

Urban Travel Time:
Impact of Traffic Calming on OD-pair time requirement

Course: CEE 5061

Team Members: Qingbang Wen, Tianyi Zhang, Xin He, Zihao Cai, Leah Goddard

Advisor: Dr. Francis M. Vanek

Fall 2025

ABSTRACT

Traffic calming measures are widely implemented to enhance pedestrian safety and neighborhood livability, yet their quantitative impact on urban travel efficiency remains debated and difficult to isolate. This project developed a comparative framework to measure the impact of traffic calming on vehicle travel time. Focusing on Spokane, Washington, we analyzed 30 matched origin-destination (OD) route pairs, where each pair consists of a calmed route and a geometrically similar uncalmed control route.

We introduced the Weighted Device Exposure (WDE) index to quantify the intensity of traffic calming interventions, and the Device-Normalized Delay (DND) to measure the additional time cost per unit of exposure. Using data from TomTom Move, ArcGIS, and Google Maps, we applied a regression model to determine how differences in Average Daily Traffic (ADT), signal density, and intersection counts influence normalized delay.

CONTENTS

1. Our Team	1
2. Introduction.....	2
3. Scope	4
4. Background	6
4.1 National Examples.....	6
4.2 Impact Threshold Curve	7
4.3 Acceleration–Deceleration Cycling.....	8
4.4 Traffic Calming Practices in China: A Comparative Framework	9
4.5 Monte Carlo Simulation	15
4.6 Public Transportation Route Timing	16
5. Model Specification	17
5.1 WDE	17
5.2 DND.....	18
5.3 Linear Regression Model.....	18
6. Data Collection.....	18
6.1 Traffic Calming Features	19
6.2 Transportation System Performance Measures	20
6.3 Data Collection Example	20
7. Results.....	22
7.1 Regression Output	22
7.2 Standardized Coefficients	25
7.3 Visualization	26
8. Conclusion	28
8.1 Interpretation of Findings	28
8.2 Practical Implications	28
8.3 Limitations	29
8.4 Future Work.....	30
REFERENCES	32
APPENDICES.....	35
Appendix A.....	35
Appendix B.....	36

1. Our Team

Xin (Henry) He is from Hefei, China. He completed a B.S. in Civil Engineering at New York University with a Transportation Engineering minor. He is pursuing a Master's degree in Transportation System Engineering at Cornell University. After graduation, he will join an investment and real estate company.

Qingbang Wen is from Kunshan, China. He completed his B.S. in Civil Engineering at Northeastern University, where capstone focused on transportation engineering. He is currently pursuing the M.Eng. in Transportation at Cornell University. After graduation, he aims to work as a transportation/traffic engineer, applying data-driven methods to improve safety, operations, and travel-time reliability on urban corridors.

Tianyi Zhang is from Shanghai, China. She is a M.Eng student in the CEE department with a focus on Transportation System Engineering at Cornell University. She received an undergraduate degree in Transportation Engineering from Shanghai Maritime University. After graduation, she hopes to pursue a career in Transportation Engineering.

Zihao Cai is from Fuzhou, Fujian, China. He pursued undergraduate studies in Civil Engineering at Cornell University and is currently working toward a Master of Engineering degree in Transportation Systems Engineering.

Leah Goddard is from Boston, Massachusetts, United States. She earned her B.S. in Civil Engineering from Cornell University, where she is currently pursuing an M.Eng. in Civil Engineering with a concentration in Transportation Engineering. After graduation, she hopes to work in transportation engineering with an interest in accessibility, sustainability, and equity in planning.



Figure 1: CEE 5061 Project Team Members (Fall 2025). From left to right: Zihao Cai, Leah Goddard, Qingbang Wen, Xin He, Tianyi Zhang, and Dr. Francis M. Vanek (Advisor).

2. Introduction

Traffic calming is a roadway design that reduces vehicle speeds and fosters safety. Its core objective is to influence driver behavior through physical design and visual means, thus causing them to reduce vehicle speed naturally^[1]. Although these treatments are adopted widely by many cities, their effects are controversial^[2]. On one hand, numerous perspectives highlight traffic calming as a vital component for ensuring pedestrian safety and enhancing neighborhood livability, but some concerns are raised about whether these devices trigger additional delay or diminish overall network efficiency.



Figure 2: Typical Traffic Calming Devices

In order to systematically study the actual impact of traffic calming measures, we selected Spokane in Washington State as the research city for in-depth analysis. Spokane, the second-largest city in Washington State, has the characteristics of a road network typical of a medium-sized city in the United States; specifically, the city has major transportation corridors and numerous residential streets, making it an ideal case for assessing the effects of traffic calming.

Although there has been much discussion about traffic calming, empirical evidence to quantify the marginal impact of these facilities on road travel times is still quite limited. This mainly encounters a core methodological challenge. Once a traffic calming device is installed, it is difficult to move it to observe the situation of the same road section under the counterfactual conditions of “no device”. Thus, to evaluate the impact of these facilities on travel times, a suitable methodology involves comparing two routes that closely match in distance and geometric form, without imposing restrictions on the number of traffic-calming treatments present on either route.

Our study develops a comparative framework based on matched route pairs. For each origin–destination pair, two identified routes with similar length and functional classification. One roadway may contain more traffic-calming interventions, and another may have fewer or no traffic calming devices. The Weighted Device Exposure (WDE) index is constructed to summarize the intensity of traffic-calming features along a roadway, using weights derived from an established hierarchy of roadway facility importance. In addition, the Device-Normalized Delay (DND) metric scales the observed travel-time difference between two matched routes by their difference in WDE. Consequently, a linear regression model will interpret variations in DND across multiple OD pairs. Explanatory variables include differences in average daily traffic (Δ ADT), the number of

intersections (Δ Intersections), and the number of signalized intersections (Δ Signals). This formulation makes a convenient approach to estimate how traffic volume and intersection density interact with traffic-calming devices to influence travel times; meanwhile, it allows us to control unobserved heterogeneity across routes.

In general, this study constructs a framework to evaluate how traffic calming devices influence travel time. By comparing route pairs with similar geometric characteristics, differences in traffic calming exposure are isolated, and comparability across roadways is maintained. The WDE and DND indexes can summarize device intensity and travel time variation; a regression model performs how these differences relate to traffic conditions. Through this integrated approach, the study offers a systematic foundation for understanding the operational implications of traffic calming within urban transportation networks.

3. Scope

This study uses the urban street network in Spokane, Washington, and its spatial scope is strictly limited to the area covered by the city's officially published online "Spokane Traffic Calming map." Due to the long distance between the research team and the city of Spokane, field research is challenging to conduct, so this digital map has become the core basis for defining the study's scope and locating various traffic calming devices.

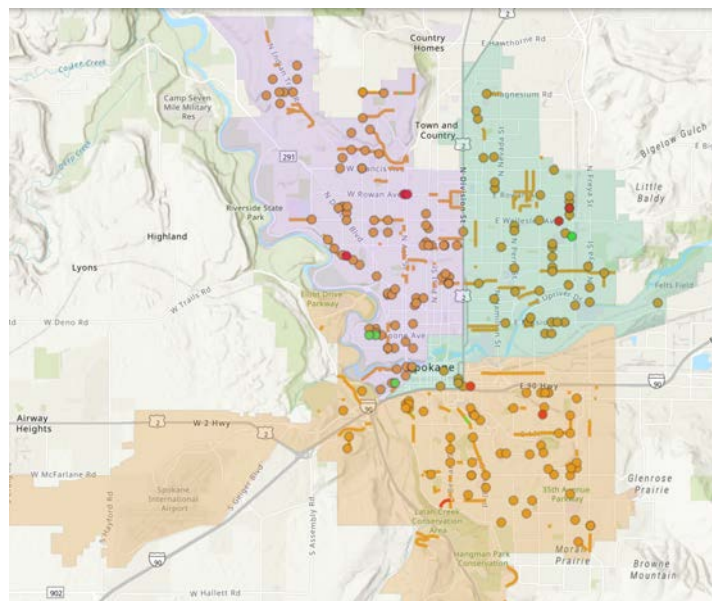


Figure 3: Map of Traffic Calming Devices in Spokane City

The map generally covers the main built-up areas of Spokane City and clearly marks the roads where traffic calming devices have been implemented. Suburbs and rural areas that do not display any traffic calming devices are excluded from the geographical scope of this study. It should be noted that although this official map is intended to provide comprehensive information on traffic calming devices, its data integrity may have specific limitations; for instance, some projects that are extremely small or have just been completed but have not yet been included in the database may not be included. Therefore, the “study area” defined in this study essentially corresponds to the collection of traffic calming devices recorded and displayed on the official map at the time of data collection, rather than an absolute complete enumeration of all traffic calming devices existing in Spokane.

Since the map displays every specific device name of traffic calming in detail, the labels of all records are categorized into five groups according to their main function and physical form: traffic signs, traffic markings, guiding facilities, safety facilities, and crosswalk-related treatments. These categories reflect the most common and diverse types of devices measured in the project list. Specifically, devices used to regulate or warn drivers are classified as traffic signs; facilities on the road are classified as traffic markings; measures used to guide the movement of vehicles or pedestrians are classified as guiding facilities; measures used to reduce risks or protect users are classified as safety facilities; facilities related to pedestrian crossing are classified as crosswalk-related treatments^[3]. This method aids in making a structured comparison of the impact on travel time while remaining consistent with the existing equipment list of the city.

The TomTom Move platform is used as the primary data source for defining time frames, vehicle types, and measurement metrics. The platform aggregates a large amount of anonymous GPS data from connected vehicles and can provide travel time and road section information in real-time. In this way, the travel times of multiple roads can be detected simultaneously to facilitate the observation of travel time differences. To reduce selection bias and ensure statistical randomness, data collection times are randomly selected during normal working hours on weekdays, thereby ensuring robustness rather than being limited to predefined traffic peak or trough periods. In addition, the study subjects were limited to typical cars to represent daily family travel or daily commuting behavior. In terms of measurement indicators, this study prioritizes the basic

performance indicators directly provided by TomTom Move, including link travel time, driving speed, and derived delay indicators. These basic indicators form the set of data variables analyzed in this study and are normalized as key inputs to the mathematical formulas introduced in the subsequent methods section.

Given the core goals and methodological design of this research, there are clear boundaries in the scope of analysis. First, traffic safety performance, such as the impact of slow-moving facilities on the frequency of traffic accidents, was not included in the assessment. Secondly, such as the increased exhaust emissions of vehicles due to frequent acceleration and deceleration, this potential environmental impact has not been quantified. Therefore, strictly limiting the focus of research to questions that can be effectively answered by such observation data is not only to ensure the feasibility of the analysis, but also to maintain the purity of the research logic.

4. Background

4.1 National Examples

One of the best use cases in the United States for traffic calming is the use of “Daylighting” in the case of Hoboken, New Jersey^[4]. “Daylighting” is the practice of removing parking spaces adjacent to the corners of intersections for the purpose of creating clear sight triangles. Curb extensions are the widening of sidewalks in the various directions surrounding the intersection and are often placed into the parking lane of the crosswalk. Along with removing parked bicycles, in Hoboken, “Daylighting” allows drivers to see pedestrians and cyclists much earlier. This allows drivers to slow down and yield to pedestrians and cyclists.



Figure 4: “Daylighting” with Curb Extensions in Hoboken

Curb Extensions increase safety at intersections in a few different ways. First, while crosswalks are moved into the parking lane, curb extensions reduce the crossing distance so that pedestrians - children, elderly people, and people with disabilities - spend less time on the roadway. Wider waiting areas with ADA ramps are a part of many designs too.^[5] Second, curb extensions reduce the effective corner radius. This discourages and slows down fast turning and wide turns, which in turn reduces right turn failure at yielding and improves sights for left turns, as mentioned in the NACTO curb extension. Finally, people closer to the travel lane improve visibility, which makes it likelier that vehicles will slow, stop, and yield^[6].

Curb extensions in Hoboken also narrow the road and travel lanes at intersections^[4]. When road lanes are narrow, drivers slow down and are more attentive; this lowers the speed at which drivers turn, and this can be done without the reliance of police enforcement and speed limit signs. Simultaneously, curb extensions reduce crossing distance and lessen the time of pedestrians, especially kids, senior citizens, and people with limited mobility, are on the road. Many of these projects start with low-cost materials such as paint, posters, and planters. This allows the city to test the design, track the speed and yield behaviors, and decide if they want to build permanent concrete curb extensions.

4.2 Impact Threshold Curve

In terms of driver behavior, traffic calming devices can also trigger drivers' subconscious

behavioral changes. Specifically, when drivers frequently encounter vertical or horizontal traffic calming devices, most find these routes inconvenient or time-consuming, thus prompting them to divert routes to nearby roads with fewer interruptions, even if the routes are slightly longer. This behavior shifts traffic inadvertently from roads where traffic is being slowed to alternative roads, resulting in an uneven distribution of traffic loads. In other words, roads with fewer traffic calming devices will cause congestion and result in longer travel time; however, roads with more traffic calming devices may have less traffic flow due to driver changes, making travel time relatively shorter. This situation is not uncommon. When there are certain comparisons in Spokane for this study, the travel time of roads with more traffic calming is less than that of roads with less traffic calming. To assess whether this redistribution of traffic is acceptable, many cities use impact threshold curves. The curve sets a quantitative limit on the amount of additional traffic that adjacent roadways can withstand after traffic calming devices are implemented^[7]. Roadways with lower traffic volumes can withstand a larger percentage of traffic growth, while roads with heavy traffic can withstand only a small percentage of additional traffic diversion. By turning these limitations into quantifiable standards, the curve prevents problems from migrating. However, due to the lack of on-site testing and time constraints, the impact threshold curve for the study of traffic calming devices in Spokane is a granular research direction for the future.

4.3 Acceleration–Deceleration Cycling

Vehicles rarely maintain a constant speed when passing through sections with traffic-calming devices. Instead, drivers usually go through a recurring cycle: slow down in front of the devices, drive slowly through them, and accelerate again after passing. Drivers slow down to forestall discomfort or violations, then try to return to their accustomed driving speed. A crucial factor affecting this behavior is the spacing between traffic calming devices. In this study, 350 feet were identified as a critical threshold^[8]. When the distance between the two devices exceeds 350 feet, the driver has enough room to accelerate back to the original cruising speed. On the contrary, when the spacing is less than 350 feet, the driver often cannot accelerate to full cruising speed before encountering the next facility, which implies that the speed will sustain at low range. Therefore, device spacing determines whether slow-moving measures function as independent interventions or as a continuous speed-control system, thereby affecting route selection and traffic dynamics.

4.4 Traffic Calming Practices in China: A Comparative Framework

China's approach to traffic calming represents a fundamentally different paradigm from Western practices, characterized by centralized policy implementation, technology-intensive enforcement, and integration within broader urban transformation strategies rather than standalone neighborhood interventions. This section contextualizes traffic calming within the Chinese urban environment and examines how these practices compare to approaches commonly used in North American cities like Spokane.

4.4.1 Historical Evolution and Policy Framework

Traffic calming as a formal concept arrived in China approximately two decades after its establishment in Western Europe, with the first documented engineering implementation occurring in 2008 at Zhaitang Town, Beijing (Tan et al., 2010). This pilot project, led by the Beijing Mentougou Highway Sub-bureau, incorporated a comprehensive suite of physical measures including speed humps, raised crosswalks, chicanes, neckdowns, center island narrowings, and pedestrian refuges. This demonstrated China's tendency toward implementing multiple integrated measures rather than isolated interventions.

The policy framework evolved substantially following the 2015 State Council Urban Working Conference, which issued directives promoting smaller urban blocks and denser street networks through the document “Opinions on Further Strengthening Urban Planning and Construction Management” (State Council of the People's Republic of China, 2015). This represented a significant philosophical shift from China’s historically vehicle-prioritized planning approach toward what Chinese planners term “people-orientedness.” The 2016 Shanghai Street Design Guidelines marked a watershed moment as China's first Complete Streets-type publication, establishing four transformational principles: prioritizing human-centered design over vehicle throughput, integrating comprehensive environmental considerations beyond pure engineering, controlling street space rather than merely road width, and balancing transportation efficiency with integrated neighborhood development (Shanghai Urban Planning and Land Resources Administration Bureau, 2016). These guidelines subsequently influenced more than 20 major Chinese cities to develop their own local standards.

Chinese traffic calming operates under a hierarchical regulatory structure. The Ministry of Housing and Urban-Rural Development (MOHURD) establishes national construction and planning standards, while the Ministry of Transport promotes public transit policies and road safety research. National design standards for road engineering (CJJ 37-2012), intersection design (CJJ 152-2010), and traffic sign placement (GB 51038-2015) provide the technical foundation, though China notably lacks a comprehensive traffic calming-specific design manual equivalent to FHWA guidance documents (Ministry of Housing and Urban-Rural Development, 2012). Local standards, such as Beijing's Code for Planning and Design on Urban Road Space (DB11/1116-2014), supplement national frameworks with jurisdiction-specific requirements.

4.4.2 Implementation Across Major Chinese Cities

Traffic calming implementations vary considerably across Chinese cities, reflecting local conditions, administrative priorities, and urban morphology. Beijing pioneered formal traffic calming at Zhaitang Town while also developing extensive pedestrianization, including the Wangfujing Street pedestrian zone established in 1999-2000 and extended in 2019 to 892 meters, accommodating up to 1.2 million visitors on peak holidays (China Radio International, 2019). Shanghai pursued transformative infrastructure changes through the Bund Waterfront Retrofit (2008-2010), which removed seven of eleven traffic lanes from the historic waterfront highway, achieving a 70% reduction in vehicle traffic while creating a seven-kilometer non-motorized transport corridor along the Huangpu River (Shanghai Urban Planning and Land Resources Administration Bureau, 2016).

Shenzhen, as China's newest major city, integrated traffic management into initial planning through smart city technologies. The city's Traffic Brain system, developed jointly with Huawei, processes 700 million pieces of vehicle data monthly with 95% detection accuracy and ten million images daily (Huawei Enterprise, 2019). This technology-intensive approach reflects Shenzhen's character as China's technology hub but also demonstrates the country's broader preference for surveillance-based enforcement over physical traffic calming devices.

Wuhan provides the most thoroughly documented case study through its World Bank Urban Transport Project (2004-2009), which implemented 26 physical junction channelizations and 242

marking-based channelizations (World Bank, 2010). The project established model junction designs featuring clear vehicle paths, safety refuge islands for pedestrians during multi-stage crossings, and optimized signal timing with conflict-free pedestrian phases. Micro-simulation confirmed increased intersection capacity alongside improved pedestrian safety, representing a rare example of rigorous before-after evaluation in Chinese traffic calming research (Liu, 2010).

Guangzhou demonstrates integration of traffic calming with Bus Rapid Transit through the Zhongshan Avenue corridor redesign (2010), which converted vehicle lanes to dedicated bus facilities and achieved a 28% increase in average speeds for remaining traffic while increasing public transport ridership from 520,000 to 830,000 daily passengers (Zhang et al., 2022). The city also completed the Cloud Pathway in 2020, an eight-kilometer elevated pedestrian walkway connecting multiple parks and cultural sites, representing a distinctly Chinese approach to pedestrian infrastructure at a scale rarely attempted elsewhere.

4.4.3 Comparative Analysis with US and Western Approaches

The philosophical foundations of traffic calming differ substantially between Chinese and Western contexts. American traffic calming typically emerges from community-driven processes requiring substantial resident approval (often 70-90%) and emphasizes local autonomy in implementation decisions. Chinese traffic calming follows top-down policy directives, with national and provincial governments establishing frameworks that local jurisdictions execute. This centralized model enables rapid, large-scale implementation but may lack the community buy-in that characterizes successful American programs.

Device preferences reflect these philosophical differences. Chinese cities historically favored pedestrian separation infrastructure, including overpasses, underpasses, and center median fencing, over at-grade traffic calming measures that Western practice increasingly emphasizes (Liu, 2018). Physical barriers preventing jaywalking remain common in downtown districts across major Chinese cities, contrasting with American approaches that typically seek to accommodate pedestrian desire lines. However, recent Chinese guidelines increasingly reference Western devices. The Shanghai Street Design Guidelines specify 30 km/h design speeds for side streets, recommend reduced lane widths (2.75m versus traditional 3.0m), and call for reduced turning radii

at intersections (Shanghai Urban Planning and Land Resources Administration Bureau, 2016). These specifications align closely with NACTO Urban Street Design Guide recommendations.

Design standards show notable differences in specificity. The American MUTCD provides comprehensive, prescriptive guidance for traffic calming devices. Speed humps require 12-foot length and 3-4 inch height, warning signage placement follows specific protocols, and pavement marking standards are codified in Section 3B.25. Chinese national standards address general road engineering but lack equivalent specificity for traffic calming devices. Speed hump dimensions vary by manufacturer and local practice rather than national specification, though typical dimensions of 1000×380×50mm appear in commercial standards (China National Standard, 2024).

The most profound difference involves enforcement methodology. Chinese cities deploy extensive automated surveillance including facial recognition systems that identify and publicly shame jaywalkers through roadside displays (Synced Review, 2018). Shenzhen's AI-enabled traffic management achieves 95% detection accuracy across city-wide networks (Huawei Enterprise, 2019). Interval-based speed enforcement, social credit integration for traffic violations, and mandatory Beidou satellite positioning in e-bikes (required by 2025 national standard GB 17761-2024) represent enforcement intensities unparalleled in American practice, where privacy concerns substantially constrain automated enforcement expansion.

Urban form fundamentally shapes traffic calming requirements. Chinese superblocks, frequently exceeding 500 meters per side with 100,000+ residents, create pedestrian environments fundamentally different from American grid systems with typical block lengths of 60-120 meters (Worldcrunch, 2018). The 2016 State Council guidelines acknowledged this challenge by promoting “narrow roads, dense street networks,” calling for average block lengths of 150 meters and opening gated residential compounds to through-traffic (State Council of the People's Republic of China, 2015). However, implementation has generated substantial middle-class resistance due to security and property value concerns.

4.4.4 Effectiveness Evidence and Research Gaps

Quantitative effectiveness data for Chinese traffic calming remains limited compared to

Western research but provides some instructive findings. A Southeast University study of parallelogram-shaped pavement markings at twelve urban road sites demonstrated statistically significant speed reductions of 3.79 km/h average (4.19 km/h at the 85th percentile) (Li et al., 2016). This is particularly meaningful given that traffic crashes between motor vehicles and pedestrians account for 30.6% of fatal and injury crashes on China's urban roads (Li et al., 2016). A three-year longitudinal study in Xi'an documented dramatic improvements in pedestrian crossing conditions when policy enforcement intensified. Driver yielding rates increased from 3.6% to 68.6%, with pedestrian waiting times reduced by 41.58% (Guo et al., 2021).

National-scale evidence demonstrates broader impacts. Following implementation of speed detection equipment in Guangdong Province after the 2004 Road Traffic Safety Law, motorway fatalities due to speeding decreased by 32.5% in 2005 compared to the previous year (Wang et al., 2012). China's overall road safety trajectory shows gradual improvement, though the country still experiences approximately 262,000 annual road traffic deaths (21% of global total) with a mortality rate of 19.4 per 100,000 (World Health Organization, 2018). This remains substantially higher than the 8.2 per 100,000 rate in high-income countries.

Research institutions actively investigating traffic calming include Tongji University's Key Laboratory of Road and Traffic Engineering, which developed the Shanghai Street Design Guidelines and operates one of the world's largest driving simulators, Southeast University's Jiangsu Province Collaborative Innovation Center for Modern Urban Traffic Technologies, and Chang'an University's School of Highway (Shanghai Urban Planning and Land Resources Administration Bureau, 2016). International collaborations through the World Bank (which has invested in road safety projects across Xinjiang, Henan, and Hubei provinces) and Asian Development Bank provide additional research capacity and evaluation frameworks (World Bank, 2010).

4.4.5 Unique Challenges in the Chinese Context

China's traffic calming must address several challenges with limited parallels in American practice. The country's 400 million e-bikes create mixed traffic environments fundamentally different from US conditions (Liu & Circella, 2018). E-bike accidents increased 39.1% between

2013-2017, with 81% of Shenzhen e-bike crashes occurring in mixed road sections. The new 2025 national standard mandates 25 km/h maximum speed, Beidou positioning, and anti-tampering technologies. These represent regulatory responses to a modal category essentially absent from American traffic calming considerations.

Population densities exceeding 10,000 persons per square kilometer in urban cores, combined with pedestrian wait times of up to 90 seconds at signalized crossings (versus 60-second German standards), create compliance challenges (Zhang, 2013). The phenomenon of “Chinese Style Road Crossing,” in which groups of pedestrians collectively ignore traffic signals under the assumption that enforcement cannot simultaneously address all violators, reflects rational responses to pedestrian-hostile infrastructure design (Liu, 2018).

Rapid urbanization, with China’s urban population projected to exceed one billion by 2030, means traffic calming must scale across simultaneously developing urban areas lacking the established street patterns and community structures that characterize American traffic calming contexts (Li et al., 2022). An evaluation of eleven Urban Street Design Guidelines adopted between 2016-2020 found average performance of only 30.9% of total possible Complete Streets scores, indicating substantial implementation gaps between policy aspirations and street-level outcomes (Shanghai Urban Planning and Land Resources Administration Bureau, 2016).

4.4.6 Implications for Comparative Practice

Chinese traffic calming offers instructive contrasts for American practitioners. The technology-intensive enforcement model demonstrates potential effectiveness. Xi'an's yielding rate improvements suggest automated enforcement can transform driver behavior (Guo et al., 2021). However, this raises fundamental questions about privacy and civil liberties that American communities must navigate. China's experience with superblock redesign and street network densification provides evidence for long-term benefits of walkable urban form, even as implementation challenges illustrate the difficulty of retrofitting established development patterns. The integration of traffic calming within broader Complete Streets frameworks, rather than as isolated neighborhood interventions, represents an approach increasingly adopted in American practice through programs like NACTO's Urban Street Design Guide. For cities like Spokane

considering traffic calming investments, the Chinese experience reinforces that physical measures achieve greatest impact when embedded within supportive policy frameworks, enforcement mechanisms, and urban design strategies that collectively prioritize pedestrian and cyclist safety.

4.5 Monte Carlo Simulation

Monte Carlo Simulation is a mathematical tool used to estimate the possible outcomes of an unknown future event. This is done by using random sampling to generate many different outcomes, and modeling the probability of these outcomes to calculate the average result. The goal is to incorporate randomness into calculations without assuming values are known for certain. Some benefits of taking randomness into account are an increase in accuracy and a more realistic representation of variability in real-world systems.

The Monte Carlo Simulation method can be applied to estimate total travel time along a corridor with signalized intersections. An example was conducted using a 2.3 mile long corridor with one signalized intersection. To find the average travel time along this corridor, the first step was to calculate parameters including the length of the intersection and the distance unaffected by it to get the travel time unaffected by any signal condition. Then, the probability of getting a red versus green light was calculated using the 90 second signal cycle and 30 seconds of red light to get $p(\text{green}) = 0.67$ and $p(\text{red}) = 0.33$. Using the speed limit of 30 mph, the additional time in the intersection if the light is red was calculated by adding the time for acceleration and deceleration to and from a stop to the 30 seconds of waiting at the light, resulting in an additional 46 seconds added to the base 276 seconds of unaffected travel time. If the light is green, only 8 seconds are added to the travel time to pass through the intersection. After these parameters were determined, Monte Carlo simulation was used to generate 1,000 random outcomes using the probabilities of each outcome, green or red lights, and the average total travel time was calculated to be 296.39 seconds, a 20 second increase from the time excluding the intersection.

The key parameters and results of this simulation are summarized in Table 1 below, and the frequency of total travel time outcomes (red or green) are visualized in Figure 4 below.

Table 1: Summary of Monte Carlo Simulation Parameters and Results

Signal Outcome	Total Travel Time (s)	Probability
Green light	284	0.67
Red light	322	0.33
Average	296.39	-
Std. Dev.	17.82	-
CV	6%	-

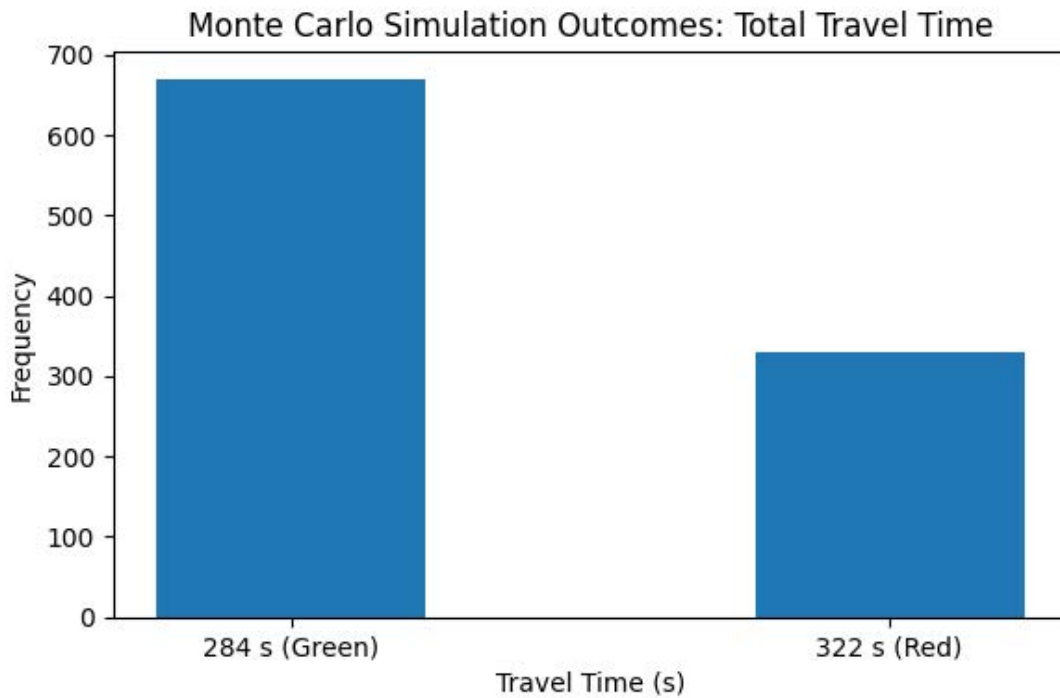


Figure 5: Monte Carlo Simulation Outcome Frequency Chart

This shows that it is important to incorporate randomness because travel time along a corridor with a signalized intersection varies depending on whether a driver encounters a red light, which can significantly increase travel time. When conducting more complex travel time calculations and modeling, it is more accurate to use a calculated travel time that accounts for the fact that many drivers will experience delay due to traffic signals at intersections along these corridors.

4.6 Public Transportation Route Timing

Public transportation route timing could provide important insight into how traffic calming

measures affect overall travel times, for both riders and private vehicle drivers. Buses, and other modes of transit that run in the street, operate within the same roadway as general traffic. This means that changes to street geometry and vehicle travel times directly influence their travel time and reliability. Looking at route timing before and after traffic calming implementation can therefore help analyze the benefits and tradeoffs of these interventions with respect to travel time and delay due to traffic calming.

One possible way this could be implemented is by examining bus route schedules and comparing the scheduled time that a bus is expected to reach a specific destination to the actual time it takes to reach that destination. This can be done multiple times and across multiple routes to account for variability and random fluctuations in travel conditions. To go a step further, tools such as Spokane Transit's GPS bus tracking app could be used alongside Spokane's online ArcGIS Traffic Calming Web Map, which identifies the locations and types of traffic calming devices. Depending on the precision of the GPS data, the time required for a bus to travel through a traffic calming device could be measured and compared to the expected travel time if no traffic calming devices were present, using the average bus speed on that roadway and the distance between stops. This analysis could also be conducted across routes with different numbers and types of devices to identify general patterns in how traffic calming measures affect travel times. This approach allows for a comparison of scheduled versus observed travel times, helping to isolate the effects of traffic calming devices on travel time and delay.

5. Model Specification

5.1 WDE

To compare routes with very different combinations of traffic calming devices, a single exposure index is needed rather than just counting the raw number of devices. The Weighted Device Exposure (WDE) index serves this purpose. It is defined as:

$$WDE = \sum_j w_j * n_j \quad [1]$$

where n_j is the number of devices of type j on a route, and w_j is the weight assigned to that device type. The weight reflects the expected strength of its influence on travel time. Hence, WDE combines both the quantity and the severity of traffic calming along a route into one scalar measure, which can be used as the main explanatory variable for travel time.

5.2 DND

The project is interested in how differences in exposure between two similar routes translate into differences in travel time. The Device Normalized Delay (DND) index captures this idea:

$$DND = \frac{Totaltime_A - Totaltime_B}{WDE_A - WDE_B} \quad [2]$$

$Totaltime_A$ and $Totaltime_B$ are the observed travel times on route a and route b, and WDE_A and WDE_B are their corresponding WDE values. DND can be interpreted as the change in travel time per unit of change in device exposure within a matched route pair. The magnitude of DND shows how sensitive travel time is to additional traffic calming exposure. This kind of normalization makes comparisons much cleaner across two similar corridors. DND links the travel-time difference to a standardized difference in device exposure, so the two routes can be compared on a common scale ^[29].

5.3 Linear Regression Model

Using a linear regression framework allows DND to be explained by key roadway differences beyond traffic calming exposure. It also provides an interpretable way to quantify how much each factor contributes to variation in normalized delay across matched route pairs.

$$DND_i = \gamma_0 + \gamma_1 \cdot \Delta ADT_i + \gamma_2 \cdot \Delta Signals_i + \gamma_3 \cdot \Delta Intersections_i + \epsilon_i \quad [3]$$

Where γ_0 means the baseline expected DND when the observed corridor differences are zero; γ_i means the marginal effects of differences in key corridor characteristics between paired routes on DND_i ; ϵ_i means the residual capturing unobserved factors affecting DND for route pair i.

6. Data Collection

Our data collection process integrates traffic-calming features, traffic volumes, and observed travel-time information. We focus on 30 matched route pairs in Spokane, Washington. Each origin-destination (OD) pair includes two parallel corridors of similar length. One route contains a higher intensity of traffic-calming devices, while the second contains fewer or no devices. This paired-route structure allows us to isolate the effect of traffic calming while holding trip length and purpose approximately constant.

6.1 Traffic Calming Features

Traffic calming treatments along each route were identified using Spokane’s online ArcGIS Traffic Calming Web Map. This dataset provides detailed, location-specific information on the presence of measures such as curb extensions, marked crosswalks, speed feedback signs, enhanced markings, and traffic signals. For each route, we manually documented the quantity and type of every traffic calming device. This data formed the basis for constructing the Weighted Device Exposure (WDE) index.

Device weights were adapted from a published roadway safety evaluation framework, which ranks roadway facilities by their relative influence on operational performance. Each device type was matched to its corresponding subcategory, and its weight was multiplied by the observed frequency on the route. Summing the weighted values across all device types yielded the total WDE for each route.

Table 2: Weights

Rule layer	Weight	Subindex	Combined Weight	Weight × Combined Weight	Weight (%)	w_j for WDE
Traffic facility	0.15	Traffic sign	0.3	0.045	24.725	2.5
	0.15	Traffic marking	0.13	0.0195	10.714	1
	0.15	Guiding facility	0.2	0.03	16.484	1.7
	0.15	Safety Facility	0.37	0.0555	30.495	3
Traffic environment	0.1	Crosswalk	0.32	0.032	17.582	1.8
				0.182	100	10

6.2 Transportation System Performance Measures

(1) Average Daily Traffic (ADT)

Traffic volume information was obtained from Spokane's ArcGIS Open Data Portal. The ADT database provides roadway-level counts collected by the city. For each route, we extracted the most recent ADT value associated with the relevant road link. Since many Spokane residential roads operate as two-way streets, two-direction ADT counts were converted into directional averages by dividing total ADT by two.

(2) Route Travel Time and Distance

We used TomTom Move, a cloud-based routing and congestion analytics platform, to obtain time-of-day travel-time observations for both routes in each OD pair. TomTom Move provides real-time and historical corridor performance data, updated at one-minute intervals, allowing us to retrieve consistent travel-time measurements under comparable traffic conditions.

For every OD pair, we extracted repeated travel-time observations within the same time window and computed the average travel time. These travel-time averages serve as the basis for computing the Device-Normalized Delay (DND) metric.

(3) Intersection and Signal Counts

We manually counted the number of intersections and signalized intersections along each route using Google Maps and Google Street View. This included both minor and major cross streets to reflect the total number of potential stopping, slowing, or yielding events a driver may encounter. These counts were then converted into route-level differences ($\Delta\text{Intersections}$ and $\Delta\text{Signals}$) for use in the regression model. After completing the four data collection steps for all 30 route pairs, we compiled a comprehensive dataset containing DND, ΔADT , $\Delta\text{Signals}$, and $\Delta\text{Intersections}$.

6.3 Data Collection Example

To illustrate the practical application of the methodology described in Sections 6.1 and 6.2, this section details the data collection and processing workflow for a specific route pair. We selected OD Pair 1 from our dataset of 30 matched pairs to demonstrate how raw data is converted into model inputs.

The OD pair example compares Wellesley Avenue (Route 1) and Garland Avenue (Route 2), both located between Ash and Crestline. The routes are approximately 2.7 miles in length and operate as two-way, four-lane roads.



Figure 6: Example Route Pair Map

Using Spokane’s online ArcGIS Traffic Calming Web Map, we identified the existing treatments on both corridors. Route 1 contains only 1 device, identified as a “Four-Section Flashing Yellow Arrow Traffic Signal”. Route 2 contains 10 total devices: 3 crosswalks, 3 bumpouts, 3 permanent speed signs, and 1 instance of enhanced street markings.

We applied the weighting system in Table 2 to these raw counts to calculate the WDE. As detailed in Table 3, Route 1 yielded a WDE of 1.7, while Route 2 yielded a substantially higher WDE of 22.9.

Table 3: WDE

Subindex	devices	Route 2	WDE	Route 1	WDE
Traffic sign	Permanent Speed Sign	0	0	3	7.5
Traffic marking	Change Street Markings	0	0	1	1
Guiding facility	Four-Section Flashing Yellow Arrow Traffic Signal	1	1.7	0	0
Safety Facility	Bumpouts	0	0	3	9
Crosswalk	Crosswalk	0	0	3	5.4

WDE
 Δ WDE

1.7
21.2

22.9

Using the City of Spokane's ArcGIS open data portal, the database of ADT provided the most recent counts for the specific road links. Route 1 had 6169 vehicles/day. Route 2 had 6946 vehicles/day.

Using the TomTom Move analytics platform, we got travel time and road length data. Route 1 recorded a travel time of 8.5 minutes for 2.7miles. Route 2 recorded a travel time of 9.5 minutes for 2.7 miles. These values were subsequently used to calculate the numerator for the DND metric.

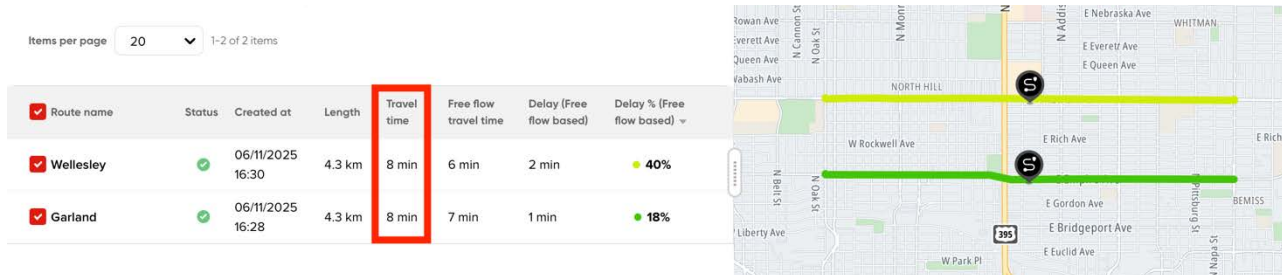


Figure 7: Travel Time & Length Data from TomTom Move

Finally, we utilized Google Maps and Street View to manually count the intersections and signals along the corridors. Route 1 contains 33 intersections and 10 signalized intersections. Route 2 contains 30 intersections and 2 signalized intersections.

These processes were repeated for all 30 route pairs. The aggregated data, including the calculated differences in ADT, signals, and intersections, was compiled into the final dataset used for the regression analysis presented in Section 7.

7. Results

All modeling, data cleaning, and visualization were conducted using the R programming language within the RStudio environment.

7.1 Regression Output

Coefficient estimates and significance levels

Table 4: The coefficients confidence interval

	2.5%	97.5%
Intercept	-4.507733018	4.04279122
Delta-ADT	-0.002198647	0.00356292
Delta_Signals	-2.403834835	4.11708062
Delta_Intersections	2.409401460	8.16677229

Table 4 presents the OLS regression analysis with DND being the dependent variable and having three independent variables, namely, Δ ADT, Δ Signals, and Δ Intersections. The intercept is, however, not statistically different from zero. The coefficients of Δ ADT are the smallest and statistically insignificant, which shows that the differences in the average daily traffic of the calm and not calm routes do not explain the variation in DND. The coefficients of Δ Signals are somewhat larger, and this too, is statistically insignificant; their 95% confidence intervals are inclusive of zero, and therefore, we cannot arrive at the conclusion that the provided sample is in any way conclusive in stating that signalized intersections do either increase or decrease the device-normalized delay in this case.

On the other hand, the coefficient for Δ Intersections is not only substantial, but it is also significantly higher than zero. That is, the positive relationship between Δ Intersections and DND is almost guaranteed, since the entire confidence interval is above zero. More precisely, for the calmed route, if the number of intersections is greater than the comparison route, it is expected that the OD pair will have substantially higher, albeit device-normalized, delay, which will hold even when controlling for volume and signal density.

Key finding: Δ Intersections have the strongest effect on DND.

```

Residuals:
    Min       1Q   Median       3Q      Max
-30.026  -1.489   1.110   3.441  20.699

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)   -0.2322654    2.0797837   -0.112  0.911937
Delta_ADT       0.0006821    0.0014015    0.487  0.630530
Delta_Signals    0.8566229    1.5861888    0.540  0.593758
Delta_Intersections  5.2880869    1.4004593    3.776  0.000836 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 8.532 on 26 degrees of freedom
Multiple R-squared:  0.7545,    Adjusted R-squared:  0.7261
F-statistic: 26.63 on 3 and 26 DF,  p-value: 4.336e-08

```

Figure 8: The Linear regression model result

According to the regression output in Figure 8 Δ Intersections unarguably have the largest impact on DND. With respect to the OLS model, Δ Intersections has an estimated coefficient of around 5.29, and its corresponding t and p values are 3.78 and 0.000836, respectively. This coefficient is large in magnitude and highly significant, indicating a strong positive association between the difference in the number of intersections and the device-normalized delay. In other words, when the calmed route has more intersections than the comparison route, the DND tends to increase substantially.

However, this is in stark contrast to the coefficients for Δ ADT (≈ 0.00068) and Δ Signals (≈ 0.86), which are much less and are statistically insignificant ($p \approx 0.63$ and $p \approx 0.59$, respectively). Thus, there is an absence of significance such that in this data set, the difference in DND is not explained by difference in average daily traffic and the number of signalized intersections.

The overall model fits the data well, with a Multiple R-squared equal to 0.7545 and an Adjusted R-squared equal to 0.7261, indicating that roughly 75% of the variation in DND across OD pairs can be explained by these variables. With such a high degree of explained variation, we can interpret the strong and significant Δ Intersections coefficient as being an important factor in explaining device-normalized delay in the data through the sample because of its being a key driver.

7.2 Standardized Coefficients

Residuals:

Min	1Q	Median	3Q	Max
-1.84184	-0.09134	0.06806	0.21106	1.26967

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	3.953e-17	9.555e-02	0.000	1.000000
scale(Delta_ADT)	6.683e-02	1.373e-01	0.487	0.630530
scale(Delta_Signals)	1.017e-01	1.883e-01	0.540	0.593758
scale(Delta_Intersections)	7.325e-01	1.940e-01	3.776	0.000836 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.5233 on 26 degrees of freedom

Multiple R-squared: 0.7545, Adjusted R-squared: 0.7261

F-statistic: 26.63 on 3 and 26 DF, p-value: 4.336e-08

Figure 9: the Standardized coefficient

To compare the relative importance of the three predictors, the model was re-estimated using standardized variables. In this specification, each coefficient measures the change in DND associated with a one-standard-deviation change in the corresponding Δ variable.

The standardized coefficient for Δ Intersections is about 0.73 and remains highly significant ($p = 0.000836$), while the standardized coefficients for Δ ADT and Δ Signals are small (≈ 0.07 and 0.10) and statistically insignificant. Thus, even after putting all variables on the same scale, the difference in the number of intersections clearly has the largest impact on DND. The overall fit of the standardized model is unchanged, with $R^2 = 0.7545$ and Adjusted $R^2 = 0.7261$, confirming that the set of predictors still explains roughly three-quarters of the variation in device-normalized delay.

These normalized results match the unstandardized regression in Section 7.1 intersection density being the primary contributor to higher level of device delay normalized but differences in traffic volume and signalized intersections barely contribute to the dataset in this case and are minor.

7.3 Visualization

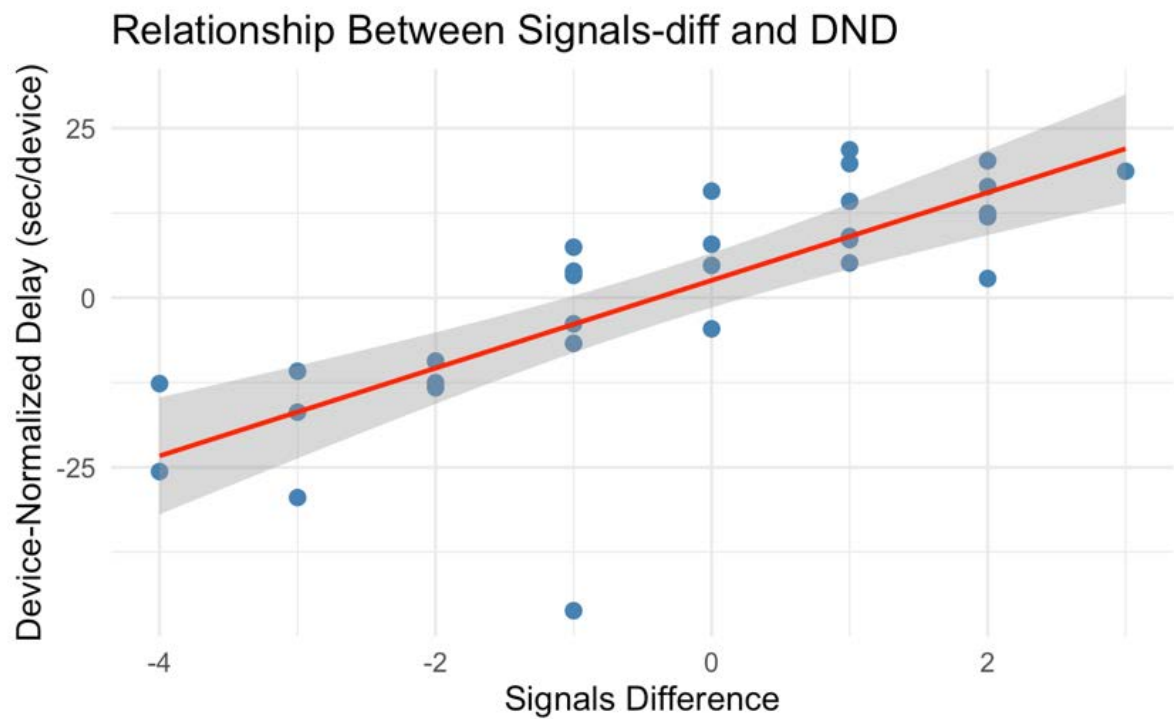


Figure 10: DND vs. Δ Signals Scatter plots

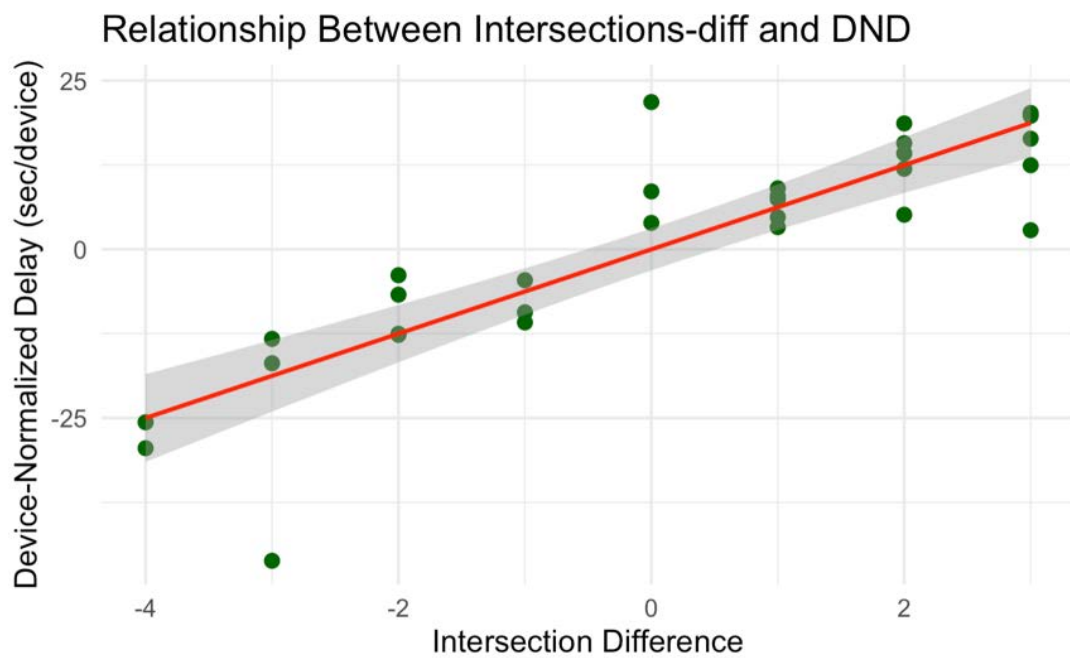


Figure 11: DND vs. Δ Intersections Scatter plots

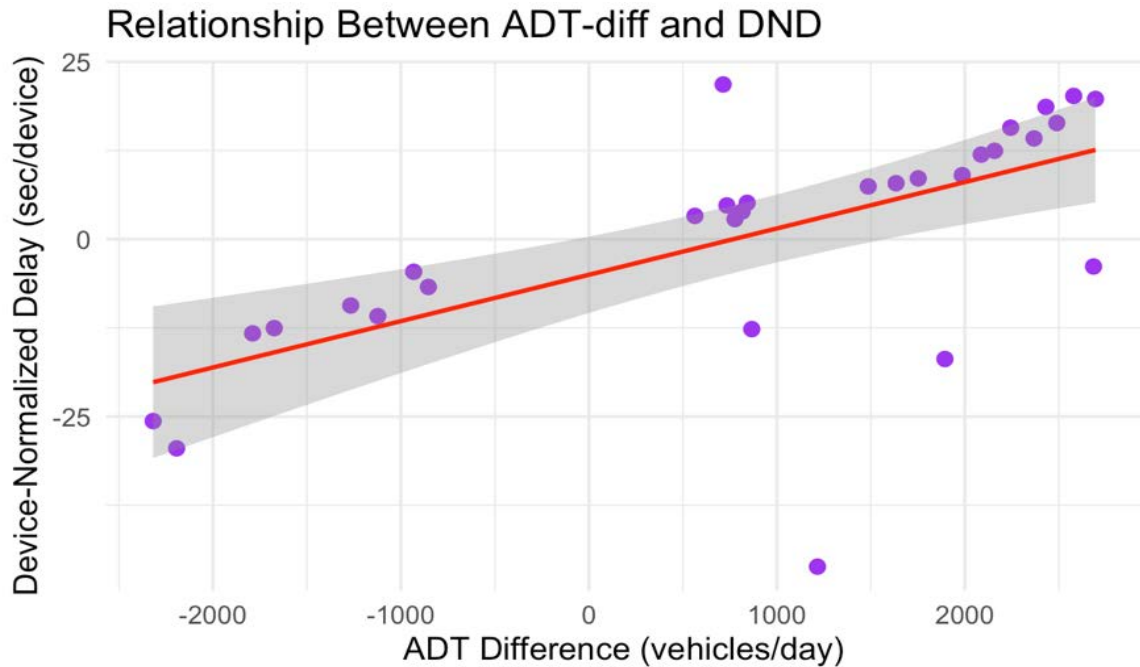


Figure 12: DND vs. Δ ADT Scatter plots

Figure 10, Figure 11, Figure 12 presents three scatter plots that illustrate the bivariate relationships between DND and each explanatory variable: Δ Signals, Δ Intersections, and Δ ADT. In all three plots, the red line shows the fitted simple linear trend, and the gray band represents the confidence interval.

In the case of the DND vs. Δ Signals panel, the data points surrounding the fitted line are rather dispersed, and even though the fitted line shows a positive slope, several data points are positioned far away from the line, and the confidence band is also rather wide. Therefore, this suggests that differences in the number of signalized intersections may be associated with higher DND, but the differences in isolation are associated with a rather weak and noisy signal.

The DND vs. Δ ADT also depicts a similar trend. Once again, the fitted line shows a positive slope, suggesting that pairs of OD where the calmed route is carrying heavier traffic have a higher device normalized of that delay and has more of a positive slope. However, the significant unexplained variability, demonstrated by the surrounding points, the outliers, and the lack of a significant variability in the Δ ADT in the regression, confirms that the fitted line also has a weak positive slope.

In comparison, the DND vs. Δ Intersections scatter plot shows the most obvious linear pattern. There is a dense cloud of points that trail closely along a line with positive slope, and the confidence region is narrower than the other two. The visual evidence is consistent with the regression results showing that Δ Intersections most strongly and most robustly correlate with DND.

Overall, the visualization reinforces the main empirical finding: while all three variables show weak positive trends with DND in simple scatter plots, the difference in the total number of intersections between the paired routes stands out as the most consistent predictor of device-normalized delay.

8. Conclusion

8.1 Interpretation of Findings

The results of regression analysis show that the presence of intersections is the most important factor of device-normalized delay (DND). Because of how many intersections are compared on the calm route and the comparison route, the coefficient on Δ Intersections was 5.29 which indicates that while holding Δ ADT and Δ Signals, DND increases by 5.29 seconds per device for each additional intersection on the calm route on average. DND is positively correlated with intersection density, meaning that the greater the number of intersections on the route, the greater the delay of the traffic calming device.

In contrast, Δ ADT and Δ Signals are not statistically significant in the model. Confidence intervals include zero, and the coefficients are small as well as are estimated imprecisely. This implies that there is a lack of evidence within the dataset that average daily traffic and the differences in the number of signalized crossings systematically impact DND, all else equal. This strongly implies that, for the OD pairs examined in the current study, the intersection volume is much more significant than the traffic volume or signalization in determining the additional delay caused by traffic-calming measures.

8.2 Practical Implications

The analysis shows that traffic calming devices do increase travel time, but the important point is that this effect can be measured instead of just guessed. Using the device-normalized delay (DND),

we can estimate approximately how many extra seconds of delay are added when there are more intersections and calming devices on a route. In other words, drivers and planners can forecast the travel-time impact of different design alternatives rather than relying on judgment alone.

Balancing safety and efficiency are always a challenge for transport agencies. There is certainly a trade-off in time when implementing traffic calming measures for the safety and protection of pedestrians and cyclists versus the time taken for drivers and bus users to reach their destination. The level of optioneering and trade-off analysis in designing is not always a gut feeling. Measures such as DND allow agencies to identify whether it is better to implement calming devices on uninterrupted streets or if the direct route safety trade-offs are worth the delay. DND measures the safety and speed of route alternatives and allows agencies to build routes based on justifiable, efficient, and safe routes. The transparent nature of evidence improves the more effective DND tradeoffs. This improves the ability for agencies to be systematic and rational in implementing traffic calming.

8.3 Limitations

Several limitations for this study should be considered while analyzing the results. Firstly, the sample size is quite small with only 30 observations. This limited sample size means that estimates become highly contingent on single observations; meaning results may not be fully applicable to other cities or network configurations. Increasing the sample size would make stability of coefficients, assessing other variables, or additional testing of interaction effects possible.

Secondly, this analysis is based on outcomes estimated using a linear regression model, which assumes that the relationship between DND and each explanatory variable is linear. Additionally, the model assumes that all observations are independent of one another. However, some of the variables included in the analysis (such as intersections, traffic volume, and signals) may introduce a non-linear effect on the overall delay.

Finally, the study uses secondary data sources, specifically the approximate travel times derived from Google Maps, approximations of vehicle traffic taken from websites, and information regarding traffic calming devices gathered through the internet. All of these data sources that are

convenient and widely accepted, but, of course, can be erroneous and may be influenced by unusual conditions, such as atypical congestion, accidents affecting traffic, or atypical driving behavior for the given weekday. Moreover, there are no professional-grade instruments, nor field studies that would allow measuring speeds, delays, or conditions of the study routes. The lack of field verification of the data collected online means that the actual data for the road and traffic conditions may be highly erroneous. These conditions indicate that the results are likely inconclusive, and therefore, there is a need for other research that incorporates field work and additional secondary data. Field work and other secondary data would greatly complement the research approach taken here.

8.4 Future Work

There are several ways this study can be improved and expanded upon in the future. First, expanding our datasets to add more OD pairs and extra cities would be useful. In this case, a larger and more diverse sample would make the results more generalizable and help us determine if a strong effect of intersection density on DND exists in other diverse urban forms, traffic patterns, and policy contexts.

Furthermore, additional explanatory variables, in the form of non-linear regression, might be more suitable for assessing the intersections. It could be that the relationship between traffic calming and the delay is indeed non-linear, and that other design characteristics of the intersections are critical as well. A pertinent example is the study by Dumbaugh and Li^[30], which demonstrated that an additional foot of lane width is statistically associated with an increase of 2.9 mph of operational speed. It is, therefore, hoped that other variables and the ones related to the current study, such as lane width, posted speed limits, lane count, and presence of on-street parking, will be included in future studies. It is possible that non-linear models, or more appropriately for this, machine learning, will explain better some of the complexities closing the relationship of the variables in question.

Lastly, future studies could focus on primary data collection rather than just secondary sources. In the presence of sufficient funding, it would also be realistic to acquire basic detection instruments (e.g. portable traffic control devices, and speed detectors) and evaluate the study's routes. This

would focus on estimating the primary data regarding the traffic situation, the delays and speed, and the accuracy of Google Maps time estimations. Furthermore, there could be field surveys, i.e. questionnaires or remote interviews, directed towards the public as drivers/passengers to assess their perception of delays and safety on route segments with and without traffic control. If appropriate data collection instruments are implemented, alongside direct observations and public input, the effect of traffic calming devices could be significantly enhanced.

REFERENCES

- [1] Module 2: Traffic Calming Basics | FHWA. (n.d.). Retrieved November 21, 2025, from highways.dot.gov website: <https://highways.dot.gov/safety/speed-management/traffic-calming-eprimer/module-2-traffic-calming-basics>
- [2] Dan Woomer. (2018, January 13). Linthicum Shipley Improvement Association Inc. Retrieved December 2, 2025, from Linthicum Shipley Improvement Association Inc website: <https://www.lsia.net/news/2018/1/13/speed-humps-pros-cons>
- [3] Yuan, L., Yuan, H. W., Ma, Y. F., & Ren, Y. W. (2014). Development of a safety evaluation model for provincial highway. *Discrete dynamics in nature and society*, 2014(1), 394846.
- [4] Hullinger, J., & Hullinger, J. (2024, March 12). *How ‘daylighting’ helped Hoboken make its streets safer—and how other cities can follow its lead*. Fast Company. <https://www.fastcompany.com/91055859/how-daylighting-helped-hoboken-make-its-streets-safer-and-how-other-cities-can-follow-its-lead>
- [5] National Association of City Transportation Officials. (2024, December 12). Curb extensions NACTO. <https://nacto.org/publication/urban-street-design-guide/street-design-elements/curb-extensions/>
- [6] Curb extensions: Enhancing Pedestrian Safety with Curb Extensions - FasterCapital. (n.d.). FasterCapital. <https://fastercapital.com/content/Curb-extensions--Enhancing-Pedestrian-Safety-with-Curb-Extensions.html>
- [7] Impact Threshold Curve. (2012, February 2). Retrieved November 2, 2025, from NACTO website: <https://nacto.org/wp-content/uploads/City-of-Portland-2011.pdf>
- [8] Chimba, D., & Mbuya, C. (2019). Simulating the Impact of Traffic Calming Strategies. Transportation Research Center for Livable Communities. Retrieved from Transportation Research Center for Livable Communities website: https://files.wmich.edu/s3fs-public/attachments/u883/2019/TRCLC_RR_17-10.pdf
- [9] China National Standard. (2024). Safety technical specification for electric bicycles (GB 17761-2024). Standardization Administration of China.
- [10] China Radio International. (2019, December 24). Beijing extends iconic Wangfujing

pedestrian street. <http://news.cri.cn/2019-12-24/223bba9d-fdde-6a3d-de70-df70f8aa5e08.html>

- [11] Guo, Y., Li, Z., Liu, Y., & Liu, P. (2021). The effect of "yield to pedestrians" policy enforcement on pedestrian street crossing behavior: A 3-year case study in Xi'an, China. *Case Studies on Transport Policy*, 9(2), 852-861.
- [12] Huawei Enterprise. (2019). Shenzhen Traffic Police Bureau and Huawei jointly create a futuristic 'city-wide traffic brain' for safe city driving. <https://e.huawei.com/topic/leading-new-ict-jp/shenzhen-traffic-police.html>
- [13] Li, L., Chen, Y., & Li, Z. (2016). Effects of parallelogram-shaped pavement markings on vehicle speed and safety of pedestrian crosswalks on urban roads in China. *Accident Analysis & Prevention*, 95, 438-447.
- [14] Li, W., Huang, J., & Wang, Z. (2022). An adaptive traffic-calming measure and effectiveness evaluation in a large urban complex of Shanghai, China. *Sustainability*, 14(20), Article 13023.
- [15] Liu, H. (2018, July). Can Chinese cities leave the car behind? Gridlock, pollution and the future of public transportation. *Asia-Pacific Journal: Japan Focus*, 16(14).
- [16] Liu, J. (2010). Case study: Wuhan implements model junction channelisation for pedestrians. International Road Assessment Programme, Road Safety Toolkit. <https://toolkit.irap.org/case-studies/case-study-wuhan-implements-model-junction-channelisation-for-pedestrians-china/>
- [17] Liu, T., & Circella, A. (2018). Can Chinese cities leave the car behind? Gridlock, pollution and the future of public transportation. *Asia-Pacific Journal*, 16(14).
- [18] Ministry of Housing and Urban-Rural Development. (2012). Code for design of urban road engineering (CJJ 37-2012). China Architecture & Building Press.
- [19] Shanghai Urban Planning and Land Resources Administration Bureau. (2016). Shanghai street design guidelines. Tongji University Press.
- [20] State Council of the People's Republic of China. (2015, February). Opinions on further strengthening urban planning and construction management. http://www.gov.cn/zhengce/2016-02/21/content_5044367.htm

- [21] Synced Review. (2018, April). AI photographs Chinese jaywalkers; shames them on public screens. Medium. <https://medium.com/syncedreview/ai-photographs-chinese-jaywalkers-shames-them-on-public-screens-ad0a301a46a6>
- [22] Tan, Y., Wei, X., & Zhou, J. (2010). First engineering practice of traffic calming in Zhaitang Town in China. In *Proceedings of the IEEE 2nd International Conference on Information Engineering and Computer Science* (pp. 1-4). IEEE.
- [23] Wang, H., Smith, G., Deng, C., & Ezaki, C. (2012). Speed enforcement in China: National, provincial and city initiatives and their success. *Traffic Injury Prevention*, 13(4), 305-312.
- [24] World Bank. (2010). Wuhan Urban Transport Project: Technical assistance completion report (Report No. 495620). World Bank.
- [25] World Health Organization. (2018). *Global status report on road safety 2018*. WHO Press.
- [26] Worldcrunch. (2018, June). How do Chinese people cross the road? On jaywalking, poor planning, bad attitudes. <https://worldcrunch.com/culture-society/how-do-chinese-people-cross-the-road-on-jaywalking-poor-planning-bad-attitudes/>
- [27] Zhang, L., Wang, T., & Li, H. (2022). Countermeasures for urban traffic congestion in China from the perspective of system dynamics. *Computational Intelligence and Neuroscience*, 2022, Article 3509902.
- [28] Zhang, Z. (2013, April). Jaywalking in China and New York City: The pot calling the kettle black. Safe Kids Worldwide Blog. <https://www.safekids.org/blog/jaywalking-china-and-new-york-city-pot-calling-kettle-black>
- [29] Magkafas, F., Fountas, G., Anastasopoulos, P. C., & Basbas, S. (2025). Beyond Speed Reduction: A Systematic Literature Review of Traffic-Calming Effects on Public Health, Travel Behaviour, and Urban Liveability. *Infrastructures*, 10(6), 147. <https://doi.org/10.3390/infrastructures10060147>
- [30] Dumbaugh, E., & Li, W. (2010). Designing for the safety of pedestrians, cyclists, and motorists in urban environments. *Journal of the American Planning Association*, 77(1), 69–88. <https://doi.org/10.1080/01944363.2011.536101>

APPENDICES

Appendix A

Table 5: 30 Dataset for Regression Analysis

Δ DND	Δ ADT	Δ Intersections	Δ Signals
2.83	777	3	2
-3.846	2684.5	-2	-1
-12.67	866.5	-2	-4
-46.15	1216	-3	-1
21.81	714	0	1
5.12	842	2	1
-9.34	-1267	-1	-2
7.89	1634	1	0
12.46	2158	3	2
-6.73	-854	-2	-1
18.65	2431	2	3
-13.27	-1789	-3	-2
9.03	1986	1	1
15.72	2244	2	0
-16.88	1894	-3	-3
4.76	734	1	0
20.19	2579	3	2
-10.84	-1123	-1	-3
8.57	1752	0	1
3.28	564	1	-1
-25.63	-2318	-4	-4
11.93	2087	2	2
19.77	2695	3	1
-4.59	-932	-1	0
14.21	2368	2	1
3.91	815	0	-1
-12.53	-1674	-2	-2
16.38	2489	3	2
7.44	1486	1	-1
-29.47	-2193	-4	-3

Appendix B

R Code Used for Modeling

```
# Step 1: Import Excel and organize variables
```{r setup, include=FALSE}
library(readxl)
library(dplyr)
library(ggplot2)
library(tidyr)
df_raw <- read_excel("Transportation Project Dataset (Xin He).xlsx",
 sheet = 1)

df <- df_raw %>%
 transmute(
 DND = as.numeric(`DND-diff`),
 Delta_ADT = as.numeric(`ADT-diff`),
 Delta_Intersections = as.numeric(`Intersections-diff`),
 Delta_Signals = as.numeric(`Signals-diff`)
) %>%
 drop_na()
print(dim(df))
print(summary(df))
```

# Step 2: Linear regression model
```{r}
model <- lm(DND ~ Delta_ADT + Delta_Signals + Delta_Intersections,
 data = df)
summary(model)
```

# Step 3: Coefficient confidence interval
```{r}
confint(model)
```

# Step 4: Diagnostic diagram
```{r}
par(mfrow = c(2, 2))
plot(model)
par(mfrow = c(1, 1))
```

# Step 5: Standardized regression (Checking relative importance)
```{r}
model_std <- lm(
 scale(DND) ~ scale(Delta_ADT) + scale(Delta_Signals) + scale(Delta_Intersections),
 data = df
)
summary(model_std)
```

# Step 6: DND vs Delta Signals
```{r}
ggplot(df, aes(x = Delta_Signals, y = DND)) +
 geom_point(color = "steelblue", size = 3) +
 geom_smooth(method = "lm", se = TRUE, color = "red", linewidth = 1) +
 labs(
 title = "Relationship Between Signals-diff and DND",
 x = "Signals Difference",
 y = "Device-Normalized Delay (sec/device)"
) +
 theme_minimal(base_size = 15)
```
```

```
# Step 7: DND vs Delta Intersections
```

```
```{r}
ggplot(df, aes(x = Delta_Intersections, y = DND)) +
 geom_point(color = "darkgreen", size = 3) +
 geom_smooth(method = "lm", se = TRUE, color = "red", linewidth = 1) +
 labs(
 title = "Relationship Between Intersections-diff and DND",
 x = "Intersection Difference",
 y = "Device-Normalized Delay (sec/device)"
) +
 theme_minimal(base_size = 15)
```
```

```
# Step 8: DND vs Delta ADT
```

```
```{r}
ggplot(df, aes(x = Delta_ADT, y = DND)) +
 geom_point(color = "purple", size = 3) +
 geom_smooth(method = "lm", se = TRUE, color = "red", linewidth = 1) +
 labs(
 title = "Relationship Between ADT-diff and DND",
 x = "ADT Difference (vehicles/day)",
 y = "Device-Normalized Delay (sec/device)"
) +
 theme_minimal(base_size = 15)
```
```