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ROAD SAFETY

FINAL REPORT

A Systems Approach to Pedestrian Safety, PHASE II: Using System Dynamics Tools to Examine Congestion Pricing Policies

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16. Abstract

Pedestrian deaths in the U.S. have increased substantially over the last several years. Between 2009 and 2019, the number of pedestrian deaths increased 51%, from 4,109 to 6,205. The majority of these deaths (82%) occurred in urban areas. In a previous project (Phase 1 of this work), we engaged a diverse range of experts familiar with different aspects of pedestrian injury and death in the application of qualitative systems science tools to explore hypothesized and interconnected factors underlying the overall increase in pedestrian death rates. Detailed maps were created to depict these interconnections and clearly lay out the hypothesized mechanisms causing pedestrian death increases. The overall goal of this Phase 2 project was to develop a quantitative system dynamics simulation model that could be used as a learning tool to explore the pedestrian safety impacts of specific, current policy approaches in a defined U.S. setting. Given the recent focus and proposed implementation of congestion pricing policies in the U.S. (and specifically in New York City), we chose to explore the pedestrian safety impacts of these policies, illustrating how system dynamics tools can be used to create virtual learning environments and explore potential system-wide effects of policies prior to implementation. To inform the model we also completed a bibliometric analysis of congestion pricing policy research broadly, as well as a detailed review of congestion pricing policy studies focused on safety impacts. These reviews and analyses illuminated several key gaps for future research consideration, including gaps in equity considerations of these policies, policy impacts on specific road user types (e.g., pedestrians, bicyclists), and safety impacts for all road users. Our system dynamics model leveraged findings from these detailed reviews, as well as findings from Phase 1 of this work and a variety of data sources from New York City to examine potential congestion pricing policy impacts on pedestrian safety. We explored a variety of congestion pricing policy-related scenarios, examining differences in how such policies might be configured and revenue invested. While several of the policy scenarios resulted in similar congestion reductions, there was considerable variation in the pedestrian injury outcomes by scenario type. Some scenarios (e.g., scenarios that discontinued or reduced pedestrian infrastructure support or increased charges on for-hire vehicles) had deleterious effects on pedestrian injury counts, while others (e.g., scenarios investing a proportion of policy revenue in pedestrian infrastructure improvements pre- and/or post-policy implementation) offered improvements in pedestrian safety. A key policy take-away from this work is that a CPP combined with other pedestrian efforts has considerable potential for positive gains in public health. The full model is available to explore at: https://exchange.iseesystems.com/public/beckynaumann/cpp-and-pedestrian-injury/index.html#page1.

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Contents

Introduction

Pedestrian deaths in the U.S. have increased substantially over the last several years. Between 2009 and 2019, the number of pedestrian deaths increased 51%, from 4,109 to 6,205. The largest increase in death rates (38%) across this time occurred among those ages 20-69 years, from 1.6 to 2.3 deaths per 100,000 population, and the majority of these deaths (82%) occurred in urban areas (Insurance Institute for Highway Safety & Highway Loss Data Institute, 2021).

In a previous project (Phase 1 of this work), we engaged a diverse range of experts familiar with different aspects of pedestrian injury and death in the application of qualitative systems science tools to explore hypothesized and interconnected factors underlying the overall increase in pedestrian death rates. Through this work, experts discussed core factors having a direct impact on pedestrian deaths, including numbers of pedestrian-vehicle crashes, vehicle speed at the time of the crash, vehicle size/dimensions, and emergency response time. Building from that, they further explored how actions and reactions involving those core, proximal factors could lead to ripple effects throughout a larger system to generate increases in deaths over time. Hypothesized contributors within this broader system included factors in the following categories: community responses; research, policy, and industry influence; potential unintended consequences of responses to pedestrian deaths; and the role of sprawl. Detailed maps were created to depict these interconnections and clearly lay out the hypothesized mechanisms causing pedestrian death increases (Naumann, 2020). The full, synthesized map from this work is attached in Appendix 1.

What is a system?

"an interconnected set of elements that is coherently organized in a way that achieves something… A system must consist of three kinds of things: elements, interconnections and a function or purpose." (Meadows, 2008, p. 11).

This foundational work generated several insights. Specifically, the project: 1) helped experts and participants appreciate the complexity of the issue and broadened their perspective on potential contributors and intervention points; 2) demonstrated how systems methods and tools can support a rich forum to discuss and carefully describe competing goals, biases, and norms within our transportation system (e.g., speed vs. safety goals; biases in infrastructure decision-making; and distracted driving norms); and 3) assisted experts in recognizing and appreciating feedback processes (i.e., chains of causal factors that ripple through systems to further amplify or mitigate an outcome) and delays contributing to outcomes over time. While this work served as a key first step in collecting diverse hypotheses from a variety of perspectives, it was also recognized that there is considerable community-specific variation in pedestrian safety and likely also in the dynamic systems driving outcomes in different settings. Therefore, the initial systems maps and hypotheses can be viewed as broad maps of several potential feedback structures. While they serve as a valuable basis for future context and policy-specific testing, they are likely not all relevant to any one context or setting.

Therefore, the overall goal of this Phase 2 project was to develop a quantitative system dynamics simulation model that could be used as a learning tool to explore the pedestrian safety impacts of specific, current policy approaches in a defined U.S. setting. Given the recent focus and proposed implementation of congestion pricing policies (CPPs) in the U.S., we chose to specifically explore the pedestrian safety impacts of these policies, illustrating how system dynamics tools can be used to create virtual learning environments and explore potential system-wide effects of policies prior to implementation. There are a number of ways that CPPs might impact pedestrians and other vulnerable road users: 1. CPPs could lead to fewer vehicle trips, fewer opportunities for crashes with pedestrians, and overall reductions in injuries among pedestrians; 2. As vehicle users shift to other travel modes (e.g., bicycling, walking) in response to a CPP, numbers of injuries among these groups could increase as a greater number of people are exposed to traffic as vulnerable road users; 3. Reductions in congestion and traffic density could lead to faster travel speeds which could increase both the likelihood and severity of motor vehicle crashes involving pedestrians.

In this project, we both integrated key Phase 1 hypotheses and findings, as well as recent and specific literature and data related to congestion pricing. Below, we first define and provide an overview of congestion pricing, and then describe the objectives and methods of this project.

What is Congestion Pricing?

According the Federal Highway Administration, congestion pricing is “a way of harnessing the power of the market to reduce the waste associated with traffic congestion. Congestion pricing recognizes that trips have different values at different times and places and for different individuals. Faced with premium charges during periods of peak demand, road users are encouraged to eliminate lower-valued trips, take them at a different time, or choose alternative routes or transport modes where available.”(*FHWA Congestion Pricing Web Site - Congestion Pricing - FHWA Office of Operations*, 2021).

There are a number of congestion pricing strategies that are employed, often grouped according to whether or not they involve tolls. Strategies to reduce vehicle use and congestion that do not involve tolls include parking pricing, dynamic ridesharing and priced vehicle sharing, and pay as you drive policies. For more information, please see the following references (Federal Highway Administration, 2021c, 2021e, 2021d). Often more popular and utilized are strategies involving tolls. Congestion pricing strategies involving use of tolls have varying levels of implementation across the U.S. (DeCorla-Souza, 2008) and include:

- **High Occupancy Toll (HOT) Lanes.** These often involve converting high-occupancy vehicle (HOV) lanes into priced lanes, or building entirely new HOT lanes. Generally, under this type of strategy, people can buy into a HOV lane, despite not having multiple travelers. HOT lanes can improve use of sometimes underutilized HOV lanes and remove traffic from congested, regular lanes. Evaluations and project reports from Washington, Minnesota, and other states are available here: https://ops.fhwa.dot.gov/congestionpricing/strategies/involving_tolls/hot_lanes.htm (Federal Highway Administration, 2021b).
- **Express Toll Lanes** similarly involve creation of new lanes or conversion of a previous lane, generally occurring during highway expansion, such that the new lanes require a fee to gain access, with preference often provided for HOVs (e.g., free or reduced tolls for vehicles with multiple passengers). Examples of these projects are located here: https://ops.fhwa.dot.gov/congestionpricing/strategies/involving_tolls/exp_toll_lanes.htm (Federal Highway Administration, 2021a).
- **Pricing on Entire Roads.** This includes a toll across an entire roadway facility, e.g., across a bridge, tunnel, or roadway. The toll generally involves differential pricing to reduce congestion. Examples from Washington and other states can be seen here: https://ops.fhwa.dot.gov/congestionpricing/strategies/involving_tolls/entire_roadway.htm (Federal Highway Administration, 2021f).
- **Zone-based Pricing.** This can involve either cordon (charge to drive into a defined, congested area of the city) or area (per-mile charge on all roads within a defined, congested area) pricing and involve either variable or fixed charges. These projects therefore involve placing new tolls on multiple, currently free of charge, roads and therefore can often experience political and/or public resistance. These types of projects have been implemented in several large cities across the world (e.g., London, Manchester, Stockholm, Milan). Other example projects and city-specific feasibility studies can be found here: https://ops.fhwa.dot.gov/congestionpricing/strategies/involving_tolls/zone_based.htm (Federal Highway Administration, 2021h).
- **Regionwide Pricing**. This strategy involves pricing at several locations within a large region and can include pricing on new lanes or road facilities, or pricing on existing lanes and facilities. The

only pricing program of this scale exists in Singapore, although feasibility studies have been conducted in the U.S. https://ops.fhwa.dot.gov/congestionpricing/strategies/involving_tolls/regionwide.htm (Federal Highway Administration, 2021g).

While many cities and states across the U.S. utilize HOT, HOV, and express lane pricing, as well as tolls on entire roadway facilities, currently no locations in the U.S. utilize a larger regionwide pricing scheme. However, several cities are exploring zone-based pricing strategies, given increased application in large non-U.S. cities. Manhattan, New York currently has plans to implement zone-based pricing in 2022, and San Francisco and Los Angeles, among other U.S. cities, have or are in the process of conducting feasibility studies of zone-based pricing. Given the increased popularity of zone-based pricing strategies across multiple U.S. cities, coupled with increasing pedestrian death rates across the U.S., this project sought to explore the pedestrian safety impacts of this policy from a system dynamics perspective, providing an appropriate tool to take into account the complexity of the transportation system.

Project Objectives

The specific objectives of this project were to:

- Understand and summarize the current evidence base around congestion pricing policies (CPPs), specifically toll-based pricing policies.
- Develop a system dynamics learning model to explore zone-based congestion pricing impacts on pedestrian safety, as well as other system-wide metrics (e.g., vehicles traveling into a congestion pricing zone, rates of injury).
- Incorporate relevant Phase 1 project findings (interconnected factors and hypothesized system behavior producing pedestrian safety trends) into the system dynamics simulation model.
- Engage pedestrian safety and/or congestion pricing experts throughout model development to ensure creation of a stakeholder-relevant learning model that can illustrate key insights about the system dynamics approach, congestion pricing dynamics, and what would be needed to fully calibrate and validate the model for a given location.
- Develop a user-friendly version of the model that can be disseminated and used to demonstrate how system dynamics models can be used as powerful tools to facilitate transportation policy and intervention conversations.

To accomplish these objectives, the project was completed in **three core parts**:

- To explore and understand the toll-based congestion pricing literature, we first completed a bibliometric analysis to summarize research output, trends, patterns, and gaps in the evidence base.
- We then honed in on the current evidence base of safety-related impacts of these policies. To do this, we conducted a systematic search and scoping review of all research on toll-based CPP impacts on road user safety, examining a variety of crash- and injury-related outcomes.
- Using the evidence base as a foundation, along with our Phase 1 findings, we completed the third part of this project, which involved building a system dynamics learning model to explore the potential pedestrian safety impacts of a zone-based CPP under a range of scenarios. We built a user-friendly interface to allow users to explore the model and interact with the policy simulator to test different approaches.

Below, we present the objectives, methods, results, and conclusions for each of these three project parts. We then end with a discussion of key overarching takeaways and next steps.

Part 1: A Bibliometric Analysis of Toll-based Congestion Pricing Policy Research

A full manuscript detailing this piece of the project is under review: Singichetti B, Conklin JL, Dodd A, Hassmiller Lich K, Sabounchi NS, Naumann RB. Trends and Insights from Congestion Pricing Policy Research: A Bibliometric Analysis. Under review at *Transportation*. 2021.

The objective, methods, results, and key findings are summarized below.

Objective

To examine and characterize research output and patterns surrounding toll-based congestion pricing policies (CPPs), across several domains using novel bibliometric analysis methods.

Methods

To understand the historical research landscape of toll-based CPPs, we first conducted a structured search of the following databases from their dates of inception through February 7, 2021: Transport Research International Documentation (TRID), Web of Science, PubMed, and Scopus. Using the definitions of toll-based policies as outlined by the US Federal Highway Administration (described above in greater detail), we constructed a detailed list of search terms, as shown in Table 1, with the help of a university librarian with extensive expertise in systematic reviews and bibliometric analyses. Filters in each database were also used to match the following inclusion criteria: 1) peer-reviewed publications or reports, 2) abstract/summary in English, 3) examined a road traffic-related toll-based CPP. Additionally, studies were required to have a pricing component and a traffic congestion component. Studies were excluded if they did not mention a CPP, included only non-toll-related policies, or were in the format of news articles, project proposals, books, or book chapters.

Table 1. Search terms used for structured search of toll-based congestion pricing policies

Set #	Search Terms
	Scopus
1	TITLE-ABS-KEY (("congestion pricing" OR "congestion prices" OR "congestion price" OR "congestion charging" OR "congestion charges" OR "congestion charge" OR "congestion tax" OR "congestion taxes" OR "congestion taxing" OR "congestion fee" OR "congestion fees" OR "congestion toll*" OR "congestion subsidy" OR "congestion subsidies" OR "congestion policy" OR "congestion policies" OR "congestion strategy" OR "congestion strategies" OR "congestion zone" OR "congestion zones" OR cordon OR "Zone-based pricing" OR "zonal-based pricing" OR "Zone-based charg*" OR "zonal-based charg*" OR "zone pricing" OR "zone charg*" OR "zonal charg*" OR "zonal scheme" OR "zonal schemes" OR "zone scheme" OR "zone schemes" OR "distance-based pricing" OR "area-based pricing" OR "area-wide charg*" OR "area-based charg*" OR "per-mile pricing" OR "per-mile charg*" OR "network pricing" OR "mileage-based user fee" OR "mileage-based user fees" OR "entry-based pricing" OR "variable pricing lane" OR "price managed lane" OR "price managed lanes") AND (traffic OR transportation OR road OR roads OR highway OR highways OR automobile OR automobiles OR car OR cars OR vehicle OR vehicles))
2	TITLE-ABS-KEY ("road pricing" OR "road value pricing" OR "road charging" OR "road charge" OR "road charges" OR "road user charge" OR "road user charges" OR "road use charge" OR "road use charges" OR "road use charging")
3	TITLE-ABS-KEY (("toll scheme" OR "toll schemes" OR "tolling scheme" OR "tolling scheme" OR "distance-based toll" OR "distance-based tolls" OR "distance-based tolling" OR "variable toll" OR "variable tolls" OR "variable tolling" OR "dynamic toll" OR "dynamic tolls" OR "dynamic tolling") OR ((tolls OR tolling OR "high occupancy vehicle lane" OR "high occupancy vehicle lanes") AND (traffic OR road OR roads OR highway OR highways OR automobile OR automobiles OR car OR cars OR vehicle OR vehicles) AND (congestion OR congested OR "transportation demand management" OR "traffic demand management")))
4	#1 OR #2 OR #3
5	AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "rp"))
	Web of Science

1	TS=(("congestion pricing" OR "congestion prices" OR "congestion price" OR "congestion charging" OR "congestion charges" OR "congestion charge" OR "congestion tax" OR "congestion taxes" OR "congestion taxing" OR "congestion fee" OR "congestion fees" OR “congestion toll*” OR "congestion subsidy" OR "congestion subsidies" OR “congestion policy” OR “congestion policies” OR “congestion strategy” OR “congestion strategies” OR “congestion zone” OR “congestion zones” OR cordon OR “Zone-based pricing” OR “zonal-based pricing” OR “Zone-based charg*” OR “zonal-based charg*” OR “zone pricing” OR “zone charg*” OR “zonal charg*” OR “zonal scheme” OR “zonal schemes” OR “zone scheme” OR “zone schemes” OR “distance-based pricing” OR “area-based pricing” OR “area-wide charg*” OR “area-based charg*” OR “per-mile pricing” OR “per-mile charg*” OR “network pricing” OR “mileage-based user fee” OR “mileage-based user fees” OR “entry-based pricing” OR “variable pricing lane” OR “price managed lane” OR “price managed lanes”) AND (traffic OR transportation OR road OR roads OR highway OR highways OR automobile OR automobiles OR car OR cars OR vehicle OR vehicles))
2	TS=(“road pricing” OR “road value pricing” OR “road charging” OR “road charge” OR “road charges” OR “road user charge” OR “road user charges” OR “road use charge” OR “road use charges” OR “road use charging”)
3	TS=((“toll scheme” OR “toll schemes” OR “tolling scheme” OR “tolling scheme” OR “distance-based toll” OR “distance-based tolls” OR “distance-based tolling” OR “variable toll” OR “variable tolls” OR “variable tolling” OR “dynamic toll” OR “dynamic tolls” OR “dynamic tolling”) OR ((tolls OR tolling OR "high occupancy vehicle lane" OR "high occupancy vehicle lanes") AND (traffic OR road OR roads OR highway OR highways OR automobile OR automobiles OR car OR cars OR vehicle OR vehicles) AND (congestion OR congested OR “transportation demand management” OR “traffic demand management”)))
4	#1 OR #2 OR #3
5	AND Refined by: DOCUMENT TYPES: (ARTICLE OR EARLY ACCESS)
	TRID
1	("congestion pricing" OR "congestion prices" OR "congestion price" OR "congestion charging" OR "congestion charges" OR "congestion charge" OR "congestion tax" OR "congestion taxes" OR "congestion taxing" OR "congestion fee" OR "congestion fees" OR “congestion toll*” OR "congestion subsidy" OR "congestion subsidies" OR “congestion policy” OR “congestion policies” OR “congestion strategy” OR “congestion strategies” OR “congestion zone” OR “congestion zones” OR cordon OR “Zone-based pricing” OR “zonal-based pricing” OR “Zone-based charg*” OR “zonal-based charg*” OR “zone pricing” OR “zone charg*” OR “zonal charg*” OR “zonal scheme” OR “zonal schemes” OR “zone scheme” OR “zone schemes” OR “distance-based pricing” OR “area-based pricing” OR “area-wide charg*” OR “area-based charg*” OR “per-mile pricing” OR “per-mile charg*” OR “network pricing” OR “mileage-based user fee” OR “mileage-based user fees” OR “entry-based pricing” OR “variable pricing lane” OR “price managed lane” OR “price managed lanes”) AND (traffic OR transportation OR road OR roads OR highway OR highways OR automobile OR automobiles OR car OR cars OR vehicle OR vehicles)
2	“road pricing” OR “road value pricing” OR “road charging” OR “road charge” OR “road charges” OR “road user charge” OR “road user charges” OR “road use charge” OR “road use charges” OR “road use charging”
3	(“toll scheme” OR “toll schemes” OR “tolling scheme” OR “tolling scheme” OR “distance-based toll” OR “distance-based tolls” OR “distance-based tolling” OR “variable toll” OR “variable tolls” OR “variable tolling” OR “dynamic toll” OR “dynamic tolls” OR “dynamic tolling”) OR ((tolls OR tolling OR "high occupancy vehicle lane" OR "high occupancy vehicle lanes") AND (traffic OR road OR roads OR highway OR highways OR automobile OR automobiles OR car OR cars OR vehicle OR vehicles) AND (congestion OR congested OR “transportation demand management” OR “traffic demand management”))
4	#1 OR #2 OR #3
5	#4 AND Limit to Journal Articles, Reports, and Serials
	PubMed
1	(("congestion pricing"[tiab] OR "congestion prices"[tiab] OR "congestion price"[tiab] OR "congestion charging"[tiab] OR "congestion charges"[tiab] OR "congestion charge"[tiab] OR "congestion tax"[tiab] OR "congestion taxes"[tiab] OR "congestion taxing"[tiab] OR "congestion fee"[tiab] OR "congestion fees"[tiab] OR “congestion toll”[tiab] OR “congestion tolls”[tiab] OR “congestion tolling”[tiab] OR "congestion subsidy"[tiab] OR "congestion subsidies"[tiab] OR “congestion policy”[tiab] OR “congestion policies”[tiab] OR “congestion strategy”[tiab] OR “congestion strategies”[tiab] OR “congestion zone”[tiab] OR “congestion zones”[tiab] OR cordon[tiab] OR “Zone-based pricing”[tiab] OR “zonal-based pricing”[tiab] OR “Zone-based charging[tiab]” OR “Zone-based charges[tiab]” OR “Zone-based charge”[tiab] OR “zonal-based charging”[tiab] OR “zonal-based charges”[tiab] OR “zonal-based charge”[tiab] OR “zone pricing”[tiab] OR “zone charging”[tiab] OR “zone charges”[tiab] OR “zone charge”[tiab] OR “zonal charging”[tiab] OR “zonal charges”[tiab] OR “zonal charge”[tiab] OR “zonal scheme”[tiab] OR “zonal schemes”[tiab] OR “zone scheme”[tiab] OR “zone schemes”[tiab] OR “distance-based pricing”[tiab] OR “area-based pricing”[tiab] OR “area-wide charging”[tiab] OR “area-wide charges”[tiab] OR “area-wide charge”[tiab] OR “area-based charging”[tiab] OR “area-based charges”[tiab] OR “area-based charge”[tiab] OR “per-mile pricing”[tiab] OR “per-mile charging”[tiab] OR “per-mile charges”[tiab] OR “per-mile charge”[tiab] OR “network pricing”[tiab] OR “mileage-based user fee”[tiab] OR “mileage-based user fees”[tiab] OR “entry-based pricing”[tiab] OR “variable pricing lane”[tiab] OR “price managed lane”[tiab] OR “price managed lanes”[tiab]) AND ("Transportation"[Mesh:NoExp] OR "Motor Vehicles"[Mesh] OR traffic[tiab] OR transportation[tiab] OR road[tiab] OR roads[tiab] OR highway[tiab] OR highways[tiab] OR automobile[tiab] OR automobiles[tiab] OR car[tiab] OR cars[tiab] OR vehicle[tiab] OR vehicles[tiab]))
2	(“road pricing”[tiab] OR “road value pricing”[tiab] OR “road charging”[tiab] OR “road charge”[tiab] OR “road charges”[tiab] OR “road user charge”[tiab] OR “road user charges”[tiab] OR “road use charge”[tiab] OR “road use charges”[tiab] OR “road use charging”[tiab])

3	(“toll scheme”[tiab] OR “toll schemes”[tiab] OR “tolling scheme”[tiab] OR “tolling scheme”[tiab] OR “distance-based toll”[tiab] OR “distance-based tolls”[tiab] OR “distance-based tolling”[tiab] OR “variable toll”[tiab] OR “variable tolls”[tiab] OR “variable tolling”[tiab] OR “dynamic toll”[tiab] OR “dynamic tolls”[tiab] OR “dynamic tolling”[tiab]) OR ((toll[tiab] OR tolls[tiab] OR tolling[tiab] OR "high occupancy vehicle lane"[tiab] OR "high occupancy vehicle lanes"[tiab]) AND ("Motor Vehicles"[Mesh] OR traffic[tiab] OR road[tiab] OR roads[tiab] OR highway[tiab] OR highways[tiab] OR automobile[tiab] OR automobiles[tiab] OR car[tiab] OR cars[tiab] OR vehicle[tiab] OR vehicles[tiab]) AND (congestion[tiab] OR congested[tiab] OR “transportation demand management”[tiab] OR “traffic demand management”[tiab]))
4	#1 OR #2 OR #3

Results from the search described above were screened for duplicates. Once duplicates were removed, we used Covidence (Veritas Health Innovation, Melbourne, Australia, available at www.covidence.org) to screen references. We used a two-phase automated approach that relied on semi-supervised and machine learning techniques to prioritize references for manual screening, using DoCTER software (Document Classification and Topic Extraction Resource).

In the first phase, we screened a random sample of 250 references to identify a set of relevant “seed” references, which were then used for supervised clustering in DoCTER. This approach produced an ensemble score (ES) for each reference (0=least relevant to 6=most relevant), and references with the highest scores (ES 3-6) were prioritized for manual screening (single screener per publication). In the second phase, we used machine learning to prioritize references with ES of 1 or 2 (references with ES of 0 were deemed irrelevant and removed). References screened manually in the first phase were used as training data, which was then used to determine a probability score for each reference. We then manually screened references starting with the highest probability scores until we reached probability scores of 0.421 (where relevance dropped off sharply).

Once final publications were identified, we used the VOSviewer application (Centre for Science and Technology Studies, Leiden University, The Netherlands, available at https://www.vosviewer.com/) to construct network maps of title and abstract terms, authorship collaborations (all publications), and country representation (for publications available in Scopus only). The size of nodes represented frequency, while the relative connectivity of nodes was represented by the lines connecting the nodes and the proximity of the nodes. Network maps with collaboration clusters and maps with time overlays were constructed for each of the three fields (i.e., title and abstract terms, authorship collaboration, and country representation).

Results

The initial search of the four databases using the search terms in Table 1 yielded 13,026 relevant publications. Following the removal of 3,390 duplicates and 4,409 that were deemed irrelevant due to low probability scores, there were 5,227 publications remaining for the screening process. 2,333 final publications were included in the bibliometric analysis after 2,894 were excluded by either machine learning or manual screening. As seen in Figure 1, publication dates ranged from 1956 to 2021, with the

Figure 1. Publications by Year

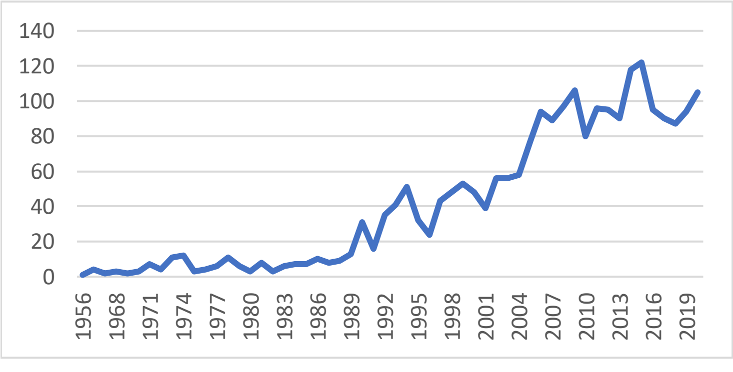
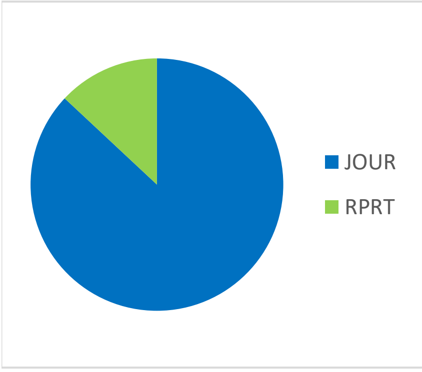


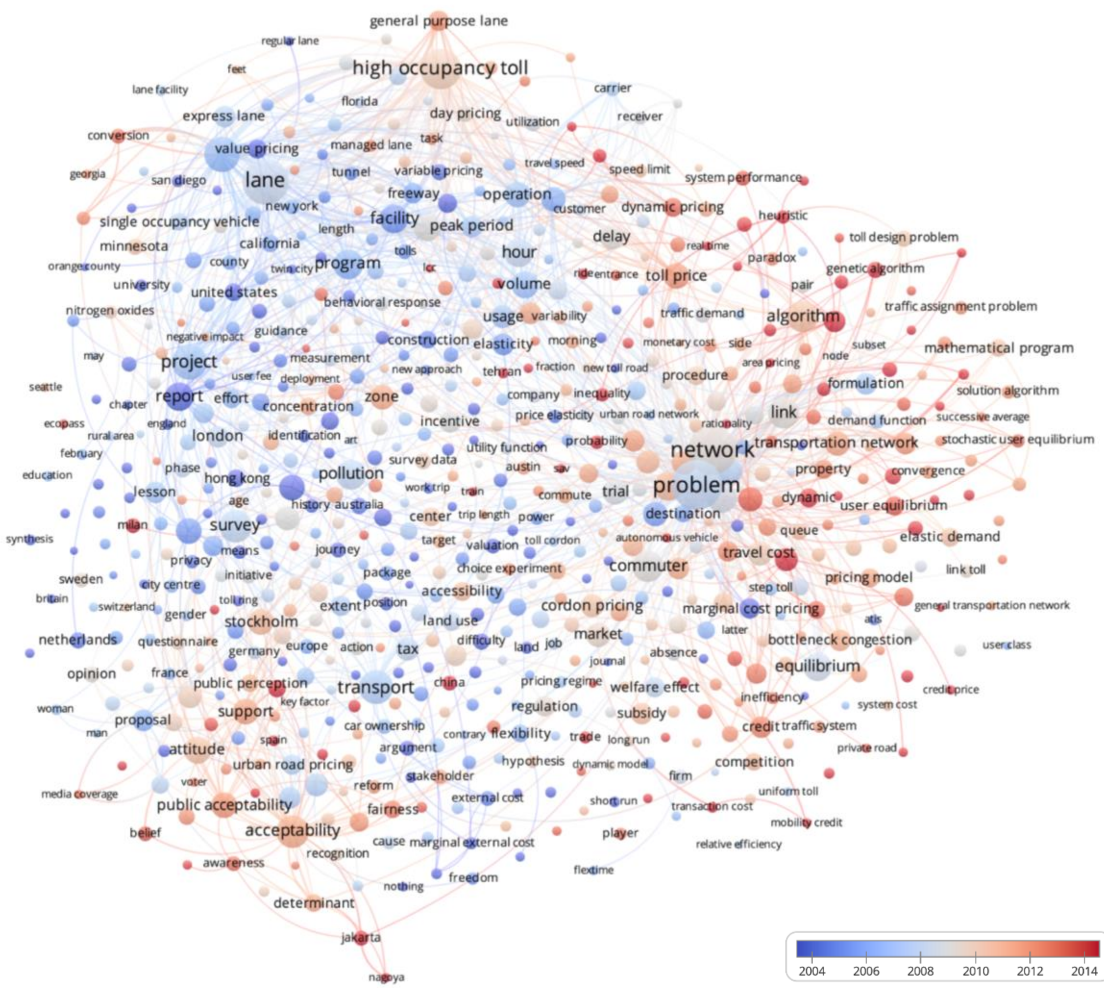
Figure 2. Document type



highest annual count in 2015 (n=122). The vast majority were peer-reviewed journal articles (about 87%; Figure 2).

Analysis of title and abstract terms identified ‘problem,’ ‘network,’ and ‘lane’ as the most common terms and identified seven distinct clusters of terms. The three largest clusters addressed the following topic areas: CPP types and structural implementation (e.g., ‘lane,’ ‘high occupancy toll,’ and ‘peak period’), transportation modeling methods and approaches (e.g., ‘network,’ ‘algorithm,’ and ‘link’), and population perceptions and relevant effects (e.g., ‘attitude,’ ‘acceptability,’ ‘pollution,’ and ‘external costs’). Analysis of patterns in term usage over time demonstrated a general shift from studies about implementation in the early 2000s to studies about acceptability and focused on different modelling and simulation approaches models after 2010 (Figure 3).

Figure 3. Title and abstract terms with time overlay



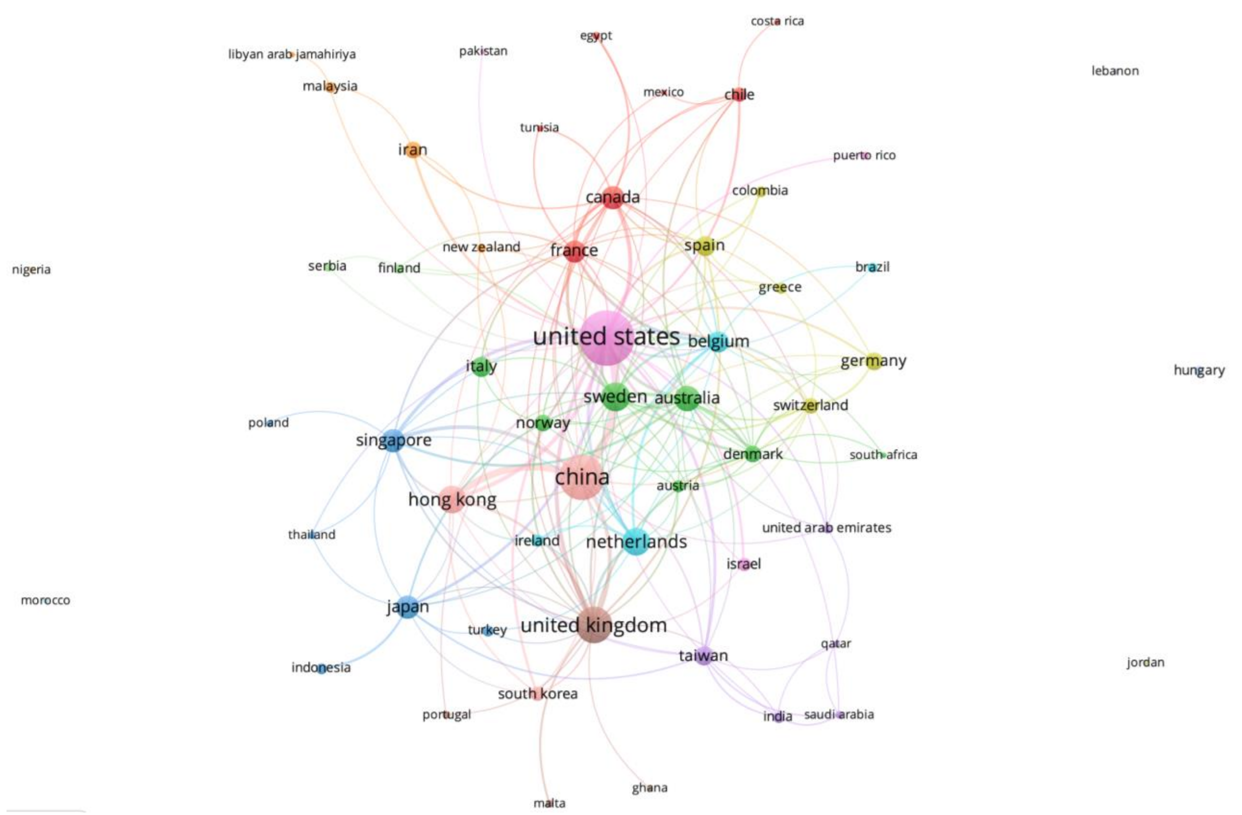
The authorship collaboration analysis identified 362 distinct authors (individuals and research groups/institutions) and 79 collaboration clusters. Transportation Research Board (n=37), Small KA (n=25), and the Texas Transportation Institute (n=16) were the most active authors/organizations with an average publication year prior to 2000. Burris MW (n=15), DeCorla-Souza P (n=14), and Mahmassani HS (n=12) were the most active authors with an average publication year between 2000 and 2004. Yang H (n=46), Verhoef ET (n=42), and Yin Y (n=28) were the most active authors with an average publication year 2005 onwards. Topic and themes of the publications by these active authors are listed in Box 1.

Box 1. Key topics and themes from most active authors

- Introductions to and descriptions of CPPs
- Evaluations and case studies of existing CPPs
- Considerations for implementation (e.g., potential barriers such as political and public acceptability, planning strategies, and design issues)
- Traveler choices in CPP networks
- Implications of CPPs (e.g., air quality, energy use, equity)
- Financial and economic aspects (e.g., revenue)
- Toll price elasticity
- Studies using simulations and modeling methods for examining aspects of CPPs, including time-varying tolls and dynamic pricing, and strategies for optimization and efficiency

Patterns of country representation (based on co-author countries) indicated that the top three represented countries were the US (n=439), China (n=265), and the United Kingdom (UK; n=154). Figure 4 displays the identified collaboration clusters of countries. The US was observed in its own cluster, despite having a high degree of relational connectivity with countries such as Sweden, Australia, and Belgium. The UK was productive in earlier years (average publication year = 2005), after which patterns shifted towards the US, the Netherlands, Canada, France, and Hong Kong by 2009. The average publication year for Sweden and Australia was around late 2011/early 2012. Countries such as Indonesia, India, and Puerto Rico have started to appear more recently in published research.

Figure 4. Country collaboration networks



Conclusions

We sought to understand the scope of existing research on toll-based CPPs and found that the number of publications grew significantly between 1956 and 2021, with highest productivity in 2015 (n=122).

Prevalent topic areas within toll-based CPP literature included the following: factors affecting policy implementation (e.g., design consideration, public perceptions, political acceptability), simulation modeling approaches to understand network dynamics, and impacts of CPP implementation (e.g., traveler choices, air quality/emissions). There were numerous collaborations between authors from different countries, and we observed notable shifts in research productivity by country, as different countries consider these policies. Research gaps identified by this analysis included equity considerations, examination of CPP impacts on specific road user types (e.g., pedestrians, bicyclists), and safety impacts for all road users. Future research should address these gaps with multidisciplinary and international collaborations to support CPP implementation that meets the needs of diverse communities and travel modes.

Part 2: A Systematic Search and Scoping Review of Toll-based Congestion Pricing Policy Impacts on Road User Safety

A full manuscript detailing this piece of the project is in press: Singichetti B, Conklin JL, Hassmiller Lich K, Sabounchi N, Naumann RB. Congestion Pricing Policies and Safety Implications: A Scoping Review. *Journal of Urban Health*. 2021.

The objective, methods, results, and key findings are summarized below.

Objective

To synthesize findings from publications examining toll-based congestion pricing policy (CPP) impacts on road user safety outcomes.

Methods

To better understand the implications of toll-based CPPs on road user safety specifically, we conducted a scoping review, following protocols described by Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) guidelines. Toll-based CPPs were defined according to the definition provided by the US Federal Highway Administration, as described in the introduction section above. Terms used in the search strategy are provided in Table 2.

Table 2. Search terms for examining congestion pricing policy impacts on safety-related outcomes

Set #	Search Terms
	Scopus
1	TITLE-ABS-KEY (("congestion pricing" OR "congestion prices" OR "congestion price" OR "congestion charging" OR "congestion charges" OR "congestion charge" OR "congestion tax" OR "congestion taxes" OR "congestion taxing" OR "congestion fee" OR "congestion fees" OR “congestion toll*” OR "congestion subsidy" OR "congestion subsidies" OR “congestion policy” OR “congestion policies” OR “congestion strategy” OR “congestion strategies” OR “congestion zone” OR “congestion zones” OR cordon OR “Zone-based pricing” OR “zonal-based pricing” OR “Zone-based charg*” OR “zonal-based charg*” OR “zone pricing” OR “zone charg*” OR “zonal charg*” OR “zonal scheme” OR “zonal schemes” OR “zone scheme” OR “zone schemes” OR “distance-based pricing” OR “area-based pricing” OR “area-wide charg*” OR “area-based charg*” OR “per-mile pricing” OR “per-mile charg*” OR “network pricing” OR “mileage-based user fee” OR “mileage-based user fees” OR “entry-based pricing” OR “variable pricing lane” OR “price managed lane” OR “price managed lanes”) AND (traffic OR transportation OR road OR roads OR highway OR highways OR automobile OR automobiles OR car OR cars OR vehicle OR vehicles))
2	TITLE-ABS-KEY (“road pricing” OR “road value pricing” OR “road charging” OR “road charge” OR “road charges” OR “road user charge” OR “road user charges” OR “road use charge” OR “road use charges” OR “road use charging”)
3	TITLE-ABS-KEY ((“toll scheme” OR “toll schemes” OR “tolling scheme” OR “tolling scheme” OR “distance-based toll” OR “distance-based tolls” OR “distance-based tolling” OR “variable toll” OR “variable tolls” OR “variable tolling” OR “dynamic toll” OR “dynamic tolls” OR “dynamic tolling”) OR ((tolls OR tolling OR "high occupancy vehicle lane" OR "high occupancy vehicle lanes") AND (traffic OR road OR roads OR highway OR highways OR automobile OR automobiles OR car OR cars OR vehicle OR vehicles) AND (congestion OR congested OR “transportation demand management” OR “traffic demand management”)))
4	#1 OR #2 OR #3
5	TITLE-ABS-KEY (safety OR safe OR injury OR injuries OR mortality OR mortalities OR fatality OR fatalities OR casualty OR casualties OR death OR deaths OR crash OR crashes OR accident OR accidents)
6	#4 AND #5
7	#6 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "rp"))
	Web of Science

1	TS=(("congestion pricing" OR "congestion prices" OR "congestion price" OR "congestion charging" OR "congestion charges" OR "congestion charge" OR "congestion tax" OR "congestion taxes" OR "congestion taxing" OR "congestion fee" OR "congestion fees" OR “congestion toll*” OR "congestion subsidy" OR "congestion subsidies" OR “congestion policy” OR “congestion policies” OR “congestion strategy” OR “congestion strategies” OR “congestion zone” OR “congestion zones” OR cordon OR “Zone-based pricing” OR “zonal-based pricing” OR “Zone-based charg*” OR “zonal-based charg*” OR “zone pricing” OR “zone charg*” OR “zonal charg*” OR “zonal scheme” OR “zonal schemes” OR “zone scheme” OR “zone schemes” OR “distance-based pricing” OR “area-based pricing” OR “area-wide charg*” OR “area-based charg*” OR “per-mile pricing” OR “per-mile charg*” OR “network pricing” OR “mileage-based user fee” OR “mileage-based user fees” OR “entry-based pricing” OR “variable pricing lane” OR “price managed lane” OR “price managed lanes”) AND (traffic OR transportation OR road OR roads OR highway OR highways OR automobile OR automobiles OR car OR cars OR vehicle OR vehicles))
2	TS=(“road pricing” OR “road value pricing” OR “road charging” OR “road charge” OR “road charges” OR “road user charge” OR “road user charges” OR “road use charge” OR “road use charges” OR “road use charging”)
3	TS=((“toll scheme” OR “toll schemes” OR “tolling scheme” OR “tolling scheme” OR “distance-based toll” OR “distance-based tolls” OR “distance-based tolling” OR “variable toll” OR “variable tolls” OR “variable tolling” OR “dynamic toll” OR “dynamic tolls” OR “dynamic tolling”) OR ((tolls OR tolling OR "high occupancy vehicle lane" OR "high occupancy vehicle lanes") AND (traffic OR road OR roads OR highway OR highways OR automobile OR automobiles OR car OR cars OR vehicle OR vehicles) AND (congestion OR congested OR “transportation demand management” OR “traffic demand management”)))
4	#1 OR #2 OR #3
5	TS=(safety OR safe OR injury OR injuries OR mortality OR mortalities OR fatality OR fatalities OR casualty OR casualties OR death OR deaths OR crash OR crashes OR accident OR accidents)
6	#4 AND #5
7	#6 AND Refined by: DOCUMENT TYPES: (ARTICLE OR EARLY ACCESS)
TRID	
1	("congestion pricing" OR "congestion prices" OR "congestion price" OR "congestion charging" OR "congestion charges" OR "congestion charge" OR "congestion tax" OR "congestion taxes" OR "congestion taxing" OR "congestion fee" OR "congestion fees" OR “congestion toll*” OR "congestion subsidy" OR "congestion subsidies" OR “congestion policy” OR “congestion policies” OR “congestion strategy” OR “congestion strategies” OR “congestion zone” OR “congestion zones” OR cordon OR “Zone-based pricing” OR “zonal-based pricing” OR “Zone-based charg*” OR “zonal-based charg*” OR “zone pricing” OR “zone charg*” OR “zonal charg*” OR “zonal scheme” OR “zonal schemes” OR “zone scheme” OR “zone schemes” OR “distance-based pricing” OR “area-based pricing” OR “area-wide charg*” OR “area-based charg*” OR “per-mile pricing” OR “per-mile charg*” OR “network pricing” OR “mileage-based user fee” OR “mileage-based user fees” OR “entry-based pricing” OR “variable pricing lane” OR “price managed lane” OR “price managed lanes”) AND (traffic OR transportation OR road OR roads OR highway OR highways OR automobile OR automobiles OR car OR cars OR vehicle OR vehicles)
2	“road pricing” OR “road value pricing” OR “road charging” OR “road charge” OR “road charges” OR “road user charge” OR “road user charges” OR “road use charge” OR “road use charges” OR “road use charging”
3	(“toll scheme” OR “toll schemes” OR “tolling scheme” OR “tolling scheme” OR “distance-based toll” OR “distance-based tolls” OR “distance-based tolling” OR “variable toll” OR “variable tolls” OR “variable tolling” OR “dynamic toll” OR “dynamic tolls” OR “dynamic tolling”) OR ((tolls OR tolling OR "high occupancy vehicle lane" OR "high occupancy vehicle lanes") AND (traffic OR road OR roads OR highway OR highways OR automobile OR automobiles OR car OR cars OR vehicle OR vehicles) AND (congestion OR congested OR “transportation demand management” OR “traffic demand management”))
4	#1 OR #2 OR #3
5	(safety OR safe OR injury OR injuries OR mortality OR mortalities OR fatality OR fatalities OR casualty OR casualties OR death OR deaths OR crash OR crashes OR accident OR accidents)
6	#4 AND #5
7	#6 AND Limit to Journal Articles, Reports, and Serials
PubMed	
1	(("congestion pricing"[tiab] OR "congestion prices"[tiab] OR "congestion price"[tiab] OR "congestion charging"[tiab] OR "congestion charges"[tiab] OR "congestion charge"[tiab] OR "congestion tax"[tiab] OR "congestion taxes"[tiab] OR "congestion taxing"[tiab] OR "congestion fee"[tiab] OR "congestion fees"[tiab] OR “congestion toll”[tiab] OR “congestion tolls”[tiab] OR “congestion tolling”[tiab] OR "congestion subsidy"[tiab] OR "congestion subsidies"[tiab] OR “congestion policy”[tiab] OR “congestion policies”[tiab] OR “congestion strategy”[tiab] OR “congestion strategies”[tiab] OR “congestion zone”[tiab] OR “congestion zones”[tiab] OR cordon[tiab] OR “Zone-based pricing”[tiab] OR “zonal-based pricing”[tiab] OR “Zone-based charging[tiab]” OR “Zone-based charges[tiab]” OR “Zone-based charge”[tiab] OR “zonal-based charging”[tiab] OR “zonal-based charges”[tiab] OR “zonal-based charge”[tiab] OR “zone pricing”[tiab] OR “zone charging”[tiab] OR “zone charges”[tiab] OR “zone charge”[tiab] OR “zonal charging”[tiab] OR “zonal charges”[tiab] OR “zonal charge”[tiab] OR “zonal scheme”[tiab] OR “zonal schemes”[tiab] OR “zone scheme”[tiab] OR “zone schemes”[tiab]

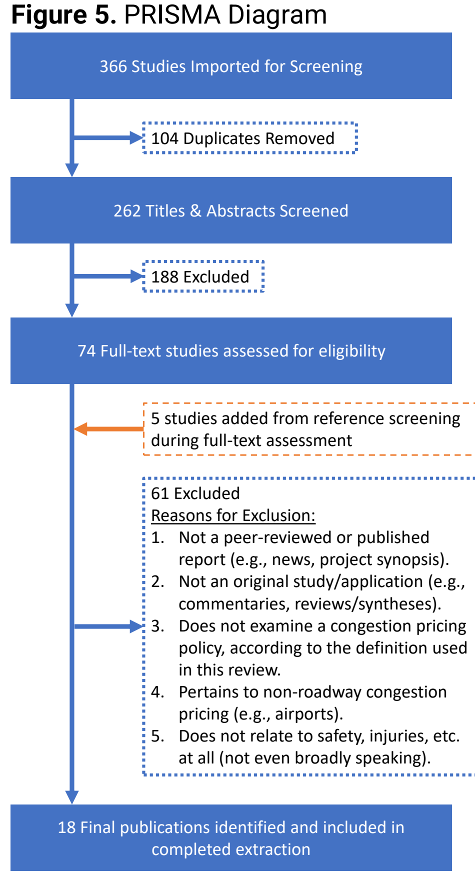
	OR “distance-based pricing”[tiab] OR “area-based pricing”[tiab] OR “area-wide charging”[tiab] OR “area-wide charges”[tiab] OR “area-wide charge”[tiab] OR “area-based charging”[tiab] OR “area-based charges”[tiab] OR “area-based charge”[tiab] OR “per-mile pricing”[tiab] OR “per-mile charging”[tiab] OR “per-mile charges”[tiab] OR “per-mile charge”[tiab] OR “network pricing”[tiab] OR “mileage-based user fee”[tiab] OR “mileage-based user fees”[tiab] OR “entry-based pricing”[tiab] OR “variable pricing lane”[tiab] OR “price managed lane”[tiab] OR “price managed lanes”[tiab]) AND ("Transportation"[Mesh:NoExp] OR "Motor Vehicles"[Mesh] OR traffic[tiab] OR transportation[tiab] OR road[tiab] OR roads[tiab] OR highway[tiab] OR highways[tiab] OR automobile[tiab] OR automobiles[tiab] OR car[tiab] OR cars[tiab] OR vehicle[tiab] OR vehicles[tiab]))
2	(“road pricing”[tiab] OR “road value pricing”[tiab] OR “road charging”[tiab] OR “road charge”[tiab] OR “road charges”[tiab] OR “road user charge”[tiab] OR “road user charges”[tiab] OR “road use charge”[tiab] OR “road use charges”[tiab] OR “road use charging”[tiab])
3	(“toll scheme”[tiab] OR “toll schemes”[tiab] OR “tolling scheme”[tiab] OR “tolling scheme”[tiab] OR “distance-based toll”[tiab] OR “distance-based tolls”[tiab] OR “distance-based tolling”[tiab] OR “variable toll”[tiab] OR “variable tolls”[tiab] OR “variable tolling”[tiab] OR “dynamic toll”[tiab] OR “dynamic tolls”[tiab] OR “dynamic tolling”[tiab]) OR ((toll[tiab] OR tolls[tiab] OR tolling[tiab] OR "high occupancy vehicle lane"[tiab] OR "high occupancy vehicle lanes"[tiab]) AND ("Motor Vehicles"[Mesh] OR traffic[tiab] OR road[tiab] OR roads[tiab] OR highway[tiab] OR highways[tiab] OR automobile[tiab] OR automobiles[tiab] OR car[tiab] OR cars[tiab] OR vehicle[tiab] OR vehicles[tiab]) AND (congestion[tiab] OR congested[tiab] OR “transportation demand management”[tiab] OR “traffic demand management”[tiab]))
4	#1 OR #2 OR #3
5	("Safety"[Mesh] OR "Accidents, Traffic"[Mesh] OR "Wounds and Injuries"[Mesh] OR "Death"[Mesh] OR "Mortality"[Mesh] OR safety[tiab] OR safe[tiab] OR injury[tiab] OR injuries[tiab] OR mortality[tiab] OR mortalities[tiab] OR fatality[tiab] OR fatalities[tiab] OR casualty[tiab] OR casualties[tiab] OR death[tiab] OR deaths[tiab] OR crash[tiab] OR crashes[tiab] OR accident[tiab] OR accidents[tiab])
6	#4 AND #5

The search strategy was applied to four databases: Transport Research International Documentation (TRID), Web of Science, PubMed, and Scopus. No restriction was placed based on year of publication, and therefore we included all articles meeting search criteria from database inception through January 2021. Identified publications were then input into Covidence (https://www.covidence.org), an online tool that streamlines the screening and data extraction steps of the systematic review process.

Inclusion criteria included publication type (peer-reviewed literature or published reports) and an abstract or summary written in English. Publications were required to discuss the safety impacts of at least one toll-based roadway CPP – either as an observation of an implemented policy or simulation of a hypothetical policy. Policies created for the purpose of purely generating revenue, and not focused on congestion reduction, did not meet our definition of a CPP and were, therefore, excluded.

Figure 5 details the screening and review process. In the first stage, we screened the title and abstract. Next, we conducted a full-text screen to ensure articles met inclusion criteria. In addition to an assessment of criteria, the full-text screening step included a review of included studies' references to ensure that publications were not missed in our initial search of databases. Publications identified in this way were then subject to a full-text review. All steps of the screening process were conducted independently by two study team members. Any decision disagreements were identified by Covidence and then further reviewed for a final decision (agreed upon by both reviewers). Final publications that met all criteria were then examined, and key information was extracted using a data extraction form developed collaboratively by the study team. The form outlined several elements for extraction, including study purpose, policy(ies) examined, and safety-specific results. A comprehensive list of all form elements is provided in Box 2.

Figure 5. PRISMA Diagram



*Transport for London (TfL) Impact Monitoring Series counted as one publication in this diagram and in this review

Box 2. List of form elements

- Authors
- Year
- Title
- Journal/source
- Researcher extracting information
- Source for scoping review
- Purpose/objective of paper
- Congestion pricing policy type examined
- Observed or simulated data
- Location/setting
- Study time period
- Major data sources for safety-related outcomes
- Method/model used to examine impact
- Safety a primary focus? (Y/N)
- Road safety outcome(s) measured/examined
- Road safety-specific results
- Other outcomes examined
- Assumptions made for simulated data (if applicable)
- Strengths
- Limitations
- Key conclusions/take home points

Results

The search strategy yielded a total of 366 publications. 104 duplicates were identified and removed, leaving 262 articles and reports for input into Covidence. In the title and abstract screening stage, 188 publications were deemed irrelevant, and 74 publications moved to the full-text review. During the full-text review, we also identified 5 additional studies from the reference lists of relevant studies, so we completed a full-text review of 79 total publications. Of these, only 18 publications met all eligibility criteria and were included in the final extraction process (Albalate, 2011; Balwani & Singh, 2009; de Palma & Lindsey, 2006; deCorla-Souza & Gupta, 1989; Ding et al., 2021a, 2021b; Eliasson, 2009; Fagnant & Kockelman, 2014; Green et al., 2016; Li et al., 2012; Li & Gao, 2019; Mayeres, 2000; Noland et al., 2008; Percoco, 2016; Quddus, 2008; Transport for London, 2003, 2004, 2005, 2006, 2007, 2008; Wier et al., 2011; Yu et al., 2019). For the purposes of this review, a series of reports by Transport for London (six annual reports) were counted as a single publication as these reports used similar methods to update findings each year.

Table 3 details key characteristics and findings of each study. Below, we summarize characteristics and findings across studies. Publication dates for the final 18 studies ranged from 1989 to 2021, with study settings in the US (n=4), the UK (n=9), and in other European countries (n=5). London was the setting for eight publications. Two publications were reports, while the remaining 16 were from peer-reviewed journals. Ten publications used observed data only, six used simulated data only, and two used some combination of simulated and observed data. The most evaluated CPP type was 'zone- and cordon-based CPPs' (n=13). The most common type of safety outcome measured was crashes (including injury and non-injury crashes) (n=11). Other measures included injury crashes specifically and economic valuations corresponding to at least one direct safety measure. Analyses that included evaluations of specific vehicles and/or road users included results for bicyclists (n=6), motorcyclists (n=4), pedestrians (n=2), taxis (n=2), and buses/cargo trucks/other heavy vehicles (n=2).

Findings from the 18 studies indicated that overall, there were potential safety benefits for multiple road users with CPP implementation. Reductions in the number of road traffic crashes were as high as 35% per month (Green et al., 2016). Some studies observed no changes in overall fatalities following implementation, while others observed reductions of up to 33% (Percoco, 2016; Quddus, 2008). Studies of the impacts of CPPs in London demonstrated reductions in injury crashes ('car casualties') of up to 27% by two years post-implementation (Quddus, 2008). One report estimated that by the third year after implementation, the CPP resulted in 40-70 fewer injury crashes per year in London (Transport for London, 2007).

However, notably, trends varied when disaggregated by road user type. Some examinations of motorcycles/powered two-wheelers estimated increases in injury crashes immediately after implementation, with a reversal as time went on (Li et al., 2012; Transport for London, 2004, 2005, 2006, 2007). One report found that while the number of powered two-wheelers and associated crashes increased after CPP implementation, the number of crashes involving these road users decreased with each consecutive year (Transport for London, 2004, 2005, 2006, 2007). Similar immediate increases were observed or estimated for bicyclist injury crashes, followed by a decrease several years after implementation (Green et al., 2016; Li et al., 2012; Noland et al., 2008). In contrast, other studies observed decreases in the years immediately after implementation but increases in the longer-term (Transport for London, 2004, 2005, 2006, 2007). Multiple studies attributed observed changes in motorcyclist and bicycle injury crashes to mode shifts after policy implementation, resulting in increases in motorcycle and bicycle use (Ding et al., 2021b; Green et al., 2016; Li et al., 2012; Noland et al., 2008; Wier et al., 2011).

Mode shifts were also thought to explain changes in pedestrian crash involvement. One study estimated decreased crash involvement due to CPP implementation after a 10-year period (Wier et al., 2011), while another observed decreases immediately post-implementation followed by slight increases by three years post-implementation (Transport for London, 2004, 2005, 2006, 2007). More details by study are available in Table 3.

Conclusions

Road traffic congestion is a growing problem and has had negative impacts on air quality, expenses, productivity, and local economies. The burden is especially high in urban regions. CPPs are recognized worldwide as a potential solution, as they encourage shifts in travel behavior while also generating revenue, which may then be used to improve travel environments for users of transit, bicycles, or other modes. CPP impacts on congestion, emissions, revenue, and public perceptions have been described in the literature; however, impacts on road user safety have not been as well explored.

The 18 studies included in this structured search and scoping review included original analyses of the safety impacts of toll-based CPPs. The range of policy specifications (e.g., time-varying tolls), data used, safety outcomes measured/estimated, and methods used, make it difficult to arrive at overall conclusions regarding safety impacts of all CPPs. Publications about London's zone-based policy were the most prevalent and seemed to suggest that such policies can have positive impacts overall (for all crashes) but that the trends can vary by road user type (e.g., bicyclists, pedestrians) and over time (e.g., immediate vs. 2-3 years out). Specifically, some road users experienced temporary increases in crashes following policy implementation (e.g., bicyclists, motorcyclists), potentially due to changes in travel modes and increased exposures. In longer follow-up periods, some of these patterns ultimately reversed, resulting in lower crash and injury levels compared to pre-policy. Further research is needed to examine the generalizability of findings by policy across cities. Additionally, prior to implementing CPPs, cities and regions should consider, within the context of their own community, potential mode shifts and safety-related supports for such mode shifts, as well as equity concerns, appropriate revenue reinvestment, and if the policy can successfully be implemented and provide benefits in both short- and long-term time frames.

Table 3. Characteristics and key findings of peer-reviewed publications and reports examining congestion pricing policy impacts on safety-related outcomes

First author. Title. (Year of publication)	Publication type	Congestion pricing policy(ies) examined	Study setting	Time period	Data type	Is safety a primary focus?	Safety outcomes measured*	Other outcomes measured	Key safety-related conclusions*
Yu et al. The cost-effectiveness of competing congestion pricing plans in New York City. (2019)	Peer-reviewed article	1. Zone-based policy with charges that vary based on area (e.g., areas with public transit) 2. Zone-based policy with time-varying charges	New York City, USA	Hypothetical 10-year data for simulated policies	Simulated data only	Yes (as part of health benefits)	QALY, indicating the quality and quantity of lives	Cost-effectiveness outcomes using an incremental cost-effectiveness ratio (ICER)	Both CPPs were cost-saving/cost-effective with the same long-term costs and health benefits, including life expectancy gains and health benefits. Both policies could result in a maximum gain of approximately 0.141 QALYs per capita.
Wier et al. Health effects of road pricing in San Francisco, California. (2011) **	Report	Zone-based policy with time-varying charges	San Francisco, California, USA.	2005 real non-policy data compared to simulated 2015 data under policy and non-policy scenarios	Simulated and observed data	Yes	Pedestrian injuries from vehicle-related crashes; Bicyclist injuries from vehicle-related crashes	Active transportation via walking and cycling, air pollutants, noise; traffic volume and density; costs	Over a projected 10-year period, road pricing was estimated to avert 35 pedestrian collisions per year and avert 5 bicyclist collisions per year (compared to projected annual collision numbers if a policy were not implemented).
Percoco. The impact of road pricing on accidents: a note on Milan. (2016)	Peer-reviewed article	Zone-based policy with time-varying charges	Milan, Italy.	2001 - 2011 data involving a real policy established in Jan uary 2008	Observed data only	Yes	Total crashes, fatal and non-fatal injuries	None	A significant reduction in crashes (-18.8%) and non-fatal injuries (-16%) was observed in the charging zone. A slight, non-significant, reduction was observed in deaths.
Eliasson. A cost-benefit analysis of the Stockholm congestion charging system. (2009)	Peer-reviewed article	Zone-based policy with time-varying charges	Stockholm, Sweden.	April – May 2005 and April-May 2006 data involving a real policy (implement ed in January 2006).	Observed data only	No, part of a larger cost-benefit analysis.	Total crashes, KSI, and slightly injured, and corresponding economic valuations.	Investment and operating costs; travel times and costs; emissions; transit revenue; overall short-term and long-term effects	Estimated a 3.6% reduction in the number of traffic crashes in the charging zone. KSI decreased by ~14 per year, and slightly injured decreased by ~50 per year.

de Palma and Lindsey. Modelling and evaluation of road pricing in Paris. (2006)	Peer-reviewed article	Zone-based policy with time-varying charges and network-wide toll proportional to travel time	Ile-de-France (includes Paris), France.	2002-2012 hypothetical data involving simulated policies	Simulated data only	No	Crash costs (assumed to be proportional to distance travelled)	Number of car trips; travel time; travel cost; net cost; fractions of users; schedule delay costs; congestion delay; average auto speed; total distance travelled and travel distance per trip	Crash cost reductions (-1.2%) were observed with an initial phase of placing a cordon toll around the city center, and even greater external cost reductions (including crash costs) were observed in a final phase of expanding the charge to cover the entire region
Noland et al. The effect of the London congestion charge on road casualties: an intervention analysis. (2008)	Peer-reviewed article	Zone-based policy with time-varying charges	London, UK.	1991 - 2004 observed data involving a real policy	Observed data only	Yes	Total, car, motorcyclist, and bicyclist casualty crashes (for KSI and slightly injured)	None	No significant decrease in total casualties within inner London and the charging zone. Within the zone, there was a 3.4% decrease in car occupant casualties, but an immediate increase in bicyclist casualties. Motorcyclist casualties did not change in the zone, but increased outside the zone.
Quddus. Time series count data models: an empirical application to traffic accidents. (2008)**	Peer-reviewed article	Zone-based policy with time-varying charges	London, UK.	1991-2005 observed data involving a real policy	Observed data only	Yes	Car casualty crashes	None	The congestion charging zone reduced the number of car casualty crashes per month by 27%, and reduced the number of fatalities per month by 33% (or 13 per month).
Green et al. Traffic accidents and the London congestion charge. (2016)	Peer-reviewed article	Zone-based policy with time-varying charges	London, UK.	2000-2009 observed data involving a real policy	Observed data only	Yes	Total, KSI, and non-KSI crashes, fatal injuries, and crash rates per miles travelled for all road users, uncharged road users, and bicyclists only	None	The monthly number of crashes in the charging zone significantly decreased by 35% (40 fewer per month). Numbers of KSI and non-KSI crashes decreased per year, along with number of fatalities. There was an increase in number of bike crashes, but a decrease in the bike crash rate per mile traveled, immediately after the policy.
Li et al. The effects of congestion charging on road traffic casualties: a causal analysis using difference-in-difference estimation. (2012)	Peer-reviewed article	Zone-based policy with time-varying charges	London, UK.	2001-2004 observed data involving a real policy	Observed data only	Yes	Car casualty crash and injuries for all road users, motorcyclists, and bicyclists	None	There was a 5.2% decrease in car casualties in the charging zone. Bicycle casualty crashes increased by 13.3% immediately post-implementation. Motorcycle casualty crashes increased by 5.7%.

Li and Gao. Effects of the London Congestion Charge on Road Casualties: A Synthetic Control Study. (2019)	Peer-reviewed article	Zone-based policy with time-varying charges	London, UK.	1998-2007 observed data involving a real policy	Observed data only	Yes	Total, KSI, and slightly injured car casualty crashes	None	The charge resulted in significant reductions of total casualties, slightly injured, and KSI (decrease of 4.29%, 5.05%, and 12.12%, respectively).
Ding et al. Affected area and residual period of London Congestion Charging scheme on road safety. (2021)	Peer-reviewed article	Zone-based policy with time-varying charges	London, UK.	2005-2006 and 2011-2013 observed data involving a real policy	Observed data only	Yes	Crashes	Traffic volume/flow; average vehicle speeds	Crashes decreased by 46.3% in the charging zone. Adjacent areas up to 1.5 km away from the zone also had significant decreases, with smaller reductions further from the original zone. Residual effects lasted for only one year following removal of the CPP western extension, with an estimated crash reduction in that year of 15.2% compared to if the CPP had never been implemented in that area.
Ding et al. Effect of London cycle hire scheme on bicycle safety. (2021)	Peer-reviewed article	Zone-based policy with time-varying charges (evaluated within the context of another program occurring at the same time, a cycle hire scheme)	London, UK.	2011-2012 observed data involving a real policy	Observed data only	Yes	Total, slightly injured, and KSI bicycle crashes	Traffic volume/flow; bicycle usage	Overall bicycle crashes and slight injury bicycle crashes significantly increased by 59.1% and 57.8%, respectively, with the added congestion charge (compared to areas with the 'cycle for hire' scheme only). Non-significant increases in KSI crashes were observed in areas with both policies and with the 'cycle for hire' scheme only, relative to areas with no policy.
Transport for London. Central London congestion charging: Impacts moni toring, 1st – 6th annual reports (2003-2008) ₮**	Report	Zone-based policy with time-varying charges	London, UK.	1st annual report covered an unspecified time period of simulated predictions. 2nd-6th annual reports use observed data involving a real policy from 2001 to the most recent year (through 2007).	Simulated and observed data	No, one of many outcomes examined	Crashes, non-fatal and fatal injuries, pedestrian-related crashes that involved an injury, number and types of vehicles involved in crashes	Traffic levels; pedestrian and cycling activity; public transport activity; business and economic impacts; changes to travel patterns; environmental impacts; public attitudes and perceptions	The CPP was responsible for about 40-70 additional injury crashes averted per year, as compared to a baseline decreasing crash trend. Crash reductions were observed for some road user types, but increases in taxi and pedal cyclist crashes were observed in the first couple of years post-implementation. Pedestrians experienced crash increases two to three years post-implementation.

deCorla-Souza and Gupta. Evaluation of demand-management strategies for Toledo's year 2010. (1989)	Peer-reviewed article	Variable tolls on entire roadways (time-varying charges)	Toledo, Ohio, USA.	Hypothetical data projected out over 20 years (until 2010) involving simulated policies	Simulated data only	No, included in 'other impacts' piece	Vehicle miles traveled per work-person trip (relative exposure and probability of crash); congestion level (relative crash severity and probability of crash occurrence).	Economic efficiency; reduced traffic congestion; transit viability; economic development; social impacts; environmental impacts	Strategies which included variable tolls were projected to reduce congestion and improve other strategy goals, including safety, transit viability, and social and environmental benefits. Specifically, vehicle-miles traveled per trip decreased from 6.9 without a CPP to 4.4-5.2 with the evaluated pricing strategies.
Fagnant and Kockelman. Anticipating roadway expansion and tolling impacts: Toolkit for abstracted networks. (2014)	Peer-reviewed article	Variable tolls on roadways (time-varying charges)	Austin, Texas, USA.	Hypothetical 20-year projection involving simulated policies	Simulated data only	Yes	Crashes, crash costs	Travel patterns; traveler welfare; travel time reliability; emissions; fuel use; tolling revenue	Crash impacts varied by scenarios, with several showing decreases (one had a 6.4% decrease in total crashes and 1,708 fewer fatal and injury crashes over 20 years), while others had increases (including one resulting in an additional 22 injury crashes per year) due to shifted traffic to non-tolled roadways.
Albalate. Shifting death to their alternatives: The case of toll motorways. (2011)	Peer-reviewed article	Area-/system-wide charges	Spain.	2006 observed data involving a real policy	Observed data only	Yes	Crashes involving fatal or non-fatal injuries only	Average daily traffic; share of heavy vehicles; share of foreigners; average speed	A 1% increase in toll level on toll motorways resulted in a 0.5% increase in the number of crashes with injuries/km on adjacent roads. Roads adjacent to toll motorways experienced more crashes than roads adjacent to un-tolled motorways.
Balwani and Singh. Network impacts of distance-based road user charging. (2009)	Peer-reviewed article	Area-/system-wide charges	Leeds, UK.	Hypothetical data under simulated policies, projected out from 2006 to 2066.	Simulated data only	No	Crashes	Number and length of trips; congestion; pollution; net economic benefits and revenues	Distance-based charges can decrease the number of crashes, with an 8% reduction in annual crashes with higher charges and a 4% reduction with lower charges.
Mayeres. The efficiency effects of transport policies in the presence of externalities and distortionary taxes. (2000)	Peer-reviewed article	Variable tolls on roadways (time-varying charges)	Belgium.	Unspecified time period of a simulated policy, projected from 1990	Simulated data only	Yes	Crashes (based on total traffic volume)	Congestion; air pollution (including global warming)	Peak road pricing, higher fuel tax, and higher public transport subsidy strategies showed welfare gains. Of the three, fuel tax was projected to be the most effective in reducing crashes.

Part 3: Simulating Congestion Pricing Policy Impacts on Pedestrian Safety Using a System Dynamics Simulation Model

A full manuscript detailing this piece of the project is under review: Naumann RB, Sabounchi NS, Kuhlberg J, Singichetti B, Sandt L, Marshall SW, Hassmiller Lich K. Simulating congestion pricing policy impacts on pedestrian safety using a system dynamics approach. Under review at *Accident Analysis and Prevention*. 2021.

The objective, methods, results, and key findings are summarized below.

Objective

To develop a system dynamics (SD) learning model to explore zone-based congestion pricing impacts on pedestrian safety. Building from Phase 1 findings and Parts 1 and 2 of this project, we sought to determine whether (and if so, how can) a New York City (NYC) congestion pricing policy (CPP) improve safety for road users (and namely, pedestrians), while meeting the intended purpose of reducing congestion.

Methods

We used SD methods to examine interrelated factors and feedback loops underlying pedestrian injury trends in Manhattan. SD provides a powerful approach within the broader field of systems science (Forrester, 1994; J. Sterman, 2002; J. D. Sterman, 2000). SD posits that complex and adaptive problems, such as pedestrian injury trends, arise from factors that affect and are affected by each other through feedback processes. SD methods propose that if we can begin to understand the structure of these feedback processes, we can shape better actions by identifying critical points of leverage within the system. SD methods include qualitative (i.e., causal loop diagramming) and quantitative (i.e., SD simulation modeling) tools (J. Sterman, 2002; J. D. Sterman, 2000). Causal loop diagramming provides a process for capturing hypotheses about feedback loops and variable interactions that may be driving an outcome trend over time. SD simulation modeling can then be used to test the consistency of these hypotheses with data. Additional information on SD and causal loop diagrams (CLDs) is available here: https://thesystemsthinker.com/

SD model development and analysis involved five steps:

<u>1) CLD development</u>: We used CLDs to capture hypotheses about causal processes and dynamic factors underlying pedestrian injuries in Manhattan. In a CLD, factors are connected via causal arrows. Casual arrows with a positive sign (+) indicate that a change in a variable that the arrow originates from causes a change in the destination variable in the same direction (i.e., as one variable increases the other also increases, or as one variable decreases the other also decreases), all else held equal. Causal arrows with a negative sign (-) indicate that the two connected variables change in opposite directions. If causal connections form a closed chain of connections, over time, they create a feedback loop (Hovmand, 2014; J. D. Sterman, 2000). An example of a hypothetical feedback loop is shown below (Figure 6). This diagram depicts the example hypothesis that, all else held equal, as the real and perceived risk of injury from walking and cycling increases, local walking and cycling decreases (demonstrated through a "-" sign indicating an inverse relationship), and as local walking and cycling decreases, walking and cycling injuries also decrease due to less exposure (demonstrated though a "+" indicating that the variables move in the same direction), which reduces the real and perceived risk of injury (also indicated with a "+"

arrow). Feedback loops are critical to understand, as they can be powerful engines of changes or powerful engines of resistance to change.

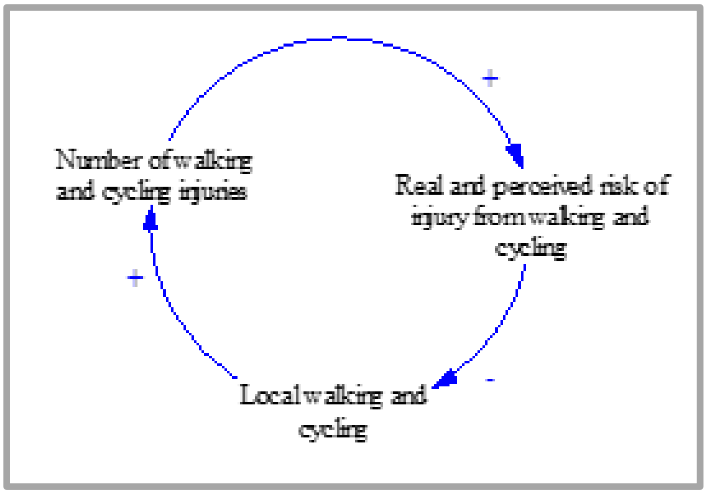


FIGURE 6. Example causal loop diagram

To develop a CLD capturing hypothesis about potential feedback loops driving pedestrian injury trends in Manhattan, we began from a CLD that our team had developed in Phase 1 of this work (Appendix 1). As part of that process, we conducted a set of group model building sessions; a detailed description of this process and the full, synthesized CLDs are available in Naumann et al. (2020). Building on this foundation, we tailored the CLD for this project to capture feedbacks believed to be most important for understanding pedestrian injuries over time in Manhattan. We conducted several interviews with experts in pedestrian safety, engineering, planning, public health, and advocacy who were from academic institutions, the NYC Department of Transportation, and a NYC-based advocacy organization focused on vulnerable road users. From this process, we narrowed our CLD to dynamics relevant for this specific research question.

<u>2) Creation and refining of SD simulation model structure:</u> We translated the CLD into a stock-and-flow model, simulating injury and vehicle trends over a 25-year period, from 2005 to 2030. The model was organized into three sections, covering all dynamics in the tailored CLD: [1] pedestrian exposure, pedestrian infrastructure investments, and potential speed-related changes affecting pedestrian injury risk; [2] transit investments, transit system wear and tear, and ridership fluctuations; [3] transportation mode shifts, average costs of for-hire vehicle trips, and roadway congestion trips by different modes, as well as changes to walking based on other mode changes. The model included persons traveling in and around the Manhattan region where the CPP is anticipated to be implemented (i.e., between 60th Street and the Battery) and did not detail any COVID-19-specific dynamics. Model outcomes included pedestrian injury counts, pedestrian injury rates per 100,000 walking trips, and average number of daily vehicle trips in the area.

<u>3) Collection of relevant data:</u> Data included pedestrian crash and injury data from the Department of Motor Vehicles Accident Information System through the NY State Traffic Safety Statistical Repository (The Institute for Traffic Safety Management and Research, 2020); data tracked through annual NYC Mobility Surveys and Reports, including information on average travel speeds in this area of Manhattan, vehicle trips into the area, transit ridership trends, and proportions of trips that are made by walking and other modes (NYC Department of Transportation, 2018, 2021a); population data from the U.S. Census and American Community Survey (US Census Bureau, 2021); freight vehicle data from the NYC Department of Transportation (NYC Department of Transportation, 2021b); taxi and for-hire vehicle data from the NYC Taxi and Limousine Commission (NYC Taxi & Limousine Commission, 2021; Schaller, 2017); intersection data for Manhattan from the NYC Pedestrian Safety Action Plan (NYC Vision Zero, 2015); and NYC Metropolitan Transportation Authority (MTA) data on transit ridership, expenditures and deficits, and average numbers of major delays on transit lines (NYC Metropolitan Transportation

Authority, 2010, 2021). We also conducted literature reviews to help define the functional form of relationships between key variables (e.g., speed and injury risk) (Dickerson et al., 2000; Martin, 2002; Zhou & Sisiopiku, 1997). The model was built using Stella Architect, version 2.0.3 (isee systems, 2021).

4.) Model verification, validation, and calibration: We assessed unit and dimension consistency, completed code verification, conducted extreme value testing, and ensured model face validity. We also calibrated the model, comparing and fitting simulated data to observed trends. Calibration was performed using a maximum likelihood estimation approach, running 25,000 simulations and allowing for up to 1,000 randomly selected search starting points to increase likelihood of identifying globally optimal parameter sets. We completed calibration in Vensim Professional, version 8.2.1 (Ventana Systems, Inc., 2021).

5) Policy analyses: The model demonstrated an ability to reproduce historical, observed numbers of pedestrian injuries and vehicles entering the Manhattan CPP area, in addition to other key trends. Based on this agreement, we then used the model to derive insights on potential impacts of CPP implementation on pedestrian injuries under a variety of scenarios. Table 4 describes the policy scenarios simulated in detail. CPP implementation in this model assumes a $6 average charge in each direction for vehicles entering and exiting the central business district beginning in 2022 with revenue from the CPP used to improve the metropolitan transit system. Other policy scenarios layered on or removed economic-, infrastructure-, or speed management-related interventions.

Table 4. Congestion pricing policy scenarios and intervention combinations

Simulated Policy	Simulated Policy Details*
A. CPP not implemented	No CPP implemented but VZ investments remain in place and unchanged.
0. CPP implemented and no other changes in policy	CPP implemented, assuming a $6 charge in each direction for vehicles entering and exiting the central business district, beginning in 2022. We assumed for-hire vehicles are not charged under the new CPP. However, they are charged under a previous congestion-related surcharge placed on these vehicles, beginning in 2019. All revenue from the CPP is used to improve the metro system. VZ investments remain in place and unchanged. Assumes that none of the other policy options listed in this table are implemented.
B. CPP implemented and VZ investments expire	CPP implemented. Assumes consistent investments in improved pedestrian infrastructure which began when NYC adopted VZ in 2014. However, this scenario assumes that political will for VZ-related investments wanes, and while the CPP is implemented, the VZ investments for improving pedestrian infrastructure are removed at the time the CPP is implemented.
C. CPP implemented and FHVs taxed	CPP implemented and additional taxes placed on FHVs when the CPP begins. The model includes the FHV surcharge placed on these vehicles to mitigate congestion beginning in 2019. This policy scenario assumes that another tax (about $2.75 per FHV trip) is placed on FHV trips when the CPP goes into effect, in an attempt to further reduce congestion.
D. CPP implemented and post CPP infrastructure investments funded by CPP	CPP implemented and a small proportion of CPP revenue is used to improve pedestrian infrastructure after CPP implementation, instead of all revenue feeding back into metro improvements. These investments are in addition to the standard VZ-related investments.
E. CPP implemented and pre & post CPP infrastructure investments	CPP implemented and additional investments are made to improve pedestrian infrastructure after CPP implementation (like in 4A), as well as in the two years *prior* to CPP implementation, aiming to prepare for potential mode shifts. These investments are in addition to the standard VZ-related investments.
F. CPP implemented with speed reduction	CPP implemented and measures put in place to keep speed consistently low post-CPP implementation, despite congestion being alleviated.
G. CPP implemented with speed reduction & post CPP infrastructure investment funded by CPP	Essentially scenario 4A combined with 5A. CPP implemented; measures put in place to keep speed consistently low post-CPP implementation, despite congestion being alleviated; and a small proportion of CPP revenue is used to improve pedestrian infrastructure after CPP implementation, instead of all revenue feeding back into metro improvements.

CPP= congestion pricing policy; FHV= for-hire vehicle; VZ= Vision Zero
*All models, except for "Vision Zero investments expire post CPP" assume consistent investments in improved pedestrian infrastructure which began when NYC adopted Vision Zero (VZ) in 2014 and that these annual investments continue into the future (i.e., through 2030).

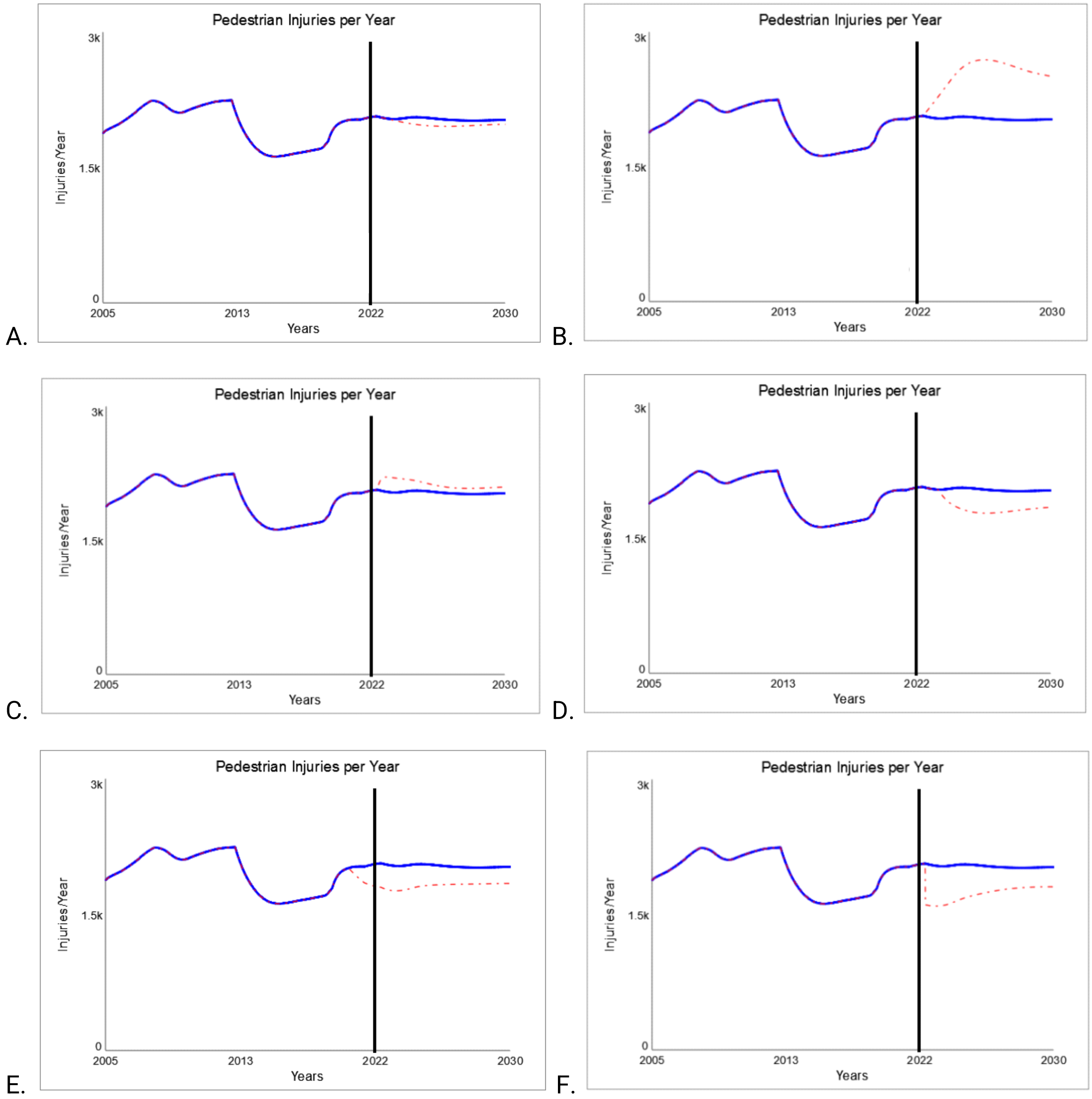
Results

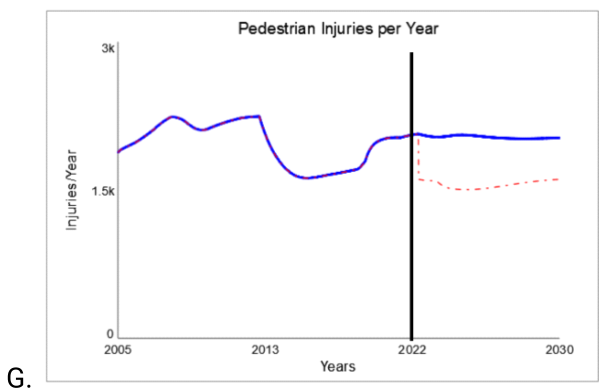
We observed excellent agreement between historical, observed and simulated data trends for annual pedestrian injuries, average daily for-hire vehicle trips, average daily metro trips, and average daily metro delay incidents produced by the final model after calibration. This increased confidence in the model as a learning tool and allowed us to conduct policy scenario analyses.

We simulated a baseline run (Scenario 0), assuming no CPP implementation; a scenario in which the CPP was implemented as anticipated (Scenario A); and six other scenarios (Scenarios B-G) in which the CPP was altered (e.g., CPP revenue was used to not only improve the metro but also to provide more funds to support safe pedestrian infrastructure) or other interventions were combined with the CPP (e.g., speed reduction interventions). A full manuscript (cited above) details scenario impacts on numbers and rates (per 100,000 walking trips) of pedestrian injuries and numbers of average daily vehicle trips. Below, we highlight impacts on the primary outcome—pedestrian injury counts (Figure 7). These results can also be generated using a policy scenario simulator tool, available here: https://exchange.iseesystems.com/public/beckynaumann/cpp-and-pedestrian-injury

Four of the eight scenarios were associated with reductions in the cumulative number of pedestrian injuries (Scenarios D-G), while two were associated with increases (Scenarios B & C) (Figure 7). Under Scenario A of no CPP implementation, pedestrian injuries were predicted to remain slightly reduced between 2020 and 2030, when compared to CPP implementation. CPP implementation resulted in additional metro trips, less for-hire vehicle trips, and slightly more pedestrian exposure to vehicles and vehicle speeds, slightly increasing the number of injuries. While additional infrastructure supports in response to increased pedestrian injuries reduced the number of injuries, projected supports based on historical dynamics did not reduce it fully to a pre-policy level.

Figure 7. Congestion pricing policy-related scenario effects on pedestrian injury counts





Scenario letters correspond to letters in Table 4. CPP= congestion pricing policy; FHV= for-hire vehicle; VZ= Vision Zero. Blue line corresponds to baseline CPP implementation (Scenario 0). Solid black vertical line corresponds to CPP implementation. Scenario A: No CPP; B: CPP implemented and VZ investments expire; C: CPP implemented and FHVs taxed; D: CPP implemented and post CPP infrastructure investments funded by CPP; E: CPP implemented and pre & post CPP infrastructure investments; F: CPP implemented with speed reduction; G: CPP implemented with speed reduction & post CPP infrastructure investment funded by CPP

Other scenarios resulting in increased numbers of pedestrian injuries, included a scenario in which the CPP was implemented but Vision Zero-related infrastructure funding was removed at the same time (Scenario B), due to a hypothetical decrease in political will for this road safety initiative. The model indicated an increase in estimated cumulative pedestrian injuries with removal of these funds, as additional pedestrian exposure coincided with reduced pedestrian infrastructure supports. Finally, increased CPP charges placed on for-hire vehicles entering or leaving the area (Scenario C) were associated with an increase in injuries, as some vehicle trips shifted to metro trips and increased pedestrian exposure and fewer vehicles resulted in slightly higher speeds.

Reductions in the cumulative number of pedestrian injuries resulted from four scenarios (Scenarios D-G): additional pedestrian infrastructure investments occurring post-CPP implementation, under a scenario in which CPP revenue was used to improve infrastructure in addition to supporting metro system improvements (Scenario D); additional pedestrian infrastructure investments occurring both pre- and post-CPP implementation (i.e., both upfront investments prior to policy implementation and investments resulting from CPP revenue; Scenario E); 3) speed reduction interventions implemented at the same time as the CPP to keep speeds down even if some congestion is relieved (Scenario F); and, 4) speed reduction interventions combined with post-CPP infrastructure investments (Scenario G).

Accounting for the number of walking trips each year, rates of pedestrian injuries followed similar patterns as were observed for counts. Finally, all scenarios with CPP implementation resulted in a reduction in the average daily vehicles traveling in and around the Manhattan central business district, as compared to no CPP implementation.

As noted above, a model interface to explore the model in more detail and to run policy simulations, as demonstrated above, is available at: https://exchange.iseesystems.com/public/beckynaumann/cpp-and-pedestrian-injury/index.html.

Conclusions

Our project extends previous research on CPP impacts. We built an SD simulation model to explore the potential feedback structure and mechanisms producing pedestrian injuries over time and the effects of a CPP (and corresponding interventions) on injury outcomes. We found that policy scenarios involving differences in how the CPP is configured and revenue is invested resulted in similar congestion reductions. However, there was considerable variation in the pedestrian injury outcomes by scenario type. Some scenarios had deleterious effects on pedestrian safety (Scenarios B & C), while others (Scenarios D-G) offered improvements in pedestrian safety, while also limiting congestion. **One important policy take-away from this work is that a CPP combined with other pedestrian efforts has considerable potential for positive gains in public health.** On the other hand, adopting a CPP and discontinuing infrastructure investments in safety could have a strong negative effect on safety (e.g., Scenario B).

Discussion and Next Steps

Congestion pricing policies (CPPs) have been implemented in cities such as London, Milan, and Stockholm and continue to be considered in urban regions worldwide. There is a large body of research on CPPs including research on CPP impacts on traffic flow and vehicle efficiencies, driver choices/behaviors, air pollution and vehicle emissions, and public perceptions and acceptability. In this three-part research project, we:

- Conducted a bibliometric analysis to summarize research output, trends, patterns, and gaps in the CPP evidence base.
- Synthesized research on safety-related impacts of CPPs, examining a variety of crash- and injury-related outcomes.
- Used the evidence base as a foundation, along with our Phase 1 findings, to build a system dynamics learning model to explore the potential pedestrian safety impacts of a zone-based CPP under a range of scenarios.
- Built a user-friendly interface to allow individuals to explore the CPP system dynamics model and interact with a policy simulator to test the effects of different CPP-related policies on injury outcomes.

Key takeaways from this work included:

- CPP research grew significantly between 1956 and 2021, with the highest productivity in 2015 (n=122 articles/reports).
- Prevalent topic areas within CPP literature included: factors affecting policy implementation (e.g., design consideration, public perceptions, political acceptability), simulation modeling approaches to understand network dynamics, and impacts of CPP implementation (e.g., traveler choices, air quality/emissions).
- Research gaps identified by this analysis included equity considerations, examination of CPP impacts on specific road user types (e.g., pedestrians, bicyclists), and safety impacts for all road users.
- Only 18 studies or reports analyzed safety impacts of CPPs with considerable heterogeneity in policy specifications (e.g., time-varying tolls), data used, safety outcomes measured/estimated, and methods used, make it difficult to arrive at overall conclusions regarding safety impacts of all CPPs.
- Publications about London's zone-based policy were the most prevalent and seemed to suggest that such policies can have positive impacts overall but that the trends can vary by road user type (e.g., bicyclists, pedestrians) and over time (e.g., immediate vs. 2-3 years out). Some road users may experience temporary increases in crashes following policy implementation, potentially due to changes in travel modes and increased exposures (e.g., bicyclists, motorcyclists); however, these patterns may reverse in longer follow-up periods, resulting in lower crash and injury levels compared to pre-policy. An exception to this was pedestrian injuries, which experienced increases two to three years post-implementation. Further research is needed to examine the generalizability of London CPP findings to other contexts.
- We built a SD simulation model to conduct an original analysis of NYC's potential CPP implementation on future pedestrian injury trends, exploring effects based on a range of policy scenarios. We found that policy scenarios involving differences in how the CPP is configured and revenue is invested resulted in similar congestion reductions. However, there was considerable variation in the pedestrian injury outcomes by scenario type. Some scenarios had deleterious effects on pedestrian injury counts, while others offered improvements in pedestrian safety.
- One important policy take-away from this work is that a CPP combined with other pedestrian efforts has considerable potential for positive gains in public health. On the other hand, adopting a CPP and discontinuing or reducing infrastructure investments in safety could have a strong negative effect on safety.

Next steps include understanding how COVID-19 dynamics interact with CPP dynamics to alter outcomes. Additionally, future research should examine broader impacts of these policies on other health outcomes and safety outcomes for other road users (e.g., cyclists), as well as carefully explore equity impacts.

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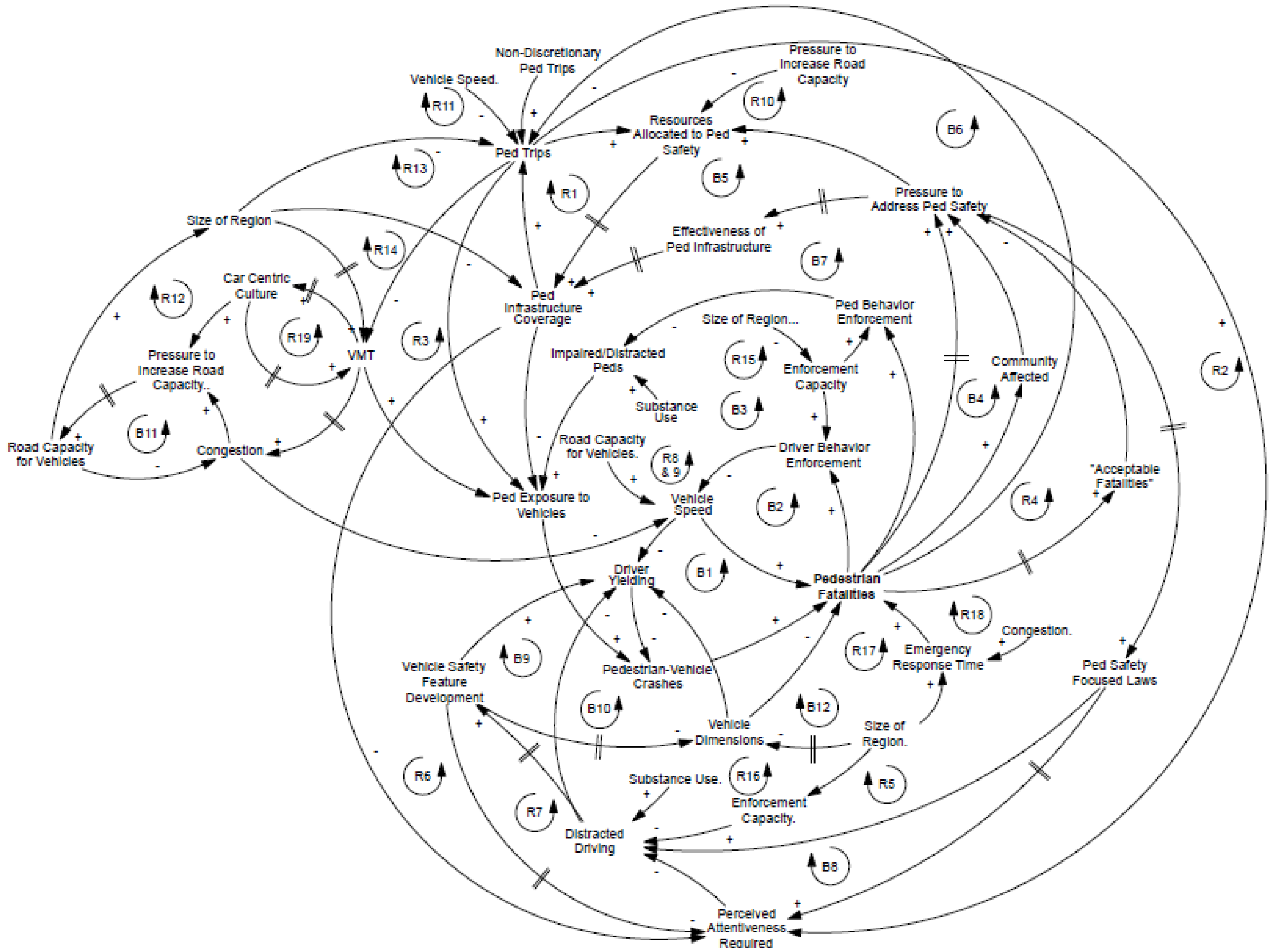
Appendix

Appendix 1. Causal loop diagram of hypothesized mechanisms driving increased pedestrian death rates



Note: For a complete description of this diagram, data collection and analysis methods, and key takeaways, please see: Naumann RB, Kuhlberg J, Sandt L, Heiny S, Kumfer W, Marshall SW, Hassmiller Lich K. Integrating complex systems science into road safety research and practice, Part 2: Applying systems tools to the problem of increasing pedestrian death rates. Injury Prevention. 2020;26:424-431.

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