets.
- Increasing speeds and reducing delays on streets where City engineers *do* want traffic (e.g. the major arterials) reduces the incentive for cut-through traffic to use local streets.
- Installing cycle tracks instead of bike lanes prevents encroachment and illegal parking by motor vehicles.

Whether a driver's behavior is better explained better by a normative theory, an instrumental theory, or some third alternative depends on the specific driver and the specific situation; therefore a combination of approaches is needed. The City should try to foster intrinsic good behavior with sensible, transparent rules, but also with self-enforcing roadway designs that result in "spontaneous" compliance.

2.4 Risk Compensation and Speed

The Risk Homeostasis model (also called the Risk Compensation model), proposed by Wilde in the 1980s, suggests that all drivers have a certain tolerance for risk, and they adjust their behavior as the situation demands to keep the risk constant (Wilde, 1998). Wilde points to several findings to support this theory, including:

- Drivers with anti-lock brakes tend to tailgate more than drivers of non-ABS cars
- Cars with airbags tend to be driven more aggressively
- Speeds tend to be higher on roads with better street lighting

An alternative way of looking at risk compensation that may be more useful when discussing driving behavior is *difficulty homeostasis*: people adjust their behavior to keep the difficulty of the driving task constant.

By itself, homeostasis theory seems discouraging: any measure we take to make things safer will be undone as people behave more aggressively to compensate. In the context of driving, however, the main mechanism that a driver has to increase risk/difficulty is speed. People tend to drive as fast as they feel comfortable in order to reach their destination sooner, only limiting their speed to keep the difficulty manageable. Measures that attempt to improve safety, such as adding clear zones, but that neglect speed control will be (at least somewhat) self-defeating because drivers will compensate by increasing their speeds. A sustainable approach to improving safety, therefore, must include speed control measures. Controlling drivers' speeds through infrastructure is the only way to ensure that the difficulty of the driving task never exceeds the driver's capacity.

In-vehicle activities, such as texting or playing with the radio, are another way that drivers may increase their difficulty. Efforts to combat distracted driving will likely prove fruitful, but are beyond the scope of this paper.

2.5 Safe Speeds by Roadway Context

When it comes to traffic safety, traffic speed is the elephant in the room. Higher speeds significantly increase *both* the risk of a crash *and* the severity of those crashes that occur. The variation in individual vehicles' speeds is also a risk factor (SWOV Institute for Road Safety Reseach, 2012). Achieving broad compliance with safe speed limits is perhaps the single largest step towards achieving the goal of Vision Zero.

There is overwhelming evidence connecting increased speed to decreased safety. For example:

- Finch found that every 1 km/h increase in speed results in a 3% increase in accidents (Finch, 1994)
- Nilsson found that the change in the risk for crashes, injuries, and deaths varies with the second, third, and fourth power, respectively, of the change in speed. This means that a 10% increase in speed would result in a 21% increase in crashes, a 33% increase in injuries, and a 46% increase in fatalities. Specifically:

$$R_2 = R_1 \left(\frac{v_2}{v_1}\right)^n$$

  where v_1 is the initial speed on the road, v_2 is the new speed on the road, R_1 is the initial risk, and R_2 is the resultant risk. For the risk of crashes, n=2; for the risk of injury, n=3; and for the risk of death, n=4 (Nilsson, The Effects of Speed Limits on Traffic Accidents in Sweden, 1982), (Nilsson, Traffic Safety Dimensions and the Power Model to Describe the Effect of Speed on Safety, 2004).

- AAA found that risks to pedestrians increase rapidly with impact speed (Figure 6, above) (AAA Foundation for Traffic Safety, 2011)

Based on these findings, reducing travel speeds in Boston from 30 mph to 20 mph could reduce the number of crashes by as much as 50% and fatalities by as much as 80%

Massachusetts law sets a statutory speed limit of 30 mph on most urban streets unless a different speed limit is posted (MGL 90-18). With few exceptions, most streets in Boston do not have posted speed limits, conflicting with the preponderance of research, which suggests that 30 mph is just too high to be safe for most city streets. Instead, speeds based on the type of conflicts that are expected to occur should be established.

Streets where pedestrians walk in the street: Where pedestrians regularly walk in the street, sharing space with motor vehicles, the speed limit should be no more than 10 mph. This includes streets that lack sidewalks (though there are none in Boston) and, more commonly, streets where the sidewalks have so many obstructions and traffic volumes are low enough, that they become *de facto* shared streets. Streets that are intentionally designed to be shared streets are discussed later.

Figure 8: Narrow Sidewalks with Frequent Obstructions Create De Facto Shared Streets

Streets where pedestrians regularly cross anywhere: On streets where pedestrians normally cross anywhere along the street, the speed limit should be no more than 20 mph. When impact speeds between pedestrians and motor vehicles increase above 20 mph, the risk of serious injury and fatality climb rapidly (AAA Foundation for Traffic Safety, 2011). This recommended speed accounts for both the pedestrian's physical vulnerability and the reaction times drivers need to react to unexpected situations. Residential streets where people walk between their homes and their cars parked across the street is a typical example where this speed limit might apply.

Streets with unsignalized pedestrian crossings: At locations where pedestrians primarily cross at marked, but unsignalized, crossings, speeds should be limited to 25 mph. The pedestrians are still vulnerable, but their behavior is more predictable to drivers, so a higher speed limit is tolerable. For this case, driver yielding compliance becomes the determining factor in setting the speed. It has been shown that where vehicle speeds are below 25 mph, approximately 75% of drivers yield to pedestrians. Above 25 mph, yielding rates drop below 50% (Bertulis & Dulaski, 2014).

Streets with bikes in mixed traffic: On streets where cyclists operate in mixed traffic, speeds should be limited to no more than 20 mph. This limit accounts for the vulnerability of the unprotected cyclist and for observed driver behavior. Drivers are usually able to pass a bicycle by encroaching into the oncoming lane; however, when oncoming traffic is heavy enough, drivers may need to slow down to the speed of the cyclist for some distance. 10 mph is a typical speed for an urban cyclist so a speed limit of 20 mph limits the speed differential between cyclists and motorists to only 10 mph. Research has shown that when the differential between the drivers desired speed and the speed of the cyclist is 15 mph or greater, drivers are less willing to slow down and are more likely to pass dangerously (Furth, 2008).

Locations where vehicle paths cross at 90 degrees: If vehicle-to-vehicle collisions at 90 degrees (or greater) are the only type of collision that is reasonably likely to happen, such as at unsignalized intersections or signalized intersections with permitted left turns, the speed should be limited to no more than 30 mph. In-car safety features such as seat belts, air bags, and crumple zones are relatively effective at protecting vehicle occupants, especially at low speeds. As speed increases, however, even these safety features cannot prevent all fatalities. The change in velocity (Δv) during a crash is a good predictor of crash severity and the risk of fatality is extremely sensitive to Δv. If two vehicles with roughly equal masses, each traveling 30 mph, collide at 90 degrees, there is roughly a 20% chance of a fatality. As the travel speeds increase to 40 mph, the risk of a fatality approaches 90% for a right-angle collision (Richards, 2010).

The recommended speed limits discussed in the preceding paragraphs are summarized in Table 1.

Table 1: Suggested Speed Limits by Roadway Context

Roadway Context*	**Maximum safe speed (MPH)***
Streets where pedestrians walk in the street (e.g. frequently interrupted or no sidewalk)	10
Streets where pedestrians normally cross anywhere	20
Bikes in mixed traffic	20
Locations with marked but unsignalized pedestrian crossings	25
Locations where vehicle paths cross at 90 degrees	30

*Where more than one condition applies, the lowest applicable speed limit should be used.

CHAPTER 3: THE FIVE PRINCIPLES OF SYSTEMATICALLY SAFE ROADS

Having identified the goal, relevant behavior models, and risk factors, we are ready to state the five fundamental principles that should serve as the foundation for all design, enforcement, and policy decisions. These core principles are borrowed from the Dutch Sustainable Safety (SWOV Institute for Road Safety Research, 2006), but have been expanded upon to include ideas that are implied but not stated explicitly in the Dutch literature. Terminology and emphasis has also been adapted for clarity and application to Boston.

The reader will notice that speed control is a common thread that runs through all of the principles. Indeed, speed control could be considered the zeroth principle; however, this thesis opts to treat speed as a "fundamental" due to its relevance to all of the other principles.

3.1 Homogeneity, or Speed Control and Separation

The principle of *homogeneity* states that road users with significantly different speeds, masses, or directions should not mix. That is, under most conditions, pedestrians, bicycles, and motor vehicles should each be given their own separate operating spaces. Where traffic speeds are sufficiently low, such as parking lots, driveways, and shared streets, fully mixed traffic is acceptable, but as speeds increase much above a walking pace (above, say, 10 mph), pedestrians should be given separate sidewalks. As speeds increase further, beyond that of a typical cyclist, separated bicycle facilities should be provided. Increased separation is the "price" of increased speed.

This idea is based on simple physics and is intended to limit the amount of physical trauma to which users could potentially be exposed. In a collision, the force experienced by the victims is proportional to the change in their velocities, Δv, and the relative masses of the vehicles involved. A collision between two cars traveling the same direction is unlikely to result in a death because the Δv is low and they have comparable masses; a car hitting a cyclist or an angle collision between a speeding truck and a small car could be catastrophic because Δv is high and they have very different masses. Circumstances where these more dangerous outcomes could happen should be avoided through design. This means, for example:

- Driveways (with their slowing, turning, and crossing traffic) on high-speed roads should be avoided.
- Two-lane roads are preferable to multi-lane roads. Multi-lane roads facilitate speeding and increase the exposure for crossing traffic and pedestrians.
- Minor roads crossing multi-lane or high-speed major roads should be signalized to separate conflicting movements in time.
- Protected left turns are preferred over permitted left turns.
- Cyclists should be separated from vehicular traffic on busy roads.
- Pedestrians should not have to cross major roads without protection (such as a signal).

Table 1 in the previous chapter summarizes the recommended maximum speeds for various types of potential conflicts (or, conversely, what types of interactions should be allowed on streets with a given speed limit). However, it is not sufficient to simply post the desired speed limit; as long as it is *possible* to drive faster than is safe, some percentage of drivers *will* drive faster than is safe as described in Chapter 2. Drivers' speeds should be controlled through physical design elements (e.g., traffic calming, roadway geometry, signal timing). Similarly, physical barriers are preferred over signage and line striping when separation is called for to prevent encroachment into other users' operating space, whether intentional (e.g., double parking in a bike lane) or accidental (e.g., drifting into the oncoming traffic lane).

Following the principle of homogeneity, both Sweden and the Netherlands use roundabouts as the default type of intersection. Only where space is lacking or volumes demand it will they install a signal. The design of a roundabout ensures that all entering and circulating vehicles are traveling at approximately the same speed, and the merging maneuver at entrances means that vehicles are heading in roughly the same direction. At signals, most of the potential conflicts are head-on or angle conflicts, violating the principle of separation by direction.

3.2 Predictability through Simple and Recognizable Road Design

The second principle of Sustainable Safety is *predictability*: the environment should reduce the likelihood of errors by fostering predictable behavior by all users. To achieve this, the road's design should be *recognizable* to the road users so that they know how to behave and can better predict others will behave.

This thesis expands on this principle to explicitly include the idea of *simplicity*. Urban traffic is a chaotic environment. Drivers and other road users are confronted with a huge amount of information every second and must make rapid decisions based on that information. By reducing the extraneous information and simplifying the decisions to be made, unpredictable behavior and bad decisions will be minimized.

The principle of predictability is based on the levels conscious thinking discussed in Section 2.3.2. Rather than having to make high-level, reasoning-based decisions to react to unexpected situations, more actions will be subconscious reflexes or rule-based actions in a simple and recognizable environment, minimizing the chance of mistakes (Figure 9). The same reasoning underlay the standardization of road signs in the US in the first half of the 20th century.

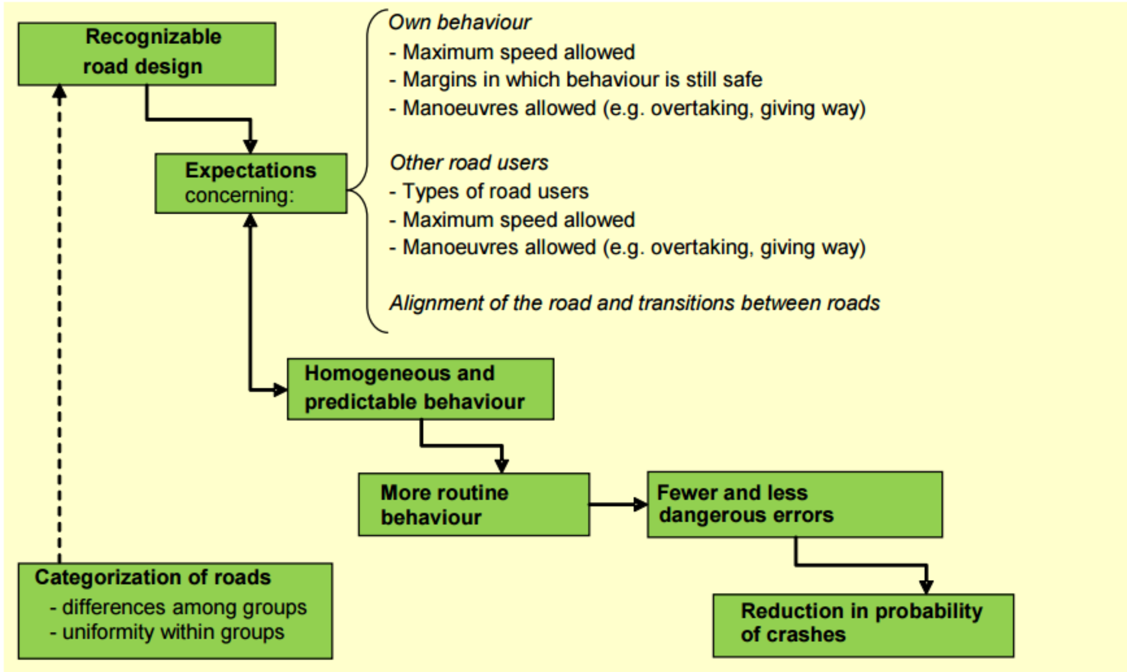


Figure 9: Relationship between Recognizable Road Design and Predictable Behavior (SWOV Institute for Road Safety Research, 2012)

3.2.1 Recognizable Characteristics

In the Netherlands, a roadway's design is tied directly to the rules for driving on that road and encourages certain types of behavior. The speed limit, for example, can be immediately determined by seeing how the road is constructed. The mechanisms that allows for this are called "Essential Recognizability Characteristics" (ERC). ERCs are continuously visible design features that are consistently applied on all roads of a given class, unlike speed limit signs, which only appear intermittently and don't physically affect how drivers interact with the road. The two official ERCs used are the type of separation between traffic directions and the edge line type:

- A center median and continuous edge lines imply, among other things, that the speed limit is 70 km/h in urban areas (100 km/h in rural areas).
- A painted center line and broken edge lines imply that the speed limit is 50 km/h.
- A traversable median (e.g., rumble strip or rubble block pavers) and no edge lines imply that the target speed is 40 km/h.

- No median and no pavement markings – no center line in particular – imply that the speed limit is 30 km/h.

A number of unofficial ERCs are also widely used in the Netherlands, including the paving material and pavement color:

- 30 km/h roads are paved with unit pavers
- 50 km/h roads are paved with asphalt
- bike lanes/cycle tracks are paved with red asphalt (SWOV Institute for Road Safety Research, 2012).

In addition to the “essentially” recognizable features, a wide variety of other design elements can be used to help drivers predict what speeds, maneuvers, and behaviors and should be expected. Some other examples of recognizable features that could be used to improve predictability:

- Raised medians make it clear where drivers can and cannot make left turns across oncoming traffic.
- Narrower lane widths signal that speeds should be lower. Wider lanes suggest faster speeds.

3.2.2 Simple Decisions for Safer Streets

Decisions that require high-level reasoning can take a long time to process and are more prone to error than automatic, subconscious behavior. To the extent possible, situations that require difficult decisions should be simplified so that only rule-based or subconscious decisions are needed. For example, protected left turns should be preferred to permitted left turns. A permitted left turn requires that drivers estimate oncoming vehicles’ speeds, judge gap lengths, gauge their own car’s acceleration, and decide on an acceptable moment to proceed. Furthermore, different drivers react very differently when confronted with the same situation, making it difficult for others to predict their behavior. When making a permitted left turn, for example, an aggressive driver might proceed when the gap in oncoming traffic is only 3 seconds, while a more timid driver might require a gap as long as 12 seconds (Ragland, Arroyo, Shladover, Misener, & Chan, 2005). A protected left turn removes these complications; left-turning drivers only have to watch for the green light. Changing a permitted left to a protected left changes reasoning-based decisions into rule-based decisions.

Other examples of designs that simplify decisions include:

- Pedestrian crossing islands make it easier to cross the street because pedestrians only need to predict gaps in traffic approaching from one direction at a time. They also make it easier for drivers to see pedestrians.
- Reducing the number of lanes on a street makes it easier for both pedestrians and left-turning vehicles to cross because they only have to judge gaps in one stream of traffic instead of two or more
- Clear wayfinding allows drivers to focus on their surroundings instead of scanning for navigational clues and avoids sudden maneuvers when drivers realize they are in the wrong lane and are about to miss their turn.
- Sudden changes in lane designation (i.e. where a lane becomes a mandatory turn lane) force drivers to merge into the through lanes unexpectedly (Figure 10). Instead, turn lanes should always begin as newly created lanes.

Figure 10: Through Lanes on Columbus Avenue Suddenly Become Turn Lanes, Forcing Drivers to Merge Unexpectedly

The US generally does a poor job of making roads recognizable. There is little correlation between a road’s design and its intended function, highlighting the need for the third principle: functionality.

3.3 Functionality

The principles of homogeneity and predictability are achieved automatically on certain types of streets. Freeways are the purest expression of homogeneity: all vehicles are traveling the same direction at roughly the same speed. Opposing traffic is separated by a median barrier and crossing traffic is grade-separated. Low-mass and low-speed travelers (i.e., pedestrians and cyclists) are simply excluded. Driving on a freeway is also very predictable: the design and expected behavior on freeways is unmistakable and the number of driving decisions to be made is very limited.

Roads at the opposite end of the spectrum—local roads—are also highly homogeneous and predictable to drive on. While not separated like freeways, all traffic on local streets is traveling slowly. Drivers know to expect pedestrians crossing, kids playing in the street, and other vehicles parking. As a result, freeways and local roads tend to be relatively safe.

Roads with the highest crash rates are roads where the previous two principles are violated because the road is designed to serve multiple, conflicting purposes (Figure 11). When different types of traffic and behaviors are mixed, it becomes very hard to predict what other drivers are going to do.

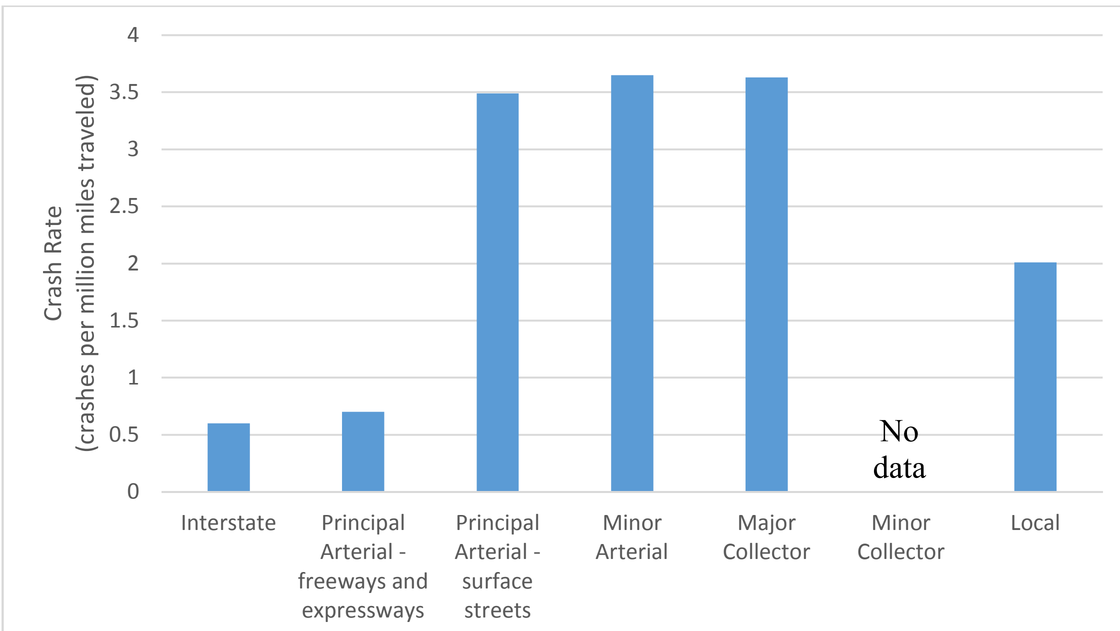


Figure 11: Urban Crash Rates by Functional Classification in Massachusetts (Massachusetts Department of Transportation, 2016)

This observation leads to a third principle of sustainable safety: *functionality.* This principle states that all of a road's functions (its intended uses) should be mutually compatible and a road's design should match its functions. Some of the functions that streets might provide for are:

- through traffic
- land access for local traffic (including parking)
- pedestrian routes along the street

- pedestrian crossings
- bike traffic
- transit lines
- "Place" functions (e.g. being residents' front yard, children's play area, places for social interactions)

Some of these functions are complementary and should almost always be paired, while others are incompatible and should be avoided on the same street. For example, streets with transit should always also prioritize safe pedestrian routes along and across the street. On the other hand, land access and through traffic are incompatible: local streets become increasingly dangerous when they carry more through traffic and through roads become increasingly dangerous when they provide intensive site access.

Functionality is a well-known but poorly implemented concept in the US. The current classifications used by the State are:

- Interstate,
- Major arterials,
- Minor arterials,
- Major collectors,
- Minor collectors, and
- Local roads (Massachusetts Department of Transportation, 2006)

These classifications are assigned based on the through-traffic function of the street, with the assumption that as through traffic increases, local-access traffic will automatically decrease. In practice, however, a high proportion of streets in the arterial and collector range often have both through traffic and intense land access functions. There is strong market pressure to locate businesses on the streets with the most traffic, so local access traffic and through traffic tend to increase together, contrary to the intent of the functional classification system. In suburban areas, this leads to strip malls along major routes. In urban areas, where space is limited, it concentrates active driveways, high-turnover parking, and pedestrian activity on the busiest streets. Compare this with European cities with strictly enforced functional classifications: many of the busiest commercial areas are car-free pedestrian zones (Kalverstraat and Cuypmarkt areas in Amsterdam, the city centers Delft, Copenhagen, Stockholm, and Stuttgart, to name a few).

Some cities and organizations have tried to develop more sophisticated classification schemes by creating additional street types that are based on factors other than through traffic, such as adjacent land use. Boston's Complete Streets Guide (City of Boston, 2013), for example, defines nine different street types with intentionally "nuanced" differences between similar types. NACTO's *Urban Street Design Guide* has 13 (National Association of City Transportation Officials, 2013). While land use should be an important factor in street design, this overabundance of street types is symptomatic of US conception of functionality: road classifications are treated as a continuum rather than as discrete classes. This continuum of street types results in a high proportion of streets serving multiple, conflicting purposes, undermining the entire purpose of the classification system.

Before the Netherlands overhauled their traffic safety program in 1992, they conceived of functionality much as we currently do in the US (Figure 12, left). After 1992, they rejected the continuum model in favor of a strictly tiered system (Figure 12, right) and worked to redesign their road network so that through traffic truly is avoided on roads serving a site access function.

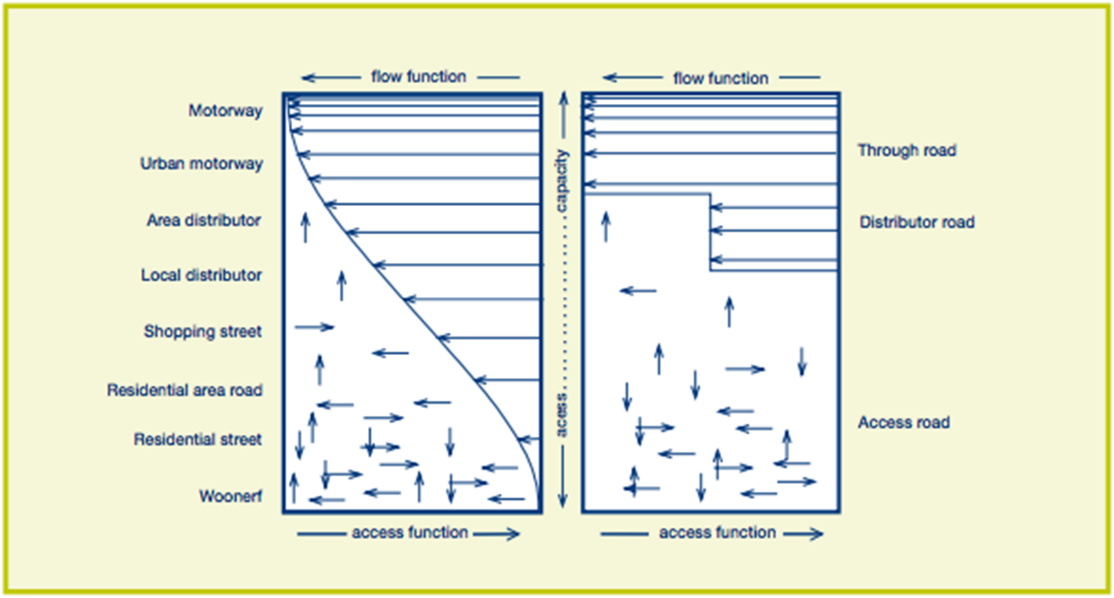


Figure 12: Old (Left) and New (Right) Conceptions of Functionality in the Netherlands (SWOV Institute for Road Safety Research, 2006)

The first iteration of Sustainable Safety reduced the number of road types from eight to three:

- through roads (maximum speed of 70 km/h in urban areas), which equivalent to our urban freeways or parkways
- distributor roads (maximum speed of 50 km/h in urban areas), equivalent to our arterials
- and access roads (maximum speed of 30 km/h in urban areas), equivalent to our local street

The intent was to make the road types maximally distinct and create a strong, recognizable link between functional classification and design. Each type of road in the Netherlands has a very strict and specific set of design criteria and design elements, so the type of road is immediately obvious to the user.

It was found, however, that historical development patterns had resulted in residential and commercial areas growing up along certain roads that were required to carry through traffic to maintain network connectivity. The network called for these roads to be classified as distributors since through traffic could not be effectively diverted to another route, but local residents would not tolerate 50 km/h traffic and pushed for classification as access roads. A fourth functional classification was introduced as a compromise: the 40 km/h “district access road” (de Groot, Breider, & Nederveen, 2005). Before this new classification could be implemented, advocates had to develop a design that that was distinct from the other three classes; simply setting a different speed limit was not sufficient. The resulting district access roads are paved with asphalt but have a mountable rubble median, can have no more than one lane per direction, and have traffic calming measures along their length. While it was not included as an official functional classification in the 2006 update to Sustainable Safety, the use and design of these 40 km/h roads has become accepted by several Dutch cities over the last decade.

The distinct designs of the four Dutch functional classifications are illustrated in the following figures. All new or reconstructed roadways are designed using one of these four basic templates:

Figure 13: Through Road

Notable features include: 70 km/h speed limit, asphalt pavement, widely spaced intersections that are grade separated or signalized, no driveways, multiple lanes per direction, raised or vegetated medians, no on-street parking, separate bicycle path, and no traffic calming.

Figure 14: Distributor Road

Notable features include: 50 km/h speed limit, asphalt pavement, intersections are at grade and can be unsignalized, no driveways, one or two lanes per direction, painted center lines, on-street parking is discouraged, cycle tracks, and traffic calming at pedestrian crossings.

Figure 15: District Access Road

Notable features include: 40 km/h speed limit, asphalt pavement, narrower lanes, intersections at grade and unsignalized, driveways permitted, one lane per direction, mountable median, parking in designated bays, cycle tracks or on-street bike lanes (cycle tracks are preferred because bike lanes make the road appear wider, promoting higher speeds), traffic calming at pedestrian crossings.

Figure 16: Access Road

Notable features include: 30 km/h speed limit, cobbles or brick pavement, intersections without priority assigned (i.e., no stop or yield signs), driveways permitted, very narrow widths (too narrow for cars to pass each other at speed), no median, on-street parking allowed, bicycles in mixed traffic, and traffic calming as needed along the road.

In stark contrast to the Netherlands, a road's classification in the US is only loosely connected to its design. The following charts (Figure 17) from MassDOT's Project Development and Design Guide illustrate this problem. According to these criteria, an urban arterial could have any speed limit between 25 and 50 mph, and could have narrower lanes than a nearby local road.

When roads are forced to serve multiple conflicting functions, as they often are in the US, design guidelines become so broad that distinctions between roadway types are of little practical importance. Dorchester Avenue and Pleasant Street (Figure 18 and Figure 19) offer a real-world example of this disconnect between functional classification and design. The former is an urban principal arterial while the later--a full two functional classifications below--is an urban collector, yet their designs are virtually identical.

Conversely, two roads of the same functional classification can have very different designs. Columbia Road and Quincy Street (Figure 20 and Figure 21) are both urban minor arterials, but Columbia Rd is a four-lane divided thoroughfare while Quincy St is a narrow two-lane residential street with frequent driveway curb cuts. One clearly emphasizes the through traffic function while the other emphasizes the land access function.

Exhibit 3-7
Design Speed Ranges (Miles per Hour)

	Roadway Type					
		Arterials		Collectors		Local
Area Type	Freeway	Major*	Minor	Major	Minor	Roads
Rural Natural	50 to 75	40 to 60*	35 to 60	30 to 60	30 to 55	20 to 45
Rural Developed	50 to 75	40 to 60*	35 to 60	30 to 60	30 to 55	20 to 45
Rural Village	N/A	30 to 45	30 to 40	25 to 40	25 to 35	20 to 35
Suburban Low Intensity Development	50 to 75	30 to 60*	30 to 55	30 to 55	30 to 55	20 to 45
Suburban High Intensity Development	50 to 75	30 to 50*	30 to 50	25 to 50	25 to 40	20 to 40
Suburban Town Center	N/A	25 to 40	25 to 40	25 to 40	25 to 35	20 to 35
Urban	50 to 75	25 to 50	25 to 40	25 to 40	25 to 35	20 to 35

N/A Not Applicable
* A higher design speed may be appropriate for arterials with full access control
Source: Adapted from A Policy on Geometric Design of Highways and Streets, AASHTO, 2004 – Chapter 3 Elements of Design

Exhibit 5-14
Range of Travel Lane Widths (In Feet)

	Roadway Type			
Area Type	Freeways	Arterials[1]	Collectors[2]	Local Roads
Rural Natural	12	11 to 12	10 to 12	9 to 12
Rural Developed	12	11 to 12	10 to 12	9 to 12
Rural Village	N/A	11 to 12	10 to 12	9 to 12
Suburban Low Density	12	11 to 12	10 to 12	9 to 12
Suburban High Density	12	11 to 12	10 to 12	9 to 12
Suburban Village/Town Center	N/A	11 to 12	10 to 12	9 to 12
Urban	12	11 to 12	10 to 12	9 to 12

1 Lane widths less than the values shown above may be used if a design exception is obtained. See Chapter 2 for a description of the design exception procedure. Situations where narrower lanes may be considered are described below.
2 Minimum 11-foot lanes are required for design speeds of 45 miles per hour or greater.
N/A Not Applicable
Source: Adapted from A Policy on Geometric Design of Highways and Streets, AASHTO 2004, Chapter 4 Cross-Section Elements.

Figure 17: Sample Design Criteria Based On Functional Classification (Massachusetts Department of Transportation, 2006)

Figure 18: Dorchester Street, Boston, an Urban Principal Arterial

Figure 19: Pleasant Street, Boston, an Urban Collector

These two streets have very different functional classifications (urban principal arterial and urban collector, respectively) but are very similar in function and design.

Figure 20: Columbia Road, Boston, an Urban Minor Arterial

Figure 21: Quincy Street, Boston, an Urban Minor Arterial

These two streets have the same classification (urban minor arterial), but are very different in function and design.

Failing to adhere to the principle of functionality creates two main problems:

- Incompatible functions exist on the same street and the street's design cannot safely accommodate all the functions demanded of it. In other words, the principle of homogeneity is violated.
- The connection between design and behavior is lost. Drivers have no way to anticipate what other vehicles are going to do, because all types of traffic are mixed. In other words, the principle of predictability is violated.

These problems are directly related to safety, as illustrated by Beacon Street, Newbury Street, and Boylston Street. These three streets run parallel to each other for eight blocks through the Back Bay. Both Beacon Street and Newbury Street keep incompatible functions separate: Beacon Street is for through traffic, Newbury Street is for shopping and pedestrians. Boylston Street, on the other hand, is lined with stores and has heavy pedestrian cross traffic, but is also a major rout for through traffic. To accommodate that through traffic, Boylston is designed like Beacon Street (three lanes, few signals, priority for through traffic) and so creates an unfriendly environment for pedestrians trying to shop, cyclists, and cars trying to park. Predictably, Boylston Street has more injury crashes than Beacon and Newbury combined (14 on Boylston vs 4 on Newbury and 8 on Beacon in 2015 (City of Boston, 2016)).

3.4 Forgivingness and Restrictiveness

The Dutch principle of *forgivingness* is extended here to include *restrictiveness*. The road environment should be *forgiving* when drivers make unintentional errors, but should also be *restrictive* to eliminate opportunities errors or intentional violations to even occur in the first place. Drivers will make mistakes, but small errors should not result in crashes. When crashes do occur, they should not result in death or major injuries. Where drivers are willing to intentionally violate traffic laws, they should be prevented from harming others.

A variety of factors work to create a forgiving road. On freeways, wide lanes, and clear zones increase reaction times for drivers traveling at high speeds. Medians, guardrail, break-away sign posts, and impact attenuators minimize damage when a car leaves the roadway. Seat belts and air bags protect drivers when there is a crash.

The principle of forgivingness is occasionally misapplied in urban areas. When wide lanes, expansive clear zones, and gentle curves are used achieve forgivingness, drivers tend to speed up, as described by the risk compensation or difficulty compensation models discussed in Section 2.4. This approach is appropriate for freeways, where high speeds are desirable, but when applied to city streets, it promotes speeding and results in designs like the snarl of intersections around the Eliot Bridge (Figure 22) that create major barriers to pedestrians and cyclists.

Figure 22: Over-Designed Intersections in Cambridge and Boston

In urban areas, traffic speeds are low enough that single-vehicle collisions with fixed roadside objects are not the concern they are on rural roads and freeways. Instead, transverse conflicts between vehicles at intersections and crashes involving pedestrians or cyclists are characteristic. To protect against these types of crashes, forgiving infrastructure should be replaced with restrictive infrastructure. Instead of providing clear zones to protect against high-speed lane departures, the roadway should preclude undesirable behavior by design. For example, curbs and rows of parked cars keep vehicles out of pedestrian areas. Likewise, traffic calming devices and thoughtfully timed signals can restrict traffic speeds. Separated cycle tracks can be used to prevent double parking in bike lanes, which forces cyclists to merge into mixed traffic. Protected left turns prevent drivers from turning into an oncoming car.

3.5 State Awareness

The final principle of sustainably safe traffic is *State Awareness*, that is, the driver's ability to assess their own driving capabilities and the particular driving conditions they are facing at any given moment. Intoxication, fatigue, and distraction are obvious impairments to state awareness.

The goal of this principle is to help drivers recognize and avoid conditions that are potentially dangerous. Strategies to improve state awareness include education, enforcement, and the use of technology to remind drivers to avoid potentially hazardous actions. Since this document mainly focuses on infrastructure improvements, state awareness will be left for others to elaborate on.

3.6 Summary of the Five Principles

Chapter 2 discussed some fundamental elements of human nature and they contribute to crashes, injuries, and fatalities. The preceding sections of Chapter 3 formalized the connection between those fundamental ideas and roadway design with the articulation of the five Principles:

- Speed is the major contributing factor in both the risk and severity of crashes. All four of the safety principles discussed here are at least partially focused on limiting speeds.
- People are fragile, so we should avoid high-energy crashes by keeping high-speed traffic separated.

- People have a limited ability to make decisions quickly, so the environment should be predictable, reducing decisions to simple reflex.
- When a road's design is based on its functions, the principles of homogeneity and predictability fall into place almost automatically. Incompatible functions should be avoided because we cannot safely design for them.
- Even with good enforcement, some people will make mistakes or violate rules intentionally, so infrastructure should prevent drivers from making dangerous decisions.

The cores of these principles are found in the Netherland's Sustainable Safety, but two have been expanded here. The idea of *simplicity* was discussed to make the connection between the types of conscious thinking and predictability more explicit. *Restrictiveness* was added as the urban counterpart to forgivingness, which is mainly applicable to rural roads and freeways.

Thus far, the discussion leading to the five principles has been somewhat theoretical. The next section will address their validity in a real-world context.

3.7 Safety Principles' Relationship to Existing Research

As described in Chapter 1, crash modification factors are one of the primary tools used in the US for improving safety. CMFs are based on countless hours of research and are the distillation of some of our best knowledge on traffic safety. As long as the CMF is applied to situations that are similar to the original experiment, we can expect reasonably consistent results. However, they can be difficult or impossible to generalize to new situations, leaving gaps in our knowledge where experiments have not yet been performed. Engineering research has focused on filling in the gaps in the list of CMFs; however, there are not, nor will there ever be, CMFs that cover every single design feature in every single context that design engineers might encounter.

Unlike in other scientific fields, American safety research has not included an effort to derive a general theory that explains all CMFs and can be used to predict future CMFs. Engineers today are like physicists would be without a theory of gravity: knowing that apples fall to earth but unable to predict whether baseballs also fall to earth without doing a new experiment. Engineers know that prohibiting left turns at signalized intersections reduces crashes by 77%, but don't know the effect of prohibiting left turns at driveways.

This thesis posits that the five safety principles take the role of the missing scientific theory in this analogy. Treating the five safety principles, along with our fundamental understanding of human vulnerability and fallibility, as a "General Theory of Traffic Safety" allows us to assess, at least qualitatively, designs for which no CMFs exist and extend existing CMFs to untested situations.

A good scientific theory should accurately describe previously observed phenomena, and, indeed, the principles of homogeneity, predictability, functionality, restrictiveness, and state awareness are consistent with established CMFs (Table 2). Unless CMF's are eventually found that either cannot be explained by the design principles (which might require an expansion or reassessment of the principles) designing according to the five principles can be expected to produce safer roads, whether or not there is an established CMF for every design feature.

Table 2: Comparison of CMFs from NCHRP 617 with Safety Principles

Treatment	**CMF***	**Principle**	**Consistent with Safety Principles?**
Install Roundabout	0.13-0.82	Controls speeds – drivers must slow down to negotiate the curved path Increases homogeneity – vehicles are separated by direction, all vehicle interactions are at merges Increases forgivingness/restrictiveness – vehicles are forced to slow down due to the physical alignment. Movements are restricted by channelizing islands.	Yes
Add Exclusive Left-Turn Lane	0.38-0.91	Increases homogeneity – turning vehicles are removed from the through traffic stream Increases predictability – driver intent is clear from their lane choice	Yes
Add Exclusive Right-Turn Lane	0.59-0.96	Increases homogeneity – turning vehicles are removed from the through traffic stream	Yes
Remove (Unwarranted) Traffic Signal on One-Way Street (Urban)	0.47-0.82	Controls speeds – signals allow for higher speeds than the stop signs that replaced them	Yes
Modify Signal Change Interval	0.63-1.00	Improves predictability – Change intervals were standardized and made consistent with travel speeds	Yes

Treatment	**CMF***	**Principle**	**Consistent with Safety Principles?**
Replace permitted left turn with protected left turn	0.01 (left-turn crashes)	Increases homogeneity – reduces or eliminates interactions between through traffic and turning traffic. Greatest benefits seen when permitted left turns are totally eliminated Increases predictability – simplifies decision for when to turn, drivers do not need to judge gaps.	Yes
Replace 8-in. Signal Heads with 12-in. Signal Heads	0.58-0.97	Increases recognizability – larger signal heads are more visible	Yes
Convert Nighttime Flash Operation to Steady Operation	0.65-0.66	Increases homogeneity – conflicting movements are separated in time Increases predictability – signal operation is consistent throughout the day	Yes
Convert to All-Way Stop Control (from two-way stop control)	0.28-0.87	Controls speeds – all approaches must stop, eliminating high-speed through movements Increases homogeneity – eliminates conflicts between high-speed through traffic and low-speed turning traffic Increases predictability – stopped drivers don't have to judge gaps in main street's traffic	Yes
Add Intersection Lighting	0.71-0.96	Increases recognizability – other vehicles and pedestrians are easier to see	Yes

Treatment	**CMF***	**Principle**	**Consistent with Safety Principles?**
Add Passing Lanes (on two-lane rural roads)	0.65-0.75	Increases homogeneity – passing vehicles do not have to cross into oncoming traffic lane	Yes
Add Two-Way Left-Turn Lane (TWLTL)	F(x)<1	Increases homogeneity – reduces interactions between high-speed through traffic and low-speed turning traffic Increases predictability – driver intent is clear from their lane choice	Yes
Increase Lane Width (on rural roads)	F(x)<1	Increases forgivingness – wider lanes on rural roads reduce head-on, run-off-road, and sideswipe accidents. CMF does not apply to low-speed urban roads.	Yes
Increase Shoulder Width and/or Type (on rural roads)	F(x)<1	Increases forgivingness – wider shoulders on rural roads reduce run-off-road accidents. CMF does not apply to urban roads.	Yes
Add Shoulder Rumble Strips (on freeways)	0.79-0.93	Increases forgivingness – drivers are alerted when the start to leave their lane, giving them time to correct course. CMF applies to freeways only.	Yes
Add Centerline Rumble Strips (on rural roads)	0.75-0.86	Increases recognizability – drivers are alerted when the start to leave their lane. CMF applies to rural two-lane roads only.	Yes
Install/Upgrade Guardrail	0.53-0.56	Increases forgivingness – prevents vehicles leaving the road from striking fixed objects.	Yes

Treatment	**CMF***	**Principle**	**Consistent with Safety Principles?**
Convert Undivided Four-Lane Road to Three-Lane and TWLTL (Road Diet)	0.53-0.81	Controls speed – would-be speeders are prevented from passing more prudent drivers Increases homogeneity – slow, turning vehicles are removed from through traffic. Opposite directions of travel are separated by TWLTL. Increases predictability – driver intent is clear from their lane choice	Yes
Increase Pavement Friction on Roadway Segment	0.43-0.83	Increases predictability – cars behave more predictably when braking if they don't skid.	Yes
Increase Median Width	0.22-1.00	Increases homogeneity – wider medians improve the separation between opposite directions of traffic Increases forgivingness – wider medians decrease the likelihood of an errant vehicle crossing into the opposing lane	Yes
Make Roadside Sideslope Flatter	0.73-0.95	Increases forgivingness – flatter sideslopes allow for drivers to recover if they leave the roadway	Yes
Add/Remove On-Street Parking	F(x)	Reduces homogeneity – in areas with parking, drivers entering or exiting their vehicles are adjacent to moving traffic. Parking vehicles must slow and/or back up in the middle of through traffic Reduces predictability – vehicles and pedestrians move in and out of through traffic in areas with parking.	Yes

Treatment	CMF*	Principle	Consistent with Safety Principles?
Add Roadway Segment Lighting	0.71-0.94	Increases predictability – lighting improves visibility and sight distances at night	Yes
Install Raised Medians at Crosswalks	0.54-0.61	Increases predictability – simplifies crossing because pedestrians only have to judge gaps in one direction at a time	Yes

*Reported crash modification factors are broken down by type, severity, road conditions, etc. in their original form. The minimum and maximum reported values are included here to illustrate the qualitative changes in crash rates.

3.8 Design Principles and a New Street Network Plan

Following the principles, of Homogeneity, Predictability, Functionality, and Restrictiveness, Boston's street network plan should be reviewed and updated using a limited number of roadway types. In doing so, the selected roadway type should be based on the *desired* behavior for each street, not the existing behavior. Too often, engineers base design decision on the *observed* traffic speeds and volumes instead of *safe* speeds, perpetuating extant problems.

The classification scheme should support the compatibility of functions within each of each road type, display consistent characteristics within each road type, and be recognizable by road users. While the principle of recognizability suggests that the number of functional classifications be limited, we should learn from the Dutch experience and include enough functional classifications to allow for some flexibility. With this in mind the following functional classifications are recommended:

- **Regional Road**. The function of a regional road is to efficiently move drivers into and out of the region. These are typically limited-access, high speed roads where traffic capacity is of primary importance. Regional Roads in the City would include I-93, I-90, Route 1, Route 1A, Storrow/Solders Field Drive, and Morrissey Boulevard. For the most part, regional roads are outside of the City's jurisdiction and so will be left out of the discussions that follow.
- **Urban Principal**. The function of an urban principal is to carry through traffic from one Neighborhood to another (In this context, "Neighborhood" refers to the relatively large Neighborhoods of Boston, e.g., Back Bay, South Boston, Roxbury). Drivers are typically traveling for relatively long distances on these streets and expect smoothly flowing traffic with few interruptions. Cross traffic and pedestrians should be encountered only at signalized intersections. The typical driver on an inter-neighborhood connector would be traveling from one area of the city to another. Examples would include Columbus Avenue and Melnea Cass Boulevard (connecting Jamaica Plain, Roxbury, Mission Hill, and

the South End); Blue Hill Avenue (connecting Mattapan, Dorchester, and Roxbury); the Arborway/Jamaicaway/Riverway/ Fenway (connecting Jamaica Plain, Mission Hill, and Fenway); and Commonweath Avenue (connecting Brighton, Allston, Fenway, and Back Bay).

- **Neighborhood Principal.** Many of Boston's neighborhoods and commercial districts developed along historical streetcar lines which have become the neighborhoods main street. These commercial areas that generate pedestrian activity and require site access remain, but the streetcar lines have given way to traffic volumes. Streets which must support relatively high traffic volumes in order to maintain network connectivity, but also must be compatible with site access functions, should be designated as neighborhood principals. These would typically be relatively long streets that span a neighborhood; however, their lower speed makes them appropriate for areas with frequent cross streets, high-turnover parking, and intense pedestrian or bicycle activity. Examples include Harvard Street in Allston, Centre Street in Jamaica Plain, and East Broadway in South Boston. The typical driver on an intra-neighborhood connector would be traveling from one part of a neighborhood to another or heading to a higher-level street to leave the neighborhood.
- **Local Road**. Local roads form the interface between the street network and the surrounding properties. Typically short streets, their primary function is to provide access to on-street parking spaces and driveways. Pedestrians crossing between parked cars and adjacent land uses should be expected anywhere along an access road. Traffic flow is a low priority. Examples include Newbury Street, Hanover Street, and most residential streets. Typically, drivers should only be on local streets within a few blocks of their origin or destination. Long distance travel on local roads should be discouraged.
- **Shared Street**. Like local roads, shared streets connect the street network with land uses, but do not segregate pedestrians, bicycles, and automobiles. A shared street functions like a driveway for the entire block. Vehicles are permitted, but expected to operate at pedestrian speeds and yield to other users. It should be safe for children to play on a shared street. Dead ends, cul-de-sacs, and "U" shaped

roads make excellent candidates for conversions to shared streets. Downtown Crossing is an example of a shared street in a commercial area (though restricted to delivery and emergency vehicles). Residential shared streets are sometimes called by the Dutch term “Woonerf” (roughly: “living zone”). Appleton Street in the Back Bay has elements of a Woonerf design. Only direct abutters should ever need to use a shared street.

Figure 23: An Example of a Shared Street (National Association of City Transportation Officials, 2013)

Design features in the roadway and roadside provide visual clues to the driver on how they should be driving and what to expect. This driving environment is much more of a factor than road signs or enforcement in determining how drivers behave. A carefully designed roadway will foster good driving behavior organically, while an over-designed roadway will encourage undesirably high speeds.

Consider the design for a school zone in Dorchester (Figure 24). The “SCHOOL” pavement markings and roadside flashing beacon show that the design intent is for this to be a safe, low-speed area because there could be children present; however, the four lane cross section, wide lanes, lack of crosswalks, and spartan sidewalks tell drivers that this is a high-speed corridor where pedestrians are not expected. As a result, traffic on Morton Street is very fast. Drivers’ actual behavior is not consistent with the intended behavior because the design encourages speeding. Several clusters of crashes can be found along the length of Morton Street and speed is likely a factor in many of these crashes.

Figure 24: A School Zone on Morton Street, Boston, Promotes High Speeds

A second example of a school zone comes from Broadway in Cambridge, MA (Figure 25). In this case, Cambridge relies on roadway design features rather than signage and warning beacons to control speeds. Lanes are narrow and the pedestrian refuge island actively calms traffic by creating a chicane and pinch point. Sidewalks are wide and pedestrian amenities such as bike racks, seating areas, and marked crossings are clearly visible, alerting drivers that pedestrians are expected here. Street trees along the curb line visually narrow the street, even as the building setbacks increase on the left.

Figure 25: A School Zone on Broadway, Cambridge, Calms Traffic

The design features on each street type should support the intended functions while discouraging incompatible functions. They should help drivers recognize each street's function and reinforce the desired behavior. Consistently applying these design features throughout the City will improve the recognizability and predictability of the street network. Following the Netherlands' lead, Boston should designate one or more features to be the Essentially Recognizable Characteristic(s), which will simplify how the new Vision Zero policies are communicated to the public and allow for enforcement without having to post speed limit signs on every street. The centerline treatment is recommended as the ERC: inter-neighborhood connectors should have a (raised or flush) median, intra-neighborhood connectors should have a double yellow centerline, and local roads receive no markings, Shared streets would also have no markings, but should be paved with a material other than black asphalt.

Table 3 summarizes the recommended functional classifications and their characteristics.

Table 3: Sample Design Features by Functional Classification

Classification / Design Feature	Shared Street	Local Street	Neighborhood principal	Urban principal
Pavement markings (Essentially Recognizable Characteristic)	No pavement markings, special paving material (e.g., unit pavers, colored asphalt)	No centerline	Double yellow centerline	Median (raised or flush) or TWLTL
Sidewalks	No	Yes	Yes	Yes
Number of Lanes	Un-marked	Un-marked	One lane per direction highly preferred	One lane per direction per direction preferred. Multi-lane if needed.
Pedestrian Crossings	Pedestrians cross anywhere. No marked crossings.	Pedestrians cross anywhere. Markings optional.	Marked crosswalks. Crossing islands desirable.	Crossings either signalized or treated to reduce speed to 25 MPH at the crosswalk.
Minimum Bicycle Accommodations	None. Bikes use full road	None. Bikes use full road	Bike Lanes (cycle tracks preferred in areas with high parking demand)	Cycle tracks
Parking	Yes	Yes	Yes	None preferred. Low-turnover residential parking otherwise.
Maximum Target Speed	10 mph	20 mph	25 mph	30 mph
Appropriate Traffic Calming Devices	Special paving material, horizontal deflection, vertical deflection, traffic diverters	Horizontal deflection, vertical deflection, traffic diverters	Horizontal deflection	Horizontal deflection

CHAPTER 4: PRACTICAL APPLICATIONS

The following actions show specific ways that the five principles of Vision Zero could be applied in Boston. This is not intended to be a comprehensive list, rather, it is meant to offer be a springboard for the future development of Vision Zero Boston.

4.1 Action #1: Establish functional road types and safe speed limits for each type

The City should adopt a hierarchy of functional classifications with speed limits as discussed in Chapter 3.

A useful functional classification scheme forms the skeleton upon which all other planning and infrastructure decisions are based. Boston's existing classification scheme, with its nine different street types, is on the right track in many ways. However, an emphasis on the principles of homogeneity, predictability, and restrictiveness is lacking. For example, there is no requirement that street types be recognizable to the user, and the connection between street type, design, and speed limit is too tenuous to be useful.

Speed limits should be tied directly to the functional classification (Table 4).

Table 4: Suggested Speed Limits by Functional Classification

Functional Classification	Speed Limit (MPH)
Regional Road	40+
Urban Principal	30
Neighborhood Principal	25
Local Street	20
Shared Street	10

This table is based on the anticipated behavior of each street according to its function and the corresponding safe speed as discussed in Chapter 2. To allow more flexibility, special overlay zones such as School zones and "business zones" (localized areas of intense commercial activity), could be used to provide fine-grained control of speed limits where the conflict types listed in Table 1 warrant. For example, Centre Street in Jamaica Plain should be classified as a neighborhood principal with a 25 mph speed limit; however, the short stretch between Green Street and South Street is the main commercial center for Jamaica Plain and pedestrians frequently cross back and forth across the street, even at unmarked locations. These few blocks could be designated as a business zone and the speed limit reduced to 20 mph, consistent with Table 1.

4.2 Action #2: Develop a canonical design for each functional classification

A standardized design that governs at least some of the important roadway features should be developed for each functional classification. At a minimum, the basic features listed in Table 3 should be specified. These standards should prioritize consistency within each particular class, and the distinction between roads of different classes to create recognizable road categories.

4.3 Action #3: Apply the new functional classification scheme and design palette to the street network

Actions #1 and #2 are planning exercises. To actually improve safety, the plans need to be realized in the real world. Reconstructing a majority of the streets in Boston will not happen overnight, but every roadway reconstruction or maintenance project should be used as an opportunity to implement the ideas of Vision Zero. Achieving zero traffic deaths will be a decades-long undertaking, but the Netherlands has shown that a sustained effort will yield ever-better results.

4.4 Action #4: Use traffic calming and other design features to ensure compliance with new speed limits

Once reasonable speed limits are established, design features should be used to bring actual speeds into conformance with the desired speed limits. Changing the posted speed limit does not affect driving behavior; changing the roadway environment does (National Cooperative Highway Research Program, 2003). To achieve the speed limits suggested above, infrastructure changes that create a "self-organizing" road and result in "spontaneous compliance" are required.

The 85th percentile speed is often used as a reference point for design decisions such as setting design speeds and determining whether traffic calming is appropriate. For some decisions in a systematically safe transportation system, the 85th percentile is too low: if 15% of drivers are speeding, it is difficult to claim that the road is "safe", especially in heavy pedestrian areas such residential streets (where children could be playing) and school zones. In areas such as these, it would be more appropriate to use, say, the 95% percentile as the measure of speed along the street.

Once the actual observed speeds are appropriate for the road (i.e., once the roadway design supports the desired normative behavior), stricter enforcement to catch outliers becomes legitimate.

4.5 Action #5: Use road diets to reduce the number of multi-lane roads

A road diet can refer to any reduction in the number of travel lane, but most commonly involves converting a four-lane roadway into a three-lane roadway: one lane in each direction with a two-way left turn lane in the middle. The leftover width can then be used for other purposes, such as bike lanes or cycle tracks.

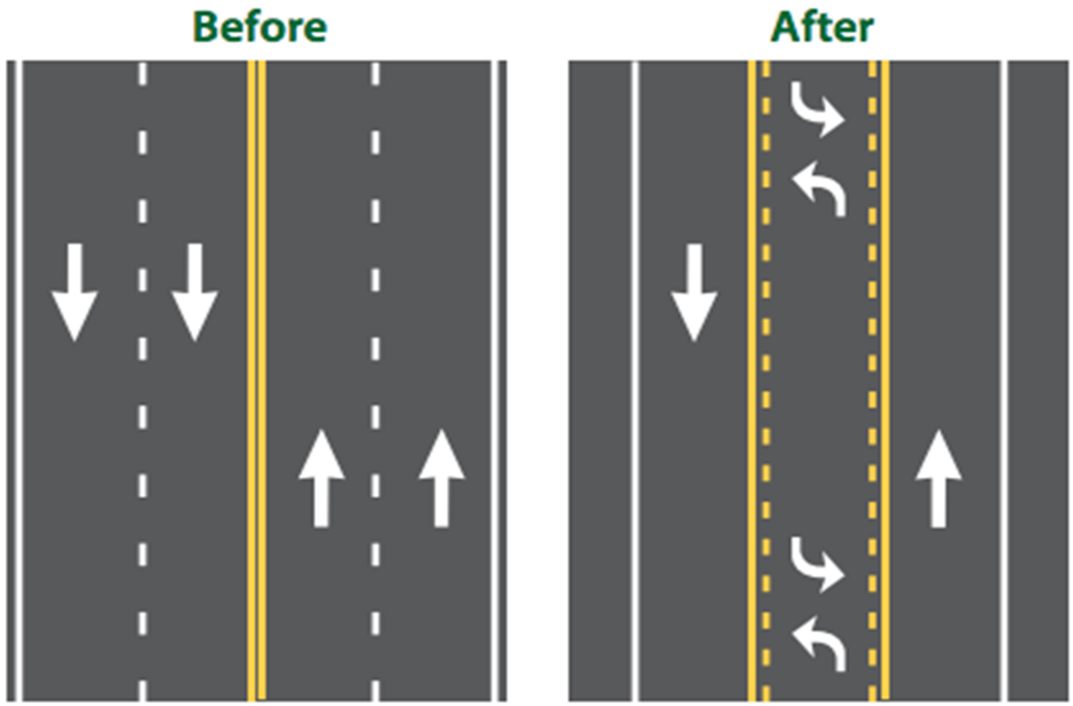


Figure 26: A Canonical Road Diet: A Four-Lane Road Reduced to a Three-Lane Road with Center Two-Way Left-Turn Lane

At first glance, eliminating half of the through lanes seems like it should devastate the traffic capacity on the street and create huge congestion problems. In practice, however, engineers have found that road diets often have minimal effect on capacity. There are two reasons for this:

1. On a four-lane road, left-turning vehicles often block one lane, leaving only one lane available for through traffic. On the post-conversion three-lane road, left-turning vehicles are separated from through traffic, so the number of usable through lanes remains unchanged.
2. Traffic capacity on a street is limited by intersections, not by the segments between the intersections. Therefore, as long as there are enough lanes at intersections to handle the demand, the segments between intersections can often be narrowed without increasing congestion.

Before-and-after studies have found that road diets typically result in crash rate reductions between 19% and 47% (FHWA Safety Program, 2014) (Transportation

Research Board, 2008). A three-lane road follows the principles of Vision Zero much more closely than the four-lane roads they replace:

- They improve homogeneity by providing separate lanes for slowing or stopped vehicles waiting to turn, through traffic, and bicycle traffic.
- They are more predictable for drivers. Through traffic does not need to watch for cars slowing ahead of them or turning left across their path. Left-turning vehicles only need to judge gaps in one lane of traffic. There are none of the merges and lane changes that are possible on a multi-lane road.
- Traffic speeds are slower. All drivers are forced to drive at the speed of the most prudent drivers. On multi-lane roads, it is very difficult to control speeds because drivers can weave in and out of traffic to pass slower drivers.
- Pedestrian crossings are greatly simplified since pedestrians only have to cross two lanes of through traffic instead of four. Pedestrian islands can be installed in the center lane to further simplify crossings.

Four-lane roads that could be good candidates for road diets include Morton Street, East Broadway in South Boston, sections of Tremont Street, Columbus Avenue, Brookline Avenue, and Boylston Street in the Fenway.

4.6 Action #6: Use gateway and transition treatments to mark the boundaries where driving behavior should change.

Gateway treatments and transition treatments should be installed at boundaries between different functional classifications and along a corridor where speed limits change. Gateway treatments are already recommended Boston's own Complete Streets guide, but they are not yet widespread.

A "gateway treatment" is a combination of design features used to mark the boundary between different functional classifications. They are typically used at the intersection of a major street with a minor street. Similar to a gateway, transition treatments are used to mark changes in driving behavior along a street, when entering a school zone or commercial district, for example.

Typical features at a gateway might include:

- Raised crosswalks across the minor street to slow turning traffic and prioritize pedestrians
- Curb extensions with tight curb radii. These also slow turning traffic, increase pedestrian visibility, and create a physical pinch point to mark the boundary.
- Architectural or landscaping features to visually frame the gateway

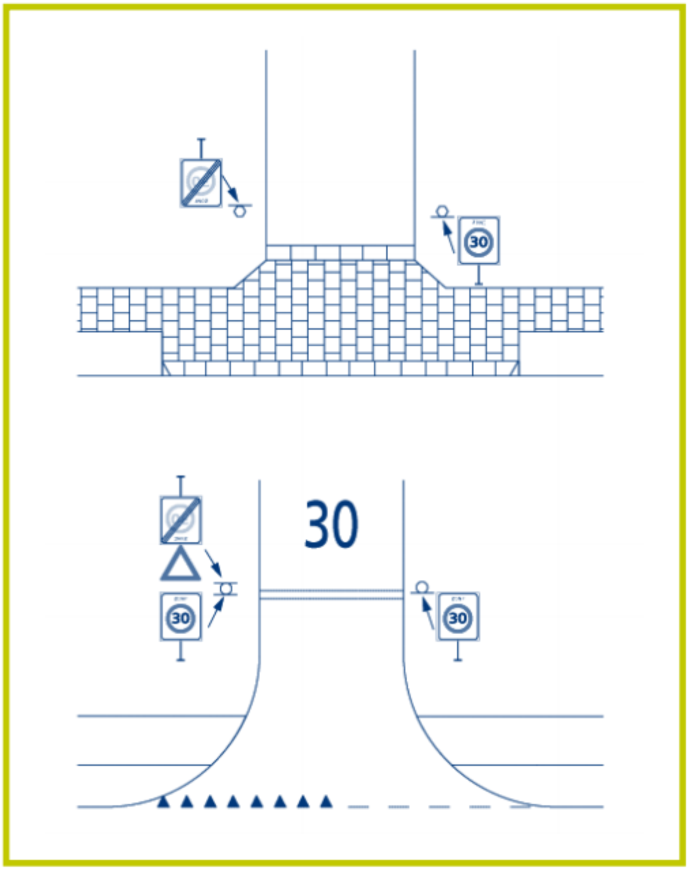


Figure 27: Schematics of Urban (Top) and Rural (Bottom) Gateway Construction

Such treatments are standard at intersection of roads with different classifications in the Netherlands (Figure 28). The sidewalk is carried across the minor street; the entrance is framed with bollards, trees, and a planter; and there is signage posted alerting drivers to the new speed limit and traffic pattern.

Figure 28: A Typical Gateway Treatment in the Netherlands

The brick columns framing the entrance to Dimock Street in Boston function as a gateway, marking the shift in context at the boundary between the multi-lane, high-speed Columbus Avenue and the campus-like Dimock Street.

Figure 29: Gateway Treatment at Dimock Street, Boston

4.7 Action #7: Establish a safe crossing policy

Boston has a reputation as a "walking city", yet 40% of the fatalities in 2015 were pedestrians (City of Boston, 2016). To protect pedestrians, Boston should systematically improve pedestrian crossings.

A safe crossing policy should be based on two basic targets:

1. Pedestrians should never have to cross more than two lanes of traffic at a time, with no more than one lane of traffic preferred and
2. Pedestrians should never have to cross against traffic traveling faster than 25 mph

Pedestrian crossing islands are particularly effective at meeting these two targets by reducing the number of lanes that a pedestrian must cross at one time and by slowing traffic to the target speed by creating a chicane effect at the crossing point. Crossing islands become particularly critical as speeds and crossing distances increase. A study of 2,000 sites found that crossing islands can cut pedestrian crashes in half (Transportation Research Board, 2008)

Another strategy to meet these targets is to apply road diets, as recommended in Action #5. Road diets reduce the number of lanes that pedestrians must cross and naturally slow traffic as described above.

On 30 mph streets, pedestrian crossings should either be locally treated with traffic calming measures to reduce speeds to 25 mph to improve yielding rates or signalized. Where signalization is the preferred approach, "High-intensity Activated crossWalK beacons" (or HAWKs) could be used at mid-block locations, or where a full signal isn't warranted.

4.8 Action #8: Establish a safe left-turn policy

The City should develop a left turn policy that avoid the use of permitted left turn phases on multi-lane roads and/or reduce the number of lanes that left-turning vehicles need to cross. Opposing left turn lanes should face each other ("no offset") or be offset to the left of each other ("positive offset") (Figure 30). Opposing left turn lanes with "negative offset" should be avoided.

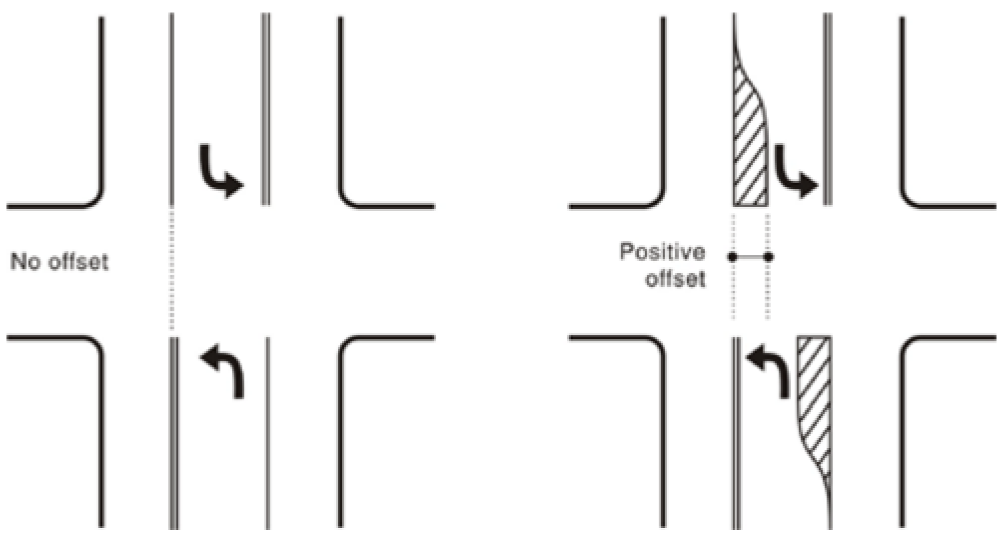


Figure 30: Left Turn Lanes with No Offset and Positive Offset (Federal Highway Administration, 2004)

Turning left across oncoming traffic is one of the most difficult maneuvers that drivers are regularly faced with. In a very short time, the driver has to correctly judge the speeds and gaps of oncoming vehicles, determine whether there are pedestrians in the crosswalk, bikes in the bike lane, and estimate their own acceleration. Vehicles in the oncoming left turn lane, oncoming headlights, and even the "A" pillar in their own car may block sight lines or otherwise make it difficult to see. Perceived "back pressure" from drivers behind often pushes drivers to accept dangerously small gaps. Multi-lane roads compound these challenges: drivers have to gauge multiple, dynamically shifting gaps and vehicles in one lane may block the visibility of vehicles in another.

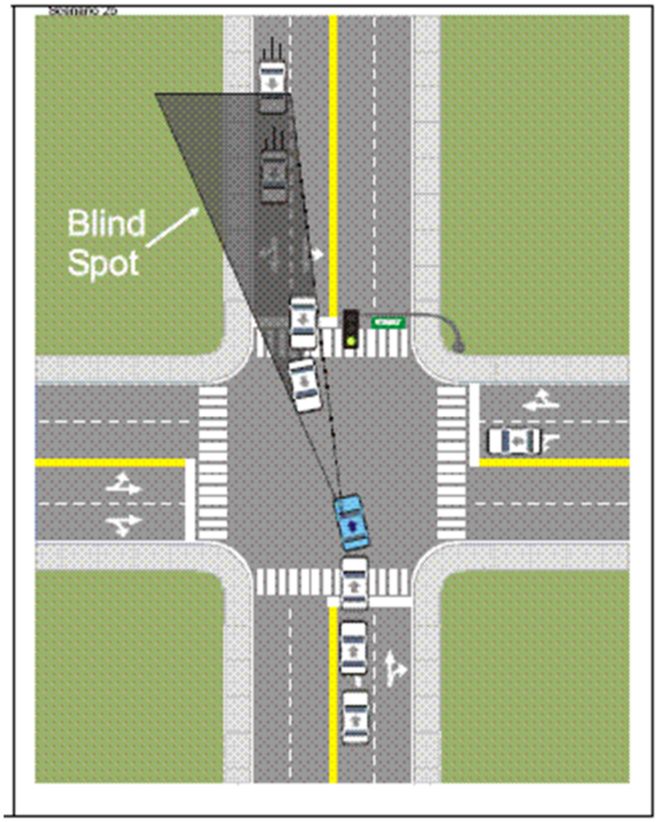


Figure 31: Blind Spot for Left Turns Across Multiple Lanes (Federal Highway Administration, 2005)

31% of severe accidents involve left-turning vehicles (Hyatt, 2016). Meanwhile, countermeasures such as providing a dedicated left turn phase or reducing the number of lanes that turning vehicles must cross can reduce left-turn injuries by over 50% (FHWA Safety Program, 2014), (New York City Department of Transportation, 2012).

Columbus Avenue in Roxbury is an illustrative example: drivers, thinking they have a gap, often begin turning across the three oncoming lanes of traffic, only to come to an emergency stop when they notice pedestrians or cyclists in the crosswalk on the Southwest Corridor bike path. They are then faced with either hitting the pedestrian or possibly being hit themselves by oncoming traffic. This situation could be avoided by providing protected-only left turning phases.

4.9 Action #9: Establish bicycle separation targets and install protected bike lanes.

The City has been aggressively pursuing its long-term bicycle network plan since 2013 (Boston Department of Transportation/Boston Bikes, 2013) and has made huge strides in improving bicycle infrastructure. The Boston Bike Network Plan outlines a 30-year vision for bicycle infrastructure in the City, lays out the proposed network, and assembles a "toolkit" of various types of bicycle facility. The general philosophy of the Network Plan is (correctly) that more separation between bicycles and motor vehicles is better, but what's missing are firm criteria for what level of separation is needed on each street. Vision Zero Boston should establish guidelines for the minimum level of bicycle separation based on traffic conditions.

As the street network plan is updated (Actions 1 and 2), the City should revisit and revise the Bike Network Plan as needed to ensure that it is consistent with the principles of Vision Zero.

4.10 Action #10: Eliminate incompatible functions on streets

The City should work to transition away from streets that serve multiple, incompatible functions. On streets with a strong through-traffic function, the City should minimize the number of driveway curb cuts. On streets with a strong site-access function, the City should develop parallel routes to divert through traffic. Ideally, driveways would be restricted primarily to Local Streets. Achieving this in reality will be difficult and take many years, given our preexisting street network. In the short- to medium-term, however, it may be possible to eliminate or consolidate some curb cuts where multiple driveways serve a single business, for example. Areas undergoing redevelopment, such as the Seaport district or along Melnea Cass Boulevard also create opportunities for the City to carefully consider the locations of proposed driveways. Right-in/right-out restrictions may be appropriate on regional roads and high-speed connectors, especially on multi-lane roads.

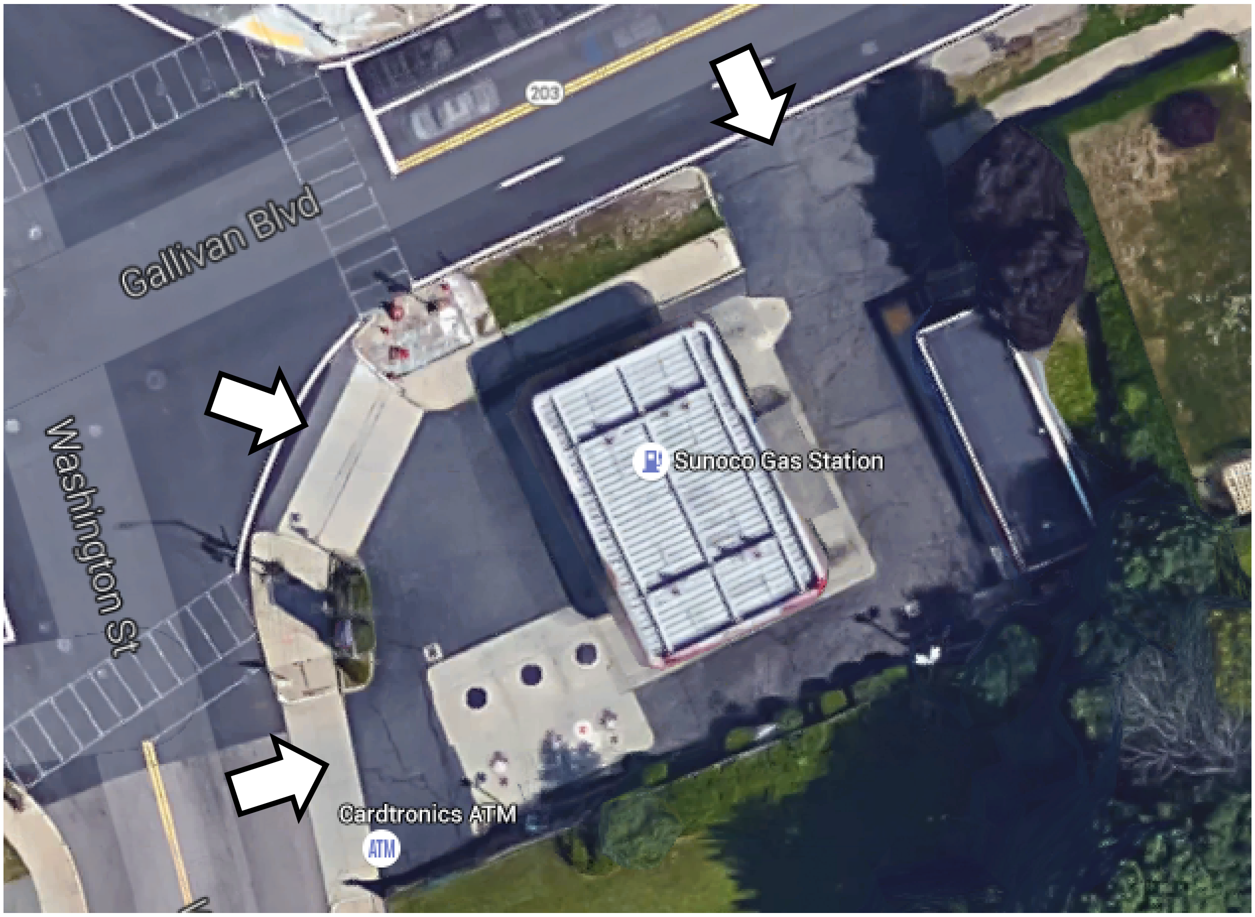


Figure 32: Three Curb Cuts Serving One Gas Station. One Opens Directly into a Signalized Intersection, but is Unsignalized.

Why: The frequency of access points is a major determining factor in crash rates along urban arterials. Studies have found that over 60% of crashes in urban areas occur at access points (Demosthenes, 2003).

In order to turn into or out of a driveway, drivers have to slow to well-below the normal operating speed along the road. Left-turning vehicles also have to cross opposing traffic lanes and may have to judge gaps in multiple traffic streams simultaneously. These large differences in speed and direction, and the cognitive load required to judge gaps, increase the likelihood and severity of crashes. This is less of a problem on Local Roads where traffic is already slow, and turning cars are expected.

CHAPTER 5: GALLIVAN BOULEVARD CASE STUDY

Existing Conditions

Gallivan Boulevard is an important east-west corridor in Dorchester. Classified as a principal arterial, Gallivan Boulevard connects the neighborhoods of Dorchester and Mattapan to Interstate 93 via Granite Avenue. From east to west, the boulevard has key intersections at Neponset Avenue, Morrissey Boulevard, Dorchester Avenue, and Morton Street. Most minor intersections are unsignalized. According to MassDOT data traffic volumes range from 14,000 to 20,000, with the higher volumes observed closer to the eastern end.

The land use around the western end of Gallivan is primarily low-density residential. Here the street is lined with single- or two-family homes, each of which has a driveway curb cut. East of Granite Avenue, higher intensity uses begin to appear: storefronts, restaurants, a car dealership, drug stores.

The cross section is consistent along the corridor with two ten-foot lanes in each direction, planting strips and sidewalks on both sides (Figure 33, Figure 34). No on-street parking or bicycle accommodations are provided.

Figure 33: Gallivan Boulevard, Boston, MA

Conformance with Safety Principles

The first step in identifying safety improvements is to consider how well the existing design aligns with the five key principles of Vision Zero:

Functionality: Gallivan's classification as a principal arterial is appropriate. Under the functional classification scheme proposed in Chapter 3, Gallivan would be classified as an urban principal. Its main function is and should be to carry through-traffic between Mattapan, Dorchester, and Quincy; however, the street also serves a conflicting "site access" function due to the frequent residential driveway curb cuts and areas of commercial development. Eliminating the site access function would, admittedly, be a challenge; residents and businesses would not willingly give up their driveways. It may be possible to consolidate some driveways, but a more realistic approach would be to minimize the conflicts between high-speed through traffic and the slower turning vehicles through separation.

Homogeneity: As currently designed, traffic on Gallivan is highly heterogeneous. High-speed through traffic shares space with low-speed local traffic due to the frequent curb cuts. Cyclists share space with cars and heavy vehicles since there are no bike accommodations. East-west traffic shares space with north-south traffic at the many unsignalized intersections. The new design should improve the separation of the different types of traffic.

Predictability through simplicity and recognizability: The multiple functions Gallivan serves and certain design features send conflicting messages to drivers: the four lane cross section, sections of steel highway guard rail, cobra-head lighting, and the right-of-way for through traffic suggests a relatively free-flowing traffic pattern. This is foiled, however, by frequent intersections with minor streets and driveway curb cuts. There are no turn lanes so the through lanes may become blocked by turning drivers, prompting sudden lane changes. Drivers might not expect a vehicle backing out of a driveway or a pedestrian crossing at one of the unsignalized side streets. Judging gaps in four lanes of traffic is very complicated, making it difficult to cross the street.

Restrictiveness: With two lanes in each direction and widely spaced signals, drivers are free to drive at their preferred speeds, even if that speed is unsafe.

Proposed Design

A design that could bring Gallivan Boulevard into closer alignment with the key principles is a road diet, described in Section 4.5 of the previous Chapter (Figure 35).

A road diet would substantially improve traffic separation by mass, speed, and direction: the two-way turn lane separates left-turning vehicles from the main traffic stream; the addition of bike lanes separates cyclists and motor vehicles; the reduction to one through lane in each direction eliminates merging conflicts and speed differentials between adjacent lanes; and turning vehicles only need to find a gap in one lane of traffic.

Traffic behavior would also become much more predictable, post-road diet. With only one through lane in each direction, traffic speeds will become much more consistent: everybody will have to travel at the speed of the most prudent drivers. There would be none of the merging and weaving that is possible on multi-lane streets. Other drivers' intended actions will also become more transparent. If they are in the center lane, they want to turn left. Drivers wouldn't have to worry as much about oncoming traffic suddenly turning in front of them or the vehicle ahead of them suddenly slowing down. The extra space created in the center of the road would allow for pedestrian refuge islands and other high-visibility pedestrian crossing features, focusing attention at areas with pedestrian activity.

The increased separation between opposing directions and the removal of cyclists from vehicular traffic would make a more forgiving environment, and the reduction in lanes would restrict willful violations. Drivers inclined to speeding would be unable to pass by weaving in and out of traffic.

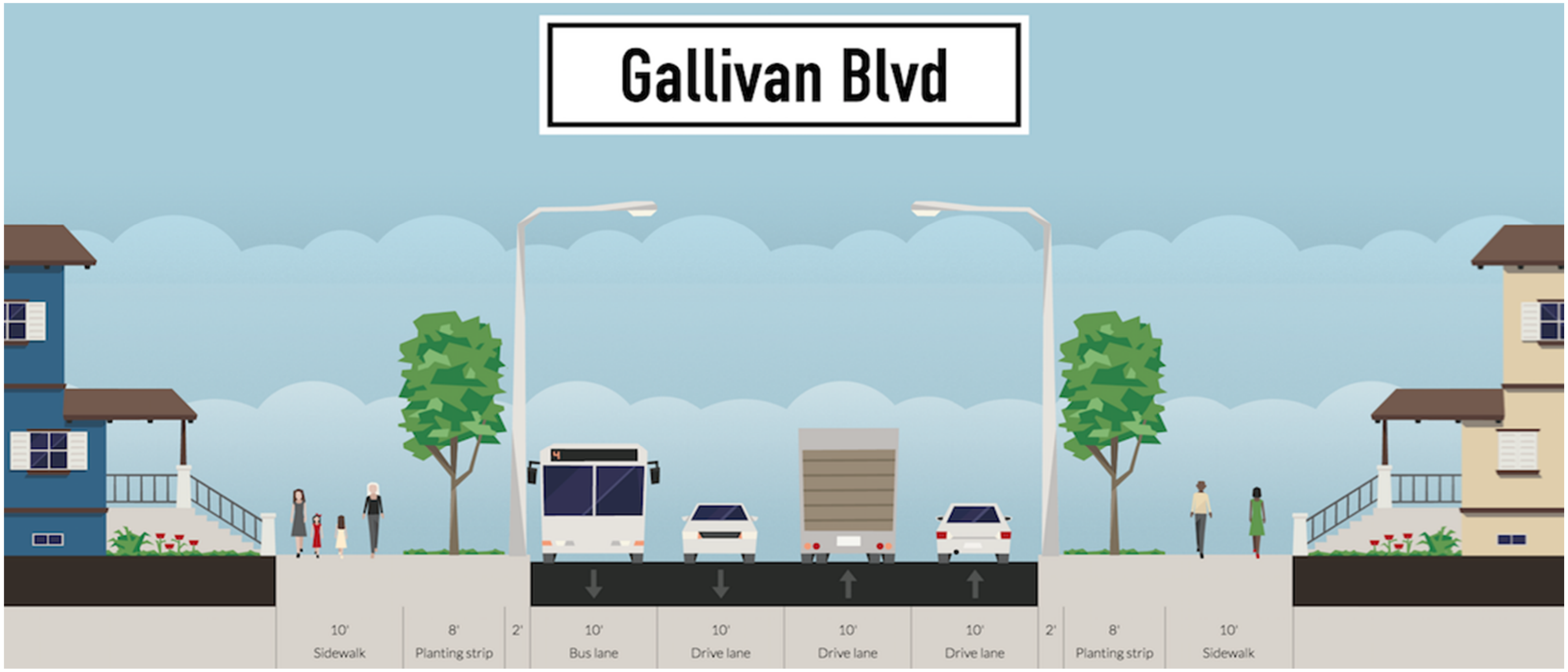


Figure 34: Existing Cross Section

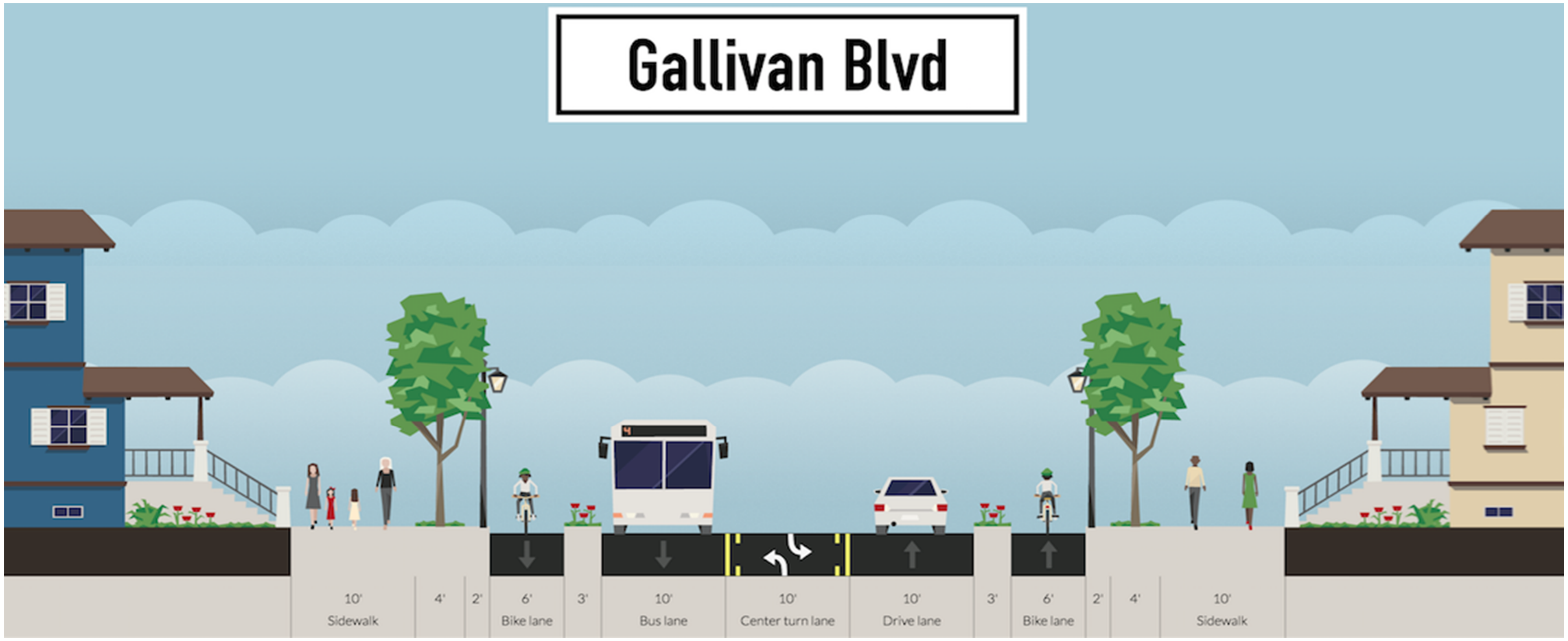


Figure 35: Proposed Cross Section

In addition to the reduction in lanes, the intersections of Gallivan at Morton (Figure 36) and Gallivan at Washington appear to have enough right-of-way to install roundabouts. The Morton Street intersection is currently unsignalized but features confusing and highly skewed geometry. Northbound traffic on Morton Street, faces a particularly difficult movement, crossing multiple lanes with poor sight lines. A roundabout at this location (Figure 37) would organize the flow of traffic (predictability), control speeds through the intersection (restrictiveness), create opportunities for safe pedestrian crossings (homogeneity), and replace the potential for head-on collisions with safer merging collisions (forgivingness).

Figure 36: A Candidate for Conversion to a Roundabout: Gallivan Boulevard at Morton Street, Boston

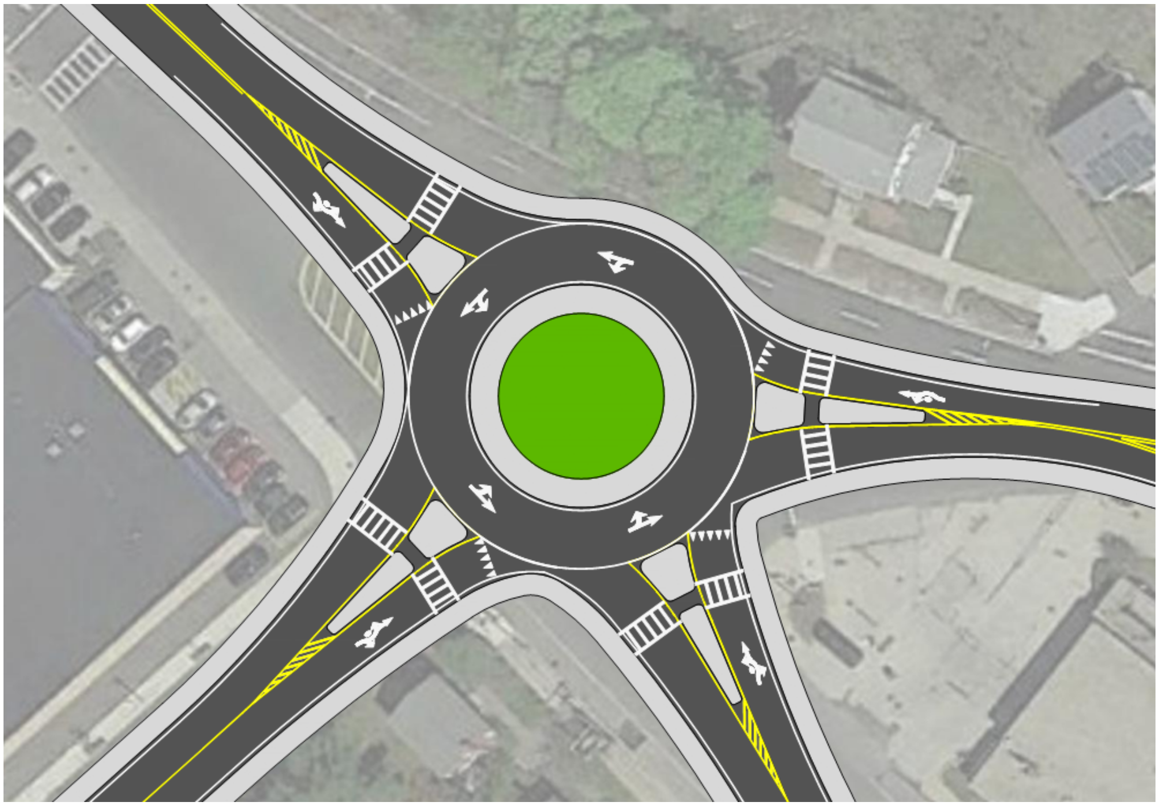


Figure 37: Potential Roundabout Configuration at Gallivan Blvd and Morton St

Feasibility

FHWA guidance on the design and application of road diets is summarized in "Road Diet: An Informational Guide" (FHWA Safety Program, 2014). FHWA suggests that 20,000 ADT be used as an upper limit for determining whether a road diet is feasible, though some jurisdictions have successfully implemented four-lane to three-lane road diets on streets with up to 25,000 ADT. Gallivan Boulevard's average daily traffic in the 14,000-20,000 range on the west end makes it a prime candidate for consideration.

The full implementation of this concept shown in Figure 35 would require moving the existing curb lines to accommodate the cycle tracks. This would involve a fairly expensive roadway reconstruction project; however, a similar design that replaced the cycle tracks with bike lanes could be accommodated within the existing curb-to-curb width with little more than pavement markings and signage. While missing out on some of the benefits of cycle tracks, this low-cost variation could be used as a low-risk trial, or as an interim solution.

Naturally, a full traffic analysis would need to be done before deciding whether it makes sense to convert Gallivan Boulevard to three lanes, but the concept illustrates how the abstract principles of Vision Zero can be applied to develop a concrete design. The concept of a road diet can then be applied to any similar roads in the City in a systematic way.

CHAPTER 6: NEXT STEPS AND CONCLUSION

Like the Netherlands 1992 Start-Up Programme, the focus of this thesis has mainly been on infrastructure improvements:

- Infrastructure problems are often easy to identify and improvements are relatively straightforward. This is low-hanging fruit.
- Roads are regularly rebuilt and repaired anyway. No new programs or initiatives are needed.
- Infrastructure improvements result in obvious changes and directly measurable results. The success a particular strategy can be easily evaluated.
- Infrastructure is well understood by public, making it easy to engage and gather public support

Infrastructure will be a major piece of the full solution to achieving Vision Zero, but it is not the only piece. As Vision Zero Boston evolves, it will need to incorporate strategies that improve state awareness, the fifth principle which was mostly neglected here. Increased attention to public outreach, education, enforcement, technology will be needed in the future.

Measures that reduce the exposure to traffic, such as transportation demand management (TDM) strategies, could also prove fruitful. Unsurprisingly, there is a direct correlation between the number of traffic fatalities and the amount that we collectively drive. Meanwhile, subways and buses are extremely safe when compared to cars. Every traveler that opts not to drive is one fewer potential casualty. Strategies that could encourage the use of modes other than single-occupancy vehicles include:

- following high-density, transit-oriented, mixed-use, and walkable development patterns
- using pricing incentives and disincentives
- working with the MBTA to improve bus service by providing bus lanes and bus priority at signals
- using demand-based parking rates

Many of these strategies are consistent with existing policy. Boston Bikes *is* rolling out the Bicycle Network Plan; the BRA *does* promote mixed-use development; and BTD *does* work with the MBTA. They are mentioned here to emphasize their effect on traffic safety, which may affect how and how vigorously they are implemented.

The one innovative item above is using a demand-based pricing model for parking. A similar model is being deployed in San Francisco where they have found:

- Parking availability improved,
- Congestion decreased,
- Traffic volume decreased,
- Vehicle miles decreased,
- Double parking decreased, and
- Average parking rates decreased, but parking revenue increased

in areas where the new pricing model was piloted (San Francisco Municipal Transportation Agency, 2014).

Vision Zero is still a young concept in the U.S., but it is spreading fast. Boston should work with the growing list of cities and states that buy into Vision Zero to share information and work towards state and national Vision Zero policies. Being a Vision Zero city offers some advantages: Boston has direct control over most of its streets, land use and transportation planning can be coordinated, and City engineers have local knowledge. By joining together, the growing network of Vision Zero cities and states, increased influence could be exerted in areas where Boston does not have jurisdiction, such as licensing requirements, vehicle safety standards, and state and federal laws.

Vision Zero Boston is an enormous undertaking. Perhaps more than the actions and policies and procedures that need to be implemented, Vision Zero represents a shift in culture, which is a project of decades, not years. If the City can maintain its commitment to prioritizing safety, we will reach zero.

REFERENCES

AAA Foundation for Traffic Safety. (2011). *Impact Speed and a Pedestrian's Risk of Severe Injury or Death.* Washington, DC: AAA Foundation for Traffic Safety.

AASHTO. (2005). *AASHTO Strategic Highway Safety Plan.* Washington, D.C.: American Association of State Highway and Transportation Officials.

Bertulis, T., & Dulaski, D. (2014). Driver Approach Speed and Its Impact on Driver Yielding to Pedestrian Behavior at Unsignalized Crosswalks. *Transportation Research Record, 2464*.

Boston Department of Transportation/Boston Bikes. (2013). *Boston Bike Network Plan.* Boston: City of Boston.

Center for Transportation Studies. (2013). *Minnesota TZD: 10 Years of Progress.* Minneapolis, MN: Center for Transportation Studies.

City of Boston - Mayor's Press Office. (2016, January 22). *Mayor Walsh Announces the Vision Zero Boston Transportation Safety Concerns Map*. (City of Boston) Retrieved April 26, 2016, from News & Press Releases: http://www.cityofboston.gov/news/default.aspx?id=20496

City of Boston. (2013). *Boston Complete Streets Design Guidelines.* Boston, MA: City of Boston.

City of Boston. (2015). *Vision Zero Boston*. Retrieved April 26, 2016, from http://www.visionzeroboston.org/

City of Boston. (2016). *Traffic Crash Map*. Retrieved from Vision Zero Boston: http://app01.cityofboston.gov/VisionZero/

City of Boston Transportation Department. (2015). *Vision Zero Boston Action Plan.* Boston: City of Boston.

City of New York. (2014). *Vision Zero Action Plan.* New York: City of New York.

de Groot, I., Breider, A., & Nederveen, J. (2005). *Stedelijke Wegencatagorisering: De Vierde Weg.* Antwerpen: Colloquium Vervoersplanologisch Speurwerk.

Demosthenes, P. (2003). How Planning Decisions Impat Highway Collision Histories. *2nd Urban Street Symposium.* Anaheim, CA.

Federal Highway Administration. (2004). *Signalized Intersections: Informational Guide.* McLean, VA: Federal Highway Administration.

Federal Highway Administration. (2005). *Driver Attidtudes and Behaviors at Intersections and Potential Effectiveness of Engineering Countermeasures.* McLean, VA: FHWA Office of Safety Research and Development.

Federal Highway Administration. (n.d.). *A Systematic Approach to Safety - Using Risk to Drive Action*. Retrieved April 26, 2016, from Office of Safety: http://safety.fhwa.dot.gov/systemic/index.htm

FHWA Safety Program. (2014). *Road Diet - Informational Guide.* Washington, DC: Federal Highway Administration.

Finch, K. L. (1994). *Speed, Speed Limits, and Crashes.* Crownthorne, UK: Transport Research Laboratory.

Fitzsimmons, E. (n.d.). Number of Traffic Deaths in New York Falls for a Second Straight Year. *New York Times*(January 1, 2016).

Furfaro, D. (n.d.). Traffic Death Down 22 Percent Since Launch of Vision Zero Plan. *New York Post*(January 1, 2016).

Furth, P. (2008). On-Road Bicycle Facilities for Children and Other "Easy Riders": Stress Mechanisms and Design Criteria. *Transportation Research Board Annual Meeting.* Washington, DC: Northeastern University.

Goodyear, S. (2016). *The Swedish Approach to Road Safety: 'The Accident is not the Major Problem'*. (The Atlantic) Retrieved April 26, 2016, from CityLab: http://www.citylab.com/commute/2014/11/the-swedish-approach-to-road-safety-the-accident-is-not-the-major-problem/382995/

Hyatt, J. (2016). *Are Left Turns a Deadly Maneuver*. (Wells Media Group) Retrieved May 2, 2016, from Claims Journal: http://www.claimsjournal.com/magazines/special-report/2014/09/29/255159.htm

Massachusetts Department of Transportation. (2006). *Project Development & Design Guide.* Massachusetts Department of Transportation.

Massachusetts Department of Transportation. (2016). *Crash Rates by Roadway Functional Classification*. Retrieved from MassDOT Highway Division: https://www.massdot.state.ma.us/highway/Departments/TrafficandSafetyEngineering/CrashData/CrashRates/RoadwayFunctionalClassification.aspx

Massachusetts Executive Office of Public Safety and Security. (2016). *2010-2012 Massachusetts Crash Statistics*. Retrieved from Crime Prevention & Personal Safety: http://www.mass.gov/eopss/crime-prev-personal-sfty/traffic-safety/2006-2008-massachusetts-crash-statistics.html

National Association of City Transportation Officials. (2013). *Urban Street Design Guide.* New York, NY: NACTO.

National Center for Statistics and Analysis. (2016). *Early Estimate of Motor Vehicle Traffic Fatalities for the First Nine Months (Jan-Sep) of 2015.* Washington, DC: National Highway Traffic Safety Administration.

National Cooperative Highway Research Program. (2003). *NCHRP Report 504: Design Speed, Operating Speed, and Posted Speed Practices.* Washington, DC: Transportation Research Board.

National Highway Traffic Safety Administration. (2008). *National Motor Vehicle Crash Causation Survey - Report to Congress.* Springfield, VA: National Technical Information Service.

Nevada Department of Public Safety & Transportation. (2016). *Fatality Statistics*. Retrieved May 2, 2016, from Zero Fatalities - Drive Safe Nevada: http://www.zerofatalitiesnv.com/stats-current-year/

New York City Department of Transportation. (2012). Left Turns and Pedestrian Safety. Washington, DC: New York City. Retrieved from http://www.nyc.gov/html/dot/downloads/pdf/2012_left-turns-pedestrian-safety_trb2012.pdf

New York City Mayor's Office of Operations. (2016). *Vision Zero: Year Two Report.* New York City: New York City Mayor's Office of Operations.

Nilsson. (1982). The Effects of Speed Limits on Traffic Accidents in Sweden. *Proceedings of the International Symposium on the Effects of Speed Limits on Traffic Accidents and Transporta Energy Use.* Dublin: OECD.

Nilsson. (2004). Traffic Safety Dimensions and the Power Model to Describe the Effect of Speed on Safety. *Bulletin 221*.

Ragland, D., Arroyo, S., Shladover, S., Misener, J., & Chan, C.-Y. (2005). Gap Acceptance for Vehicles Turning Left Across On-Coming Traffic: Implications for Intersection Decision Support Design. *TRB 2006 Annual Meeting.*

Richards, D. (2010). *Relationship between Speed and Risk of Fatal Injury: Pedestrians and Car Occupants.* London: Transport Research Laboratory.

San Francisco Municipal Transportation Agency. (2014). *SFpark Pilot Project Evaluation.* San Francisco, CA: San Francisco Municipal Transportation Agency.

SWOV Institute for Road Safety Reseach. (2012). *SWOV Fact Sheet: The Relation Between Speed and Crashes.* Leidschendam, The Netherlands: SWOV.

SWOV Institute for Road Safety Research. (2006). *Advancing Sustainable Safety - National Road Safety Outlook for 2005-2020.* Leidschendam, The Netherlands: SWOV Institute for Road Safety Research.

SWOV Institute for Road Safety Research. (2012). *SWOV Fact Sheet - Predictability by Recognizable Road Design.* Leidschendam, the Netherlands: SWOV.

SWOV Institute for Road Safety Research. (2013). *SWOV Fact Sheet - Sustainable Safety: Principles, Misconceptions, and Relations with other Visions.* Leidschendam, The Netherlands: Swov.

SWOV Institute for Road Safety Research. (2016). *SWOV Factsheet - Road Deaths in the Netherlands.* The Hague, The Netherlands: SWOV.

Transportation Research Board. (2003-2009). *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan.* Washington, DC: Transportation Research Board.

Transportation Research Board. (2008). *NCHRP Report 617: Accident Modification Factors for Traffic Engineering and ITS Improvement.* Washington, DC: Transportation Research Board.

Vision Zero Network. (2016). Retrieved April 26, 2016, from Vision Zero Network: http://visionzeronetwork.org/

Washington Traffic Safety Commission. (2013). *Washington State Strategic Highway Safety Plan.* Olympia, WA: Washington Traffic Safety Commission.

Wilde, G. (1998). Risk Homeostasis Theory: An Overview. *Injury Prevention, 4*.

Zero Fatalities. (n.d.). *Fatality Statistics*. Retrieved May 2, 2016, from Utah Zero Fatalities: http://ut.zerofatalities.com/statistics/

Zero Fatalities. (n.d.). *Statistics*. Retrieved May 2, 2016, from Iowa Zero Fatalities: http://ia.zerofatalities.com/statistics/