Congestion Pricing Policies and Safety Implications: a Scoping Review

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Abstract Congestion pricing policies (CPPs) are a common strategy for addressing urban traffic congestion. Research has explored several impacts of these policies (e.g., air quality, equity, congestion relief). The purpose of this review was to synthesize findings from publications examining CPP impacts on road user safety outcomes. We conducted a systematic

search of relevant literature in four large research databases (Transport Research International Documentation, Web of Science, PubMed, and Scopus), searching from database inception through January 2021. We identified 18 eligible publications. Safety-related outcomes included overall crashes and injury crashes with stratification by injury severity and road user type (e.g., bicyclist, pedestrian). A majority of the publications examined zone-based CPPs ($n=13$) and used observed data involving real policies ($n=10$), as compared to a predicted or simulated analysis. Decreases in overall crashes and injuries for some road users were observed (e.g., car occupants). While some studies estimated short-term increases in injuries and crashes for bicyclists and motorcyclists (likely due to shifts from personal vehicle use to other transportation modes and increased exposure), most analyses focused on longer-term impacts and generally found a reversal and eventual decrease in injuries and crashes after a few years. The relative scarcity of safety outcomes in published literature, along with the wide breadth of CPP types, implementation contexts, and outcomes measured, demonstrates that more research on safety outcomes is needed. Cities and regions planning to implement CPPs should consider potential mode shifts and safety supports for all road users (e.g., bicycle and pedestrian infrastructure).

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Introduction

Traffic congestion is a growing problem in the USA (US) and around the world, particularly in urban centers. In the USA alone, a total of 3,261,772 vehicle-miles were driven in 2019, compared to 2,691,335 in 1999[1]. Congestion that is both affecting and affected by these travel trends is likely in part generated by land use patterns characterized by sprawl with expansion of urbanized areas, corresponding increases in distances between housing and other destinations, and travel routes where more and more people are forced to take longer trips on constrained road systems. These factors have resulted in negative impacts on travel time and air quality and present a significant burden on society. A survey of almost 500 USA urban areas showed that urban Americans spent an excess of 8.8 billion hours in travel time and an excess of 3.3 billion gallons of purchased fuel as a result of congestion in 2017, amounting to \$179 billion in total congestion costs[2]. In 1982, however, total congestion costs equated to \$15 billion (in 2017 USD)—indicating that the burden of congestion in the USA has increased drastically in the last several years [2].

Congestion pricing has been explored as a way to reduce congestion and consequently reduce the aforementioned consequences, by using pricing strategies to change driving choices and behaviors to shift traffic towards less congested roadways, off-peak travel periods, to other transportation modes (e.g., transit, bicycle), or to eliminate trips altogether [3]. Congestion pricing policies (CPPs) have been implemented in cities and regions around the world, including London, Singapore, and Stockholm [3]. The structure of these policies varies. The US Federal Highway Administration groups CPPs into toll-based and non-toll-based policies. Toll-based policies include (1) variably priced lanes, (2) variable tolls on entire roadways, (3) zone-based or cordon charges, and (4) area-wide or system-wide charges [3, 4]. Non-toll-based policies include priced vehicle sharing, parking pricing, and mileage-based user fees [4]. This review focuses on toll-based policies, which are frequently researched, already exist in numerous cities and regions, and are currently being considered and/or are under development in cities such as New York City, Beijing, and San Francisco [5, 6].

There is a large body of original research, structured reviews, and other publications on CPPs including, but not limited to, simulation analyses of CPPs and their impacts on maximum traffic flow efficiency, impacts on congestion in specific cities/regions, driver choices/behaviors, air pollution/vehicle emissions, and public perceptions and acceptability [5, 7–15]; however, there appears to be relatively little research on potential safety impacts. If CPPs are successfully implemented, they can result in areas with less congested roadways, which may result in higher vehicle travel speeds—known to increase injury severity and risk of death when crashes happen [16]. Further, increased vehicle speed may inadvertently reduce vulnerable road user safety, and particularly pedestrian and bicyclist safety, travel modes that CPPs are often designed to increase.

Given the large and increasing burden of crashes, it is critical for transportation policy to center around safety. In 2019, there were an estimated 6,756,000 police-reported motor vehicle crashes across the USA, resulting in 36,096 fatalities and an estimated 2,740,000 injured people [17]. Road traffic crash fatality counts have increased by more than 10% over the last decade; and although this number decreased in 2020, the crash fatality rate (per 100 million vehicle miles traveled) has continued to increase since the start of the COVID-19 pandemic, despite fewer vehicle miles traveled [18–20]. Therefore, as cities consider such policies for reducing congestion, there is a need to understand the current state of the literature on road safety impacts overall and whether there are potential unintended consequences. As such, the purpose of this review was to systematically synthesize and summarize publications examining the association between toll-based CPPs and road user injury and safety outcomes.

Methods

Databases

We systematically searched the literature using a protocol consistent with Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines. A trained health sciences librarian and co-author on this study helped formulate the search strategy, which included the following four databases:

Transport Research International Documentation (TRID), Web of Science, PubMed, and Scopus. Released in 2011, TRID is one of the most extensive bibliographic resources on transportation research, containing over 1.25 million research records from two databases: Transportation Research Board's (TRB) Transportation Research Information Services database and the Transport Research Centre's International Transport Research Documentation database. TRID, which is produced and maintained by TRB and sponsored primarily by state Departments of Transportation and the US Department of Transportation, is cross-disciplinary and includes US and international research, including peer reviewed publications and government research reports, on all modes of transportation. Web of Science, PubMed, and Scopus each access multiple peer-reviewed journals to create comprehensive databases of research and scholarly literature. Databases were searched from their dates of inception through January 24, 2021.

Search terms

To guide the publication search process, we relied on the definition of CPPs as described by the US 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 works by shifting purely discretionary rush hour highway travel to other transportation modes or to off-peak periods..." [3]. Specifically, we focused on four types of toll-based policies: variably priced lanes (e.g., toll lanes and high occupancy toll lanes), variable tolls on entire roadways (e.g., toll roads and bridges), zone- and cordon-based charges (variable or fixed fees to drive into or within a designated area, implemented on multiple roadways/entry-points and usually for specific parts of a city), and area-wide or system-wide charges (per-mile charges on all roads within an area).

Search terms were compiled to align with the definitions above. The search strategy included combinations of terms related to (1) transportation, road, or traffic; (2) price(ing) or toll(s/ing) or charge(ing) or fee(s) or tax or policy; (3) congestion or area or zone(al) or distance or cordon or dynamic; and (4) safety, injury(ies), casualty(ies), death(s), and lives. The complete, reproducible search strategy with

detailed search terms for all four databases is provided in the Appendix.

Inclusion/exclusion criteria

We included only peer-reviewed literature and published reports (e.g., government reports) and excluded other record types (i.e., news/media articles, commentaries, position papers, reviews/syntheses). No restrictions were placed on language of the publication; however, we required all documents to have an abstract or summary in English. We included publications that simulated or predicted CPP impacts, as well as evaluations of implemented policies. Additionally, only those publications that focused on policies which met the definition of a toll-based CPP and included discussion of safety outcomes were included. Publications that discussed policies that were implemented only for the purposes of generating revenue, but not to control traffic congestion, improve travel time, or reduce traffic, were excluded. Finally, this review focused specifically on roadway CPPs and, therefore, excluded CPPs involving air, train, or other non-roadway travel.

Screening strategy and data extraction

Publications identified using the search strategy presented above were input in Covidence (<https://www.covidence.org>), an online screening and data extraction tool for streamlining the systematic review process. The first step was a title and abstract screening. Publications that remained after this step were then included in the full-text screening, which also included a review of references to identify any additional publications that may have been missed. Publications identified in this way were then screened (full-text) for inclusion in the review. For both screening steps (title/abstract and full-text review), two members of the study team reviewed the publications independently within Covidence. The reviewers discussed any screening disagreements (identified by Covidence) and made final decisions together for exclusion or inclusion into the next step of the screening process. Finally, full-text publications were reviewed for final inclusion by both reviewers independently, again with agreement reached

through discussion. A PRISMA diagram outlining this process is presented in Fig. 1. We thoroughly examined all publication meeting full eligibility criteria and extracted several key components, guided by a data extraction form designed by co-authors to align with the review purpose. Form elements included study/report purpose, policy(ies) examined, design/methods, data sources, location/setting, time period, safety outcomes/measures, safety-specific results, other outcomes examined, assumptions, strengths, limitations, and key conclusions.

Fig. 1 PRISMA Diagram* *Transport for London (TfL) Impact Monitoring Series counted as one publication in this diagram and in this review

Results

Through the multi-database search, we identified 366 publications (Fig. 1) for screening. We screened 262 titles and abstracts after removing 104 duplicates. One hundred eighty-eight were deemed irrelevant in this screening stage, leaving 74 publications for the full-text review. During review of these publications, 5 additional studies were added from references into the review. Of the 79 publications in the final full-text review, 18 publications were identified as eligible and included in the final extraction process [6, 21–42]. The impact monitoring series of six annual reports by Transport for London (TfL) is counted throughout as a single publication for the purposes of this review, as these reports incrementally built off of each other with each year adding additional data but maintaining similar methods and scope [32–37].

General study characteristics

For the 18 studies, publication years ranged from 1989 to 2021 (Table 1). Eight publications focused completely or partially on simulated data and/or projections under a hypothetical CPP, while the remaining evaluated existing policies and used observed data only ($n=10$).

Settings included four in the USA, nine in the United Kingdom (UK), and five in other European countries. Eight of the nine UK publications examined London specifically. Thirteen of the 18 publications included safety as a primary focus of the analysis and article; however, all publications presented at least one finding related to safety (per eligibility criteria). Key policy attributes, types of study data, safety-related measures, and key findings by road user type are described in Table 1.

Types of congestion pricing policies examined

Identified publications examined three of the four types of pricing policies we searched for zone- and cordon-based, variable and static tolls on entire roadways, and area- and system-wide CPPs (Table 1). Zone- and cordon-based CPPs were described in 13 publications, and all included a time-varying (e.g., time of day, weekday vs weekend) component to the charges. Some policies also included exemptions for specific vehicle types, such as taxis, buses, and

Table 1 General characteristics of safety-related congestion pricing policy publications ($n = 18$)

Characteristic	<i>N</i> (%)
Year published	
2000 and earlier	2 (11.1)
2001–2010	6 (33.3)
2011 and later	10 (55.6)
Country	
USA	4 (22.2)
UK	9 (50.0)
Other	5 (27.8)
Publication type	
Peer-reviewed journal article	16 (88.9)
Government/technical report ¹	2 (11.1)
Policy type	
Zone- and cordon-based	13 (72.2)
Variable tolls on entire roadways	3 (16.7)
Area- and system-wide	2 (11.1)
Variably priced lanes	0 (0.0)
Data type	
Simulated data only	6 (33.3)
Observed data only	10 (55.6)
Simulated and observed data	2 (11.1)
Safety as primary focus	
Yes	13 (72.2)
No	5 (27.8)
Type of safety outcomes measured²	
<u><i>Direct measures</i></u>	
Crashes (injury and non-injury crashes)	11 (61.1)
Any injury types (including overall “car casualties”) ³	10 (55.6)
Stratified injury severity categories ⁴	6 (33.3)
<u><i>Indirect measures</i></u>	
Economic valuations corresponding to at least one direct measure of safety	4 (22.2)
Changes in quality-adjusted life years	1 (5.6)
Vehicle-miles-travelled per work-person trip (for relative exposure and probability of crash)	1 (5.6)
Congestion level (for relative crash severity and probability of crash occurrence)	1 (5.6)
Specific vehicle/road user outcomes evaluated²	
Bicyclists	6 (33.3)
Motorcyclists (and other powered two-wheeled users)	4 (22.2)
Pedestrian	2 (11.1)
Taxis	2 (11.1)
Buses, cargo trucks, and other heavy vehicles	2 (11.1)

¹Transport for London (TfL) report series counted as 1 publication²Not mutually exclusive³Car casualties are defined as crashes with at least one injury of any severity⁴This category is a subset of the “Any Injury Types” category. Detailed Injury Severity categories, where available, vary and include fatal/non-fatal and slightly injured/killed-or-seriously injured

alternative-fuel vehicles, while one was combined with a network-wide toll proportional to travel time. Three publications described time-of-day variable tolls on specific roadways. Area- and system-wide charges, a less popular form of CPPs, were described in two publications. Although numerous studies of variably priced lanes were identified in the title/abstract screening stage, none were identified as discussing the policy's safety impacts and, therefore, were not included in this review.

Observed vs simulated data

Broadly, two types of data were used in CPP research examining impacts on safety-related outcomes: (1) observed data following implementation of real policies and (2) simulated data for the purpose of predicting outcomes of currently implemented policies or for hypothetical policies that had not been implemented. Of the 18 publications examined, 10 used observed data only, six used simulated data only, and two used both observed and simulated data. Studies using simulated data use scientific evidence and/or expert opinion to develop and parameterize models, which were then used to project outcomes (including safety). For example, Yu et al. built their simulation model using pre-existing data, as well as rates and other model parameters from prior research, with the study purpose of comparing simulated outcomes under two different CPPs [6]. Studies using both observed and simulated data included comparison of observed pre-CPP data to simulated post-CPP data [21], and a combination of simulated predictions published pre-CPP and observed findings published post-CPP [32–37].

Safety measures

Types of measures used to assess CPP safety impacts varied considerably across the literature and are summarized in Table 1. The most common safety impact measures were crashes ($n=11$) and injury crashes/car casualties ($n=10$; “car casualty” defined as a crash including at least one vehicle and at least one injury of any severity). Six publications provided stratified results for injury crashes by injury severity (fatal/non-fatal and slightly injured/killed or seriously injured) [22, 23, 25, 29, 32–37, 42]. One study considered risks of fatal and non-fatal injury outcomes in their calculation of life expectancies and overall

health benefits [6]. Other indirect measures of safety included additional calculations of the cost/economic valuations of the direct safety outcomes measured and efficiency (e.g., congestion level) of the roadway/region to which the CPP applied. Measures also varied by type (counts, percent changes, and rates) and over different time intervals (monthly or annually).

Key findings

Overall road traffic crashes and casualties

Sixteen of the 18 publications reported findings or estimates of reduced traffic-related harms and increased safety benefits as a result of implementing a CPP for at least one measured safety outcome and/or in at least one scenario/analysis (see Table 1 for list of measured safety outcomes; see Table 2 for findings of the 18 publications) [6, 21–30, 32–39, 41, 42]. Estimated reductions of the number of road traffic crashes following CPP implementation included 3.6% per year in Stockholm's zone-based charging area and 35% per month in London's zone-based charging area [23, 27]. Further, an additional study of London's policy observed not only a 46.3% decrease in road traffic crashes in the charging zone but also observed significant decreases in non-charged areas adjacent to the charging zone [30]. Consistent with these studies, Balwani and Singh also projected decreases in crashes as a result of congestion charges using simulated data [41].

Changes in the number of fatalities varied even more dramatically across studies, anywhere from no observed changes in the three years following CPP implementation in Milan to decreases as high as 33% in the 2 years following implementation in London [22, 26]. In London specifically, two studies of changes in car casualties in the first year post-implementation found 3.4% and 5.2% reductions (using Box and Tiao intervention and difference-in-difference approaches, respectively) [25, 28]. Other studies observed a 27% reduction over 2 years post-implementation (calculated per month) [26], and an overall 4.3% reduction over 4 years post-implementation [29]. Also in London, the fifth report of the TfL series, which compared numbers for measured outcomes from similar periods across multiple years (e.g., Mar 2003–Feb 2004 versus Mar 2004–Feb 2005), estimated that through three years post-implementation, traffic

Table 2 Key elements and attributes of safety-related congestion pricing policy publications by study ($n = 18$)

First author. Title. (Year of publication)	Congestion pricing policy(ies) examined	Study setting and time period	Is safety a primary focus?	Safety outcomes measured*	Key safety-related conclusions*
Yu et al. The cost-effectiveness of competing congestion pricing plans in New York City. (2019)	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	Yes (as part of health benefits)	QALY, indicating the quality and quantity of lives	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) **	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	Yes	Pedestrian injuries from vehicle-related crashes; Bicyclist injuries from vehicle-related crashes	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)	Zone-based policy with time-varying charges	Milan, Italy 2001–2011 data involving a real policy established in January 2008	Yes	Total crashes, fatal and non-fatal injuries	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)	Zone-based policy with time-varying charges	Stockholm, Sweden April–May 2005 and April–May 2006 data involving a real policy (implemented in January 2006)	No, part of a larger cost-benefit analysis	Total crashes, KSI, and slightly injured, and corresponding economic valuations	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

Table 2 (continued)

First author. Title. (Year of publication)	Congestion pricing policy(ies) examined	Study setting and time period	Is safety a primary focus?	Safety outcomes measured*	Key safety-related conclusions*
de Palma and Lindsey. Modelling and evaluation of road pricing in Paris. (2006)	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	No	Crash costs (assumed to be proportional to distance travelled)	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)	Zone-based policy with time-varying charges	London, UK 1991–2004 observed data involving a real policy	Yes	Total, car, motorcyclist, and bicyclist casualty crashes (for KSI and slightly injured)	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)**	Zone-based policy with time-varying charges	London, UK 1991–2005 observed data involving a real policy	Yes	Car casualty crashes	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)

Table 2 (continued)

First author. Title. (Year of publication)	Congestion pricing policy(ies) examined	Study setting and time period	Is safety a primary focus?	Safety outcomes measured*	Key safety-related conclusions*
Green et al. Traffic accidents and the London congestion charge. (2016)	Zone-based policy with time-varying charges	London, UK 2000–2009 observed data involving a real policy	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	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)	Zone-based policy with time-varying charges	London, UK 2001–2004 observed data involving a real policy	Yes	Car casualty crash and injuries for all road users, motorcyclists, and bicyclists	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)	Zone-based policy with time-varying charges	London, UK 1998–2007 observed data involving a real policy	Yes	Total, slightly injured, and KSI car casualty crashes	The charge resulted in significant reductions of total casualties, slightly injured, and KSI (decrease of 4.29%, 5.05%, and 12.12%, respectively)

Table 2 (continued)

First author. Title. (Year of publication)	Congestion pricing policy(ies) examined	Study setting and time period	Is safety a primary focus?	Safety outcomes measured*	Key safety-related conclusions*
Ding et al. Affected area and residual period of London Congestion Charging scheme on road safety. (2021)	Zone-based policy with time-varying charges	London, UK 2005–2006 and 2011–2013 observed data involving a real policy	Yes	Crashes	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 1 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)	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	Yes	Total, slightly injured, and KSI bicycle crashes	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

Table 2 (continued)

First author. Title. (Year of publication)	Congestion pricing policy(ies) examined	Study setting and time period	Is safety a primary focus?	Safety outcomes measured*	Key safety-related conclusions*
Transport for London. Central London congestion charging: Impacts monitoring, 1st–6th annual reports (2003–2008)** T	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)	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	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 3 years post-implementation
deCorla-Souza and Gupta. Evaluation of demand-management strategies for Toledo's year 2010. (1989)	Variable tolls on entire roadways (time-varying charges)	Toledo, Ohio, USA Hypothetical data projected out over 20 years (until 2010) involving simulated policies	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)	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

Table 2 (continued)

First author. Title. (Year of publication)	Congestion pricing policy(ies) examined	Study setting and time period	Is safety a primary focus?	Safety outcomes measured*	Key safety-related conclusions*
Fagnant and Kockelman. Anticipating roadway expansion and tolling impacts: Toolkit for abstracted networks. (2014)	Variable tolls on roadways (time-varying charges)	Austin, Texas, USA Hypothetical 20-year projection involving simulated policies	Yes	Crashes, crash costs	Crash impacts varied by scenarios, with several showing decreases (one had a 6.4% decrease in total crashes and 1708 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
Albalade. Shifting death to their alternatives: The case of toll motorways. (2011)	Area-/system-wide charges	Spain 2006 observed data involving a real policy	Yes	Crashes involving fatal or non-fatal injuries only (“car casualty crashes”)	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)	Area-/system-wide charges	Leeds, UK Hypothetical data under simulated policies, projected out from 2006 to 2066	No	Crashes	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)	Variable tolls on roadways (time-varying charges)	Belgium Unspecified time period of a simulated policy, projected from 1990	Yes	Crashes (based on total traffic volume)	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

* Abbreviations: QALY = Quality-adjusted life year, CPP = Congestion pricing policy, KSI = Killed and severely injured/injuries

** Articles identified through reference review, as opposed to those identified in initial Covidence review

† This is a series of 6 annual reports

changes caused by the zone-based charging scheme were ultimately responsible for the reduction of 40–70 additional injury crashes per year beyond the crash reductions that were expected to occur as the result of all road safety initiatives and a general declining trend in road traffic crashes [36].

Other studies ($n=2$) revealed observed and simulated increases in traffic-related harms as a result of CPP implementation. For example, one study evaluating an area-wide CPP in Spain documented increases in observed injury crashes, as a result of traffic patterns shifting to non-tolled areas [40]. Similarly, a simulated study of variable tolls in the USA indicated potential injury crash increases as a result of these shifting patterns [39].

Motorcyclists

Examinations of the London congestion charge were the only publications with results pertaining to motorcycles/powered two-wheelers. Li et al., using Box-Tiao intervention analysis methods, estimated a 5.7% increase in total motorcycle casualties (injuries of any severity) in the year immediately post-CPP implementation, with a 17.3% increase in the number killed or seriously injured (KSI) and a 1.8% increase in the number slightly injured [28]. In contrast, Noland et al. used a difference-in-difference estimation approach (also with different adjustment variables) and did not observe significant changes in motorcyclist casualties within the London charging zone during the same post-implementation period; however, the authors observed a slight increase in KSI and large increase in slight injuries (16%, or 40 more casualties per month) immediately adjacent to the charging zone [25]. Findings in both studies were attributed to increases in motorcycle miles traveled following CPP implementation, quantified as a 15% increase within the charging zone by Noland et al. [25]. Furthermore, the TfL series reported that the average number of powered two-wheelers was slightly greater during post-CPP years compared to prior; however, involvement of these vehicles in crashes notably decreased with each consecutive year [33–36].

Bicyclists

Observed and estimated changes in bicycle crashes and injuries varied in magnitude and direction,

particularly based on time since CPP implementation. Li et al., using a difference-in-difference approach with control cities, observed an increase of 13.3% in bicycle injuries resulting from crashes during the year immediately following London CPP implementation—consistent with findings by Noland et al. and Green et al. (using a Box and Tiao intervention approach and a difference-in-difference with synthetic control approach, respectively) [25, 27, 28]. Green et al. then observed an overall decrease several years after implementation in London. [27] In contrast, the TfL series, which compared numbers from similar periods across multiple years (e.g., Mar–Nov 2001 versus Mar–Nov 2004), observed decreases in bicycle crash involvement in the 2 years after London CPP implementation, followed by an increase in the third year bringing the number close to pre-congestion levels [33–36]. Wier et al. predicted an increase in vehicle-bicyclist injury collisions when simulating data up to 10 years post-CPP implementation in San Francisco [21]. However, this study also concluded that this increase would be less than the predicted increase without CPP implementation (i.e., 15 additional bicyclist injuries per year with CPP vs. 20 without CPP) [21]. Further, increases in bicyclist injuries also were observed when the CPP was assessed in conjunction with other road user strategies. Specifically, an examination of a “cycle for hire” scheme in London (launched to promote cycling as an alternative transport mode) found that regions with both this scheme and a CPP, compared to regions without the CPP, had significantly greater numbers of overall and slight injury bicycle crashes—which authors stated may have been due to CPP-related shifts from vehicle use to alternative modes such as bicycles and walking [31]. Although they examined CPP implementation in different cities and examined different types of data (observed vs. simulated), the publications by Green et al., Wier et al., and Ding et al. all attributed observed increases in the number of bicyclist injuries due to mode shifts and increases in bicycle use [21, 27, 31]. Specifically, following initial implementation of the London congestion charge, TfL estimated that bicycle flow increased with each year, and Green et al. observed a 66% increase in bike-miles traveled in the 6 years after initial implementation in London [27, 33–37].

Pedestrians

Similar to their 10-year predictions of bicyclist injuries, Wier et al. estimated from their partially simulated study that the number of vehicle–pedestrian injury collisions per year would remain the same (even with increased pedestrian traffic) if a CPP were implemented and that there would be a 10% increase in the count of pedestrian injuries if a CPP were not implemented [21]. The authors attributed the findings to assumptions of reduced vehicle-miles traveled under a CPP scheme while also acknowledging the model did not account for speed or other factors that could increase collision risk. The TfL series observed no significant change in the proportion of crashes affecting pedestrians (compared to vehicle occupants/riders) in the year immediately following implementation but then observed slight increases in this proportion in years two and three post-implementation [33–36]. Authors of both publications suggested these findings may be due to increased pedestrian activity and/or shifts in transportation mode (e.g., reduced vehicle activity) [21, 33].

Taxis and large vehicles (e.g., buses, trucks)

When estimating changes in the absolute numbers of taxi and bus/coach involvement in crashes following CPP implementation, the TfL series first observed an increase in the first year and a decrease in the second year. In the third year after CPP implementation, results varied as the number of taxis involved in crashes increased, while bus/coach involvement decreased. It is important to note, however, that taxis constituted a greater proportion of all vehicles entering the congestion zone during charging hours post-implementation compared to pre-implementation, while bus proportions remained somewhat stable. Finally, the TfL series observed that the number of goods vehicles (e.g., trucks) involved in crashes consistently decreased with each year post-CPP [33–36]. Green et al. assessed taxis and buses as part of a group of uncharged vehicles (including bicycles and motorcycles) under the London CPP and determined that while there was an increase in distance travelled by these vehicles, the number of crashes involving uncharged vehicles decreased by 12% [27]. Authors suggested this finding may

reflect the decreased number of charged vehicles on the road, which therefore reduced the odds of uncharged vehicle involvement in crashes.

Discussion

Traffic congestion places an increasingly significant burden on commuter travel time, expenses, quality of life, air quality, productivity, and regional economies [2, 3]. CPPs are widely recognized as a potential solution for these problems. While the impacts of such policies on congestion, emissions, revenue generation, and public acceptability have been explored [5, 7, 13–15, 43], we found a relatively sparse body of literature evaluating CPP impacts on road user safety. This review explored the findings of 18 publications with original analyses of CPP impacts on safety-related outcomes.

Publications varied between use of observed data and simulated data, safety outcomes assessed, specific policies examined, and analysis methods and approaches. The dearth of studies and range of specific policies, outcomes examined, and context creates challenges for drawing firm conclusions about policy impacts. A large proportion of studies in this review were about the London congestion charge, which was first established in 2003 and then modified and expanded in later years. Findings from London-based studies suggested that CPPs can provide some positive impacts on road user safety. However, some modes of transportation experienced initial decreases in safety immediately following CPP implementation (e.g., bicycles, motorcycles), likely due to mode shifts and increased exposure and possibly due to changing traffic flow/speeds as well. Many of these effects reversed and then improved, resulting in fewer injuries by three years post-implementation. 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 congestion charge (a zone-based CPP) findings to other contexts, particularly to other types of CPPs, and to examine longer follow-up periods to determine if impacts level-off or continue to change.

Methodologic considerations

There were several types of study designs and analysis approaches used across included publications (e.g., difference-in-differences analysis, synthetic control study design). Pre- vs. post-CPP implementation-based studies were most common, particularly among the publications analyzing the London congestion charge. Pre vs. post studies without an “unexposed” comparison group can run the risk of producing effect estimates that are biased by time-varying confounding (e.g., changes in secular trends). Examples of studies that used specific analytic features that reduced the potential for bias include those by Percoco and Noland et al., who used time series approaches designed to reduce bias from trend and seasonal effects, and Li et al., who used a difference-in-difference model to reduce bias due to regional differences [22, 25, 28]. Future research should consider potential biases, such as these, in study design and analysis approach selection. Second, the safety outcomes evaluated varied and were not always clearly defined, making comparisons across studies difficult. For example, studies that included crash counts as an outcome did not always clearly specify if their counts included crashes with motorist injuries only, or also cyclist, pedestrian, and other road user injuries. Further research and synthesis could benefit from explicit outcome definitions. Additionally, some studies measured indirect safety outcomes, such as changes in quality-adjusted life years, crash costs, and congestion levels [6, 24, 38, 42]. Although these studies provide valuable insight into safety implications of CPPs, it was not feasible to make comparisons across study findings in this review as these measures did not appear across multiple studies. Third, simulation-based studies, which can help examine the specific mechanisms that lead to CPP-related outcomes, come with their own specific considerations, primarily related to model assumptions. Among studies assessing short-term outcomes, assumptions included that changes in traffic were due to introduction of CPPs alone and that effects observed in the analyses would remain consistent several years post-implementation [23]. Studies measuring indirect effects included assumptions of proportionality—for example, that crash rates are directly proportional to vehicle-miles travelled and congestion levels [24, 38]. Most publications using simulated data explicitly acknowledged

an inverse relationship between congestion levels and vehicle speeds [6, 21, 24, 32, 38, 41, 42]; however, few considered the complex relationships between these two parameters and crash occurrence or injury severity [6, 21, 32, 38, 39]. Additional simulation studies that incorporate these complex relationships and others, drawing on systems science models such as agent-based models and system dynamics simulation models, are warranted, as they could help test and account for this complexity.

Policy and equity considerations for future CPP implementation

There are several safety-related considerations that warrant attention in future CPP research, discussion, and implementation. Equity is a rarely mentioned but necessary consideration when evaluating CPP impacts, particularly safety impacts. CPPs have the greatest impact on two groups of individuals: regular commuters and residents of charging zones (where applicable). Travelers who are able to more easily afford charges can maintain their previous travel routes, while others may be forced to make alternate plans. This may include taking a longer route, where the saved congestion charges are offset by the costs associated with additional fuel use, vehicle wear, and lost time, or switching to another mode of transportation, such as public transit or bicycling. The latter option may have the additional consequence of increased risk of injury. For example, several publications in this review attributed post-CPP increases in bicyclist collisions to shifts in travel modes and a sudden influx of new bicyclists on roadways [21, 27, 31]. Further, spatial equity concerns arise as individuals who live and work in different places would be impacted differently by congestion charges from those who live and work in the same area [44]. Re-routing may also increase congestion in other areas that are less empowered to reduce traffic flow and consequently cause changes in the number of vulnerable road users injured/killed in those areas, with a potential disproportional impact on less empowered minorities. In addition to changing travel modes, congestion pricing often provides a new revenue stream for local governments. Options for using this revenue include decreasing income taxes (particularly for lower income individuals); reinvesting in pedestrian, bicyclist, or public transit infrastructure; or providing

subsidies for using alternate routes [43, 45, 46]. Some of these options may help reduce inequities created by congestion pricing and have the additional benefit of increasing public acceptability for these policies—the extent and direction of these inequity impacts should be measured prior to policy implementation. Finally, although safety is not the primary purpose behind implementation of a CPP, it is the primary goal of other transportation-related initiatives such as Vision Zero and Safe Systems [47], which have become a significant goal in cities/regions around the world in recent years. Therefore, appropriate consideration should be given to how CPPs can fit within these frameworks and provide a safe environment for all road users, along with a clear understanding of potential changes in travel behaviors, revenue generation and reinvestment, and social and safety inequities that may result from policy implementation.

Strengths and limitations

This review had several notable strengths and limitations. First, search criteria were run through multiple databases with different target audiences, so a wide net was cast for identifying eligible publications. Although search terms and criteria varied slightly because of the different structures of these databases, we anticipate no significant impact on our final results as all identified publications were thoroughly screened for final inclusion in this review by two authors. Agreement by both authors was required at all screening stages to ensure eligibility and reduce potential bias. Second, this review included reports, as they may provide an insight different from what is presented in peer-reviewed literature. This review was also not formally restricted by dates in an effort to understand the extent of safety-related CPP literature; however, we were restricted to when databases were first created. Publications required at least an abstract or summary in English, which may have eliminated some international literature. Given that congestion pricing is a strategy used around the world, this review may be missing important conclusions from international congestion pricing studies and strategies. Third, conclusions about safety impacts may not be generalizable given the wide range of CPP types and contexts (e.g., geographic location), methods used, and the significant variation in data sources and types of measured outcomes. For example, although

the multiple publications focusing on the London congestion charge suggest significant benefits may be realized after CPP implementation for some road users, these findings may only apply to cities with similar infrastructure, demographic distributions, and type of CPP implemented. Further, the policies discussed in this review often included different combinations of policy exemptions and variation in other structural components (e.g., time-varying tolls, exemption of certain vehicle types); however, there is insufficient evidence for determining what specifically is leading to the observed differences in safety impacts. Future research, particularly simulation studies, can help disentangle the mechanisms that may be involved in generating positive safety outcomes, helping to identify CPP components critical for improving road user safety. Finally, safety is only one of the many aspects of health, so an additional, more extensive review of the literature is required to understand health implications of CPPs on a broader scale. However, by specifically examining “safety” on an international scale, this review comprehensively expands on a rarely explored aspect of CPP impacts, which is critical as more cities/regions consider road safety strategies such as Vision Zero.

Conclusions

CPPs have been developed to address increased traffic congestion, particularly in urban centers, and have been studied widely in the literature. These policies have been implemented in cities around the world, including London, Milan, and Stockholm. The findings of this review suggest that there are potential safety benefits for some road users following CPP implementation. However, benefits may vary by road user type and according to length of time post-implementation. The relative paucity of research specifically exploring the safety outcomes of these policies, along with the wide breadth of CPP types, implementation contexts, outcomes measured, and relationships modeled, indicates a need for additional research. Before implementing CPPs, cities/regions should consider, within the context of their own community, potential mode shifts and safety-related supports for such mode shifts, equity concerns, appropriate revenue reinvestment, and benefits in both short- and long-term time frames.

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