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Review

A Systematic Review of the Role of Road Network Pricing in Shaping Sustainable Cities: Lessons Learned and Opportunities for a Post-Pandemic World

Tariq Munir [1,*], Hussein Dia [1] and Hadi Ghaderi [2]

[1] Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, VIC 3122, Australia; hdia@swin.edu.au
[2] Department of Business Technology and Entrepreneurship, Swinburne University of Technology, Melbourne, VIC 3122, Australia; hghaderi@swin.edu.au
* Correspondence: tmunir@swin.edu.au

Abstract: The growing number of studies on road network pricing requires adoption of systematic methodologies to assess research outcomes and provide an unbiased summary of research findings and lessons learned. This paper aims to identify and analyse primary studies related to a set of research questions on road network pricing that primarily address the effectiveness of road network pricing as a travel demand management strategy. The paper achieves this by consolidating the fragmented evidence on the topic and identifying the role of transport pricing in steering our post-pandemic cities on a path of sustainable urban mobility. The paper uses a reliable and auditable systematic approach to examine past and current research trends, resulting in a rational assessment of the role and impacts of road network pricing as a travel demand management strategy. The paper achieves this by performing a bibliometric citation analysis that identifies 105 articles of valuable research contributions that represent fundamental knowledge in the development of research covering the period between 2007 and 2020. Importantly, the review identifies four main research themes in the literature, namely implementation impacts, innovations in technology, acceptability, and modelling methodologies for determining impacts, that are core elements of the research effort on the travel demand management and sustainability aspects of road pricing. Inductive reasoning is then used to address emerging issues, applications, and the effects of road network pricing in reducing congestion and enhancing urban centre environmental quality. The paper concludes with a discussion of policy directions for overcoming barriers to the implementation of road network pricing as an effective strategy for addressing modern-day urban mobility challenges such as rising urban populations, emissions, and pollution particularly amid and post COVID-19. Finally, the paper provides a roadmap of future research opportunities that can heighten the role of road network pricing in shaping the directions of sustainable urban transport policies and strategies.

Keywords: road network pricing; congestion charging; travel demand management; transport taxation; transport policy; sustainable transport

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1. Introduction

Transportation pricing is an established and effective intervention that aims to find an equilibrium between the demand for people travel and the shipment of goods, and the provision of multimodal transportation capacity. Transportation pricing can be assessed from various transportation development and management perspectives. For example, the goals of pricing can include the requirements for facility preservation and management of life-cycle costs; managing the demand for travel; improving safety and reducing adverse environmental impacts; and supporting economic development and productivity through provision of reliable transportation infrastructure. Transportation pricing could therefore target one or all of these goals. In this paper, we focus on one aspect, namely the role of transportation pricing in managing the demand for travel, due to its importance for cities that are starting to open up post-COVID. Evidence from recent mobility indicators already shows that road congestion has started to spike again [1] particularly as people are avoiding crowded spaces and choosing to drive instead of using public transportation services.

Travel demand management includes a number of strategies for reducing the demand for travel [2–5], shifting private vehicle use to more sustainable modes of transport [6], and improving the efficiency of existing infrastructure to reduce reliance on building additional road capacity [7,8]. Examples of travel demand management (TDM) strategies are provided in Table 1.

Table 1. Travel demand management strategies for low carbon mobility. Source: Authors. Adapted from [9].

TDM Approach	Description	Strategies	Outcomes
Avoid	Reduce or avoid the need for travel, e.g., reducing trip length or the need to use a private vehicle	Teleworking, transit-oriented and mixed land use developments, high densification of housing and employment centres	Improve road network efficiency, reduce congestion and crowding on public transport
Shift	Encourage travellers to use public transport, walk, cycle, or scoot instead of driving a private vehicle.	Improve public transport services, introduce new modes of public transport such as on-demand buses, provide incentives for electric vehicles, improve active transport infrastructure	Reduce congestion and emissions, improve mode efficiency and reduce travel times
Share	Share transport assets and resources	Sharing economy business models such as bike and scooter sharing, car sharing and ride sharing	Reduce private car ownership, reduce short-distance private vehicle use, improve amenity, reduce congestion and emissions
Improve	Improve the efficiency of existing transport through technology and digital innovations	Smart infrastructure, Intelligent Transport Systems, disruptive mobility	Reduce the need to build more infrastructure, modernise existing services, reduce congestion and improve traveller experience

Among the most promising demand management strategies, the pricing of road network trips has for long captured the interest of transport economists, engineers, and urban planners as a more equitable user-pay solution [7,10,11]. Although road pricing has been investigated for a number of decades now, the topic is receiving renewed interest because of changes in government policies, greater sensitivity to environmental issues, and rapid developments in vehicle electrification that are expected to have a significant impact on fuel excise revenue, prompting renewed thinking on road pricing as a replacement for fuel excise revenue generation [12].

The systematic literature review (SLR) framework considered in this paper follows evidence-based practices adopted by other disciplines such as medicine, economics, psychology, and health care [13]. It enables the amalgamation of knowledge in a transparent and auditable methodology and provides a basis for a comprehensive analysis of literature. The real benefit of this approach is that it frames the topic's historical progress, pointing the way for needed future studies. Influential contributions that pioneered research on the subject over time are described and addressed using evidence from a condensed corpus of 105 papers published in peer reviewed quality journals for the period 2007–2020.

1.1. Aims of a Systematic Review

The goal of this systematic review is to identify and analyse primary studies related to a set of research questions on road network pricing that need to be addressed to meet the research objectives, which primarily address the effectiveness of road network pricing as a travel demand management strategy. These questions aim to uncover information on the main topics reported in the literature, their evolution over time, and types of research methodologies considered that collectively provide valuable insights on best practices to deal with specific topics in this field. Other research questions focus on understanding the fundamentals of the topic, not only for historical framing but also to identify critical research to be investigated in future studies. These questions will be answered using a rigorous and unbiased strategy, which will be a key factor that distinguishes this systematic review from traditional reviews. This work aims to answer the following research questions (Q) to achieve these goals and objectives:

(1) **Q-1.** What are the most important topics covered in the academic literature on road network pricing, and how has research on these topics evolved over time?
(2) **Q-2.** Which articles and researchers have had the most influence on the evolution of the literature to date?
(3) **Q-3.** What is the state of scientific literature on the effects of road network pricing as a travel demand management strategy?
(4) **Q-4.** What are the main knowledge gaps, and what are the future research directions for improving knowledge in this field?

1.2. Overview of Road Network Pricing for Travel Demand Management

In the context of travel demand management, road network pricing refers to wide-ranging strategies aimed at managing private vehicle travel, reducing road congestion, and enhancing performance of the road network (Table 2). These strategies are primarily aimed at managing travel demand on public roads by discouraging the use of low occupancy private vehicles, influencing travel behaviour, and shifting travellers away from private vehicles and towards more sustainable modes of transport. They are normally deployed at a number of spatial levels at a certain road facility, cordon or zone, or with distance-based pricing. Similarly, they can be deployed at a number of temporal levels, including strategies for fixed pricing, time-of-day pricing, or dynamic pricing, as shown in Table 2. These strategies, when considered as part of a holistic approach, would result in positive impacts, including reduced congestion and emissions [14,15].

Table 2. Strategies for road network pricing for travel demand management.

Strategy	Description
Road pricing	Strategies for managing travel demand and reforming transport taxation by charging directly for use of public roads rather than relying on vehicle registration fees or fuel excise. These strategies aim to provide equitable and transparent costing of trips such that the costs are directly related to the amount of travel [16].
Congestion pricing	Congestion pricing (also known as congestion charging) aims to reduce traffic congestion in specific areas such as central business districts. Users who drive into these locations during certain times of the day (e.g., peak hours) are charged either a fixed fee or a dynamic charge according to the time of day or congestion levels [17].
Parking pricing	Parking pricing refers to a number of strategies for managing the demand for parking in congested locations through static or variable charges according to available supply and expected demand [18].
Low emissions zone pricing	Similar to congestion pricing, but the charges are triggered by degree of pollution in the area, rather than according to the degree of traffic congestion. In this scheme, low-emission vehicles such as electric or hybrid vehicles would be exempt to encourage uptake of low carbon/low emission vehicles [19].
High emitting vehicle pricing	This type of pricing targets vehicles that have high emissions (e.g., freight vehicles) particularly when they enter congested or polluted areas. The charges applied to these vehicles would be similar to congestion pricing [20].
Freight pricing	This type of road pricing applies directly to freight vehicles and could include charges per entry into a certain area, or entry to a road facility or bridge, or can be applied per kilometre of travel [21].

Table 2. *Cont.*

Strategy	Description
High occupancy lane pricing	This scheme applies a fixed or variable charge for the use of one or more lanes on a public road [4] to provide high occupancy vehicles (e.g., vehicles with two or more passengers) with access to free flowing lanes. Such strategies can help to influence behaviour and encourage drivers to carpool [6].
Spatial network deployment strategies	
Facility-based pricing	The charge is collected when using a road facility such as an express lane on a motorway, tunnel, or bridge [22].
Cordon pricing	A charge is applied to vehicles moving in and out of a specified cordon area. Vehicles that move within the cordon are not charged [23].
Zone or area pricing	A charge is applied to vehicles entering and moving within a particular zone. This can be based on kilometres of travel or durations [23].
Distance-based pricing	Charge is applied to vehicles that move within an area on a per kilometre basis. Charge can be fixed or variable according to traffic or emissions conditions [18].
Temporal network deployment strategies	
Fixed pricing	Vehicles are charged the same fee regardless of amount of congestion or time of day. This could include variable charges according to the type of vehicle but that remain fixed for each vehicle category [24].
Time-of-day pricing	This type of road pricing applies variable charges according to the time of day. For example, the charges would be higher during peak hours and lower at other times of the day [24].
Dynamic pricing	The charges vary according to changes in certain variables such as degree of congestion or emissions at that time of entry [4]. Dynamic pricing includes both reactive and pro-active dynamic pricing strategies:
	Reactive dynamic: Pricing is varied according to real-time measurements of traffic. When traffic congestion increases beyond a pre-determined threshold, the price is increased and then dynamically decreased or increased depending on traffic [25].
	Pro-active dynamic: Predictive pricing where the charge is based on traffic forecasts and what is likely to happen in the short term (e.g., 15–60 min from now). In this system, traffic congestion forecasts are based on traffic prediction algorithms [25].

2. Methodology

The SLR methodology adopted in this work includes identifying, evaluating, interpreting, and describing the existing body of knowledge about road network pricing with emphasis on its effectiveness as a travel demand management strategy. This study follows guidance from seminal articles on SLR to formulate robust and reproducible research, particularly [26–34]. The review involves the following four phases, which aim to produce unbiased, rigorous, and auditable results.

The first phase of the methodology included a planning stage for identifying the scope of work, research aims, and objectives, as well as key research questions and relevant databases to be used in the bibliographic search [35]. This phase also included identification of major research repositories and databases to be used, particularly focusing on Scopus and Web-of-Science and other databases, including IEEE Repository, Science Direct, and Google Scholar. Collectively, these sources covered the main databases where the literature on road network pricing is published.

The second phase included identification of keywords and search strings and performing a thorough search of digital libraries. The selection of keywords required careful consideration and background knowledge and experience about the topic. Suitable combinations of Boolean variables such as “AND”, “OR”, and “NOT” [16] were applied (Figure 1). The search criteria on road network pricing resulted in 249 papers in Scopus and 234 articles from the Web of Science. Collectively, this resulted in a pool of 483 articles retrieved on 26 October 2020 from both Scopus and Web of Science. The third phase identified the assessment and filtration criteria to be used for inclusion and exclusion of primary studies retrieved in the search [28]. This phase comprised three steps, which defined inclusion and exclusion criteria, refinement of search based on title and abstract, and further fine-tuning based on reading of full text and "snowballing" of articles that were not identified in the search but manually added by the authors as being important.

[("congestion pricing" OR "road pricing" OR "parking pricing" OR "freight pricing" OR "road network pricing" OR "road user charging" OR "congestion charging" OR "road pricing reform")

AND

("traffic flow management" OR "road congestion management" OR "equity pricing" OR "user heterogeneity" OR "travel demand management" OR "acceptability" OR "public acceptance" OR "scheme acceptance" OR "Behavioural responses" OR "political economy" OR "political acceptance" AND (LIMIT-TO (SRCTYPE , "j")]

SCOPUS = 249 Results, Web of Science = 234 Results

Figure 1. SLR search criteria.

Article Selection Criteria

Pre-determined inclusion and exclusion criteria were applied to select the articles to be used in the analysis to allow for an unbiased approach to answer the research questions (Figure 2). The search was based on Scopus and Web of Science databases and only papers published in refereed journals in the transportation field. Conference proceedings and technical reports were not included. Although such exclusions limit contributions from ongoing research, this criterion was used to ensure standards of quality such that only articles that met rigorous peer review were selected [36,37].

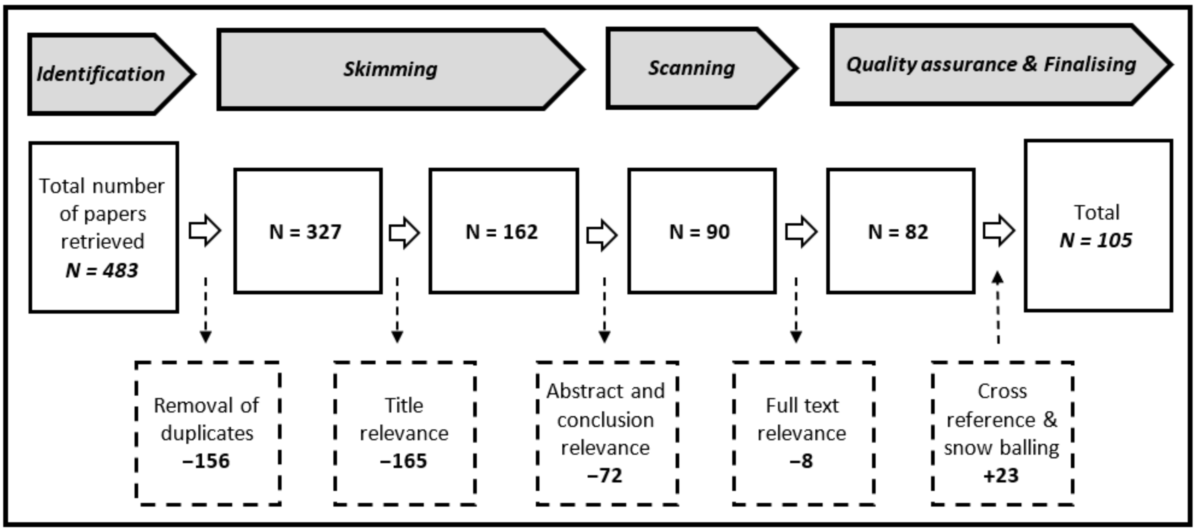

Figure 2. Assessment of search results and application of inclusion and exclusion criteria.

The inclusion and exclusion criteria included the following:

- Paper must have at least one keyword in title, abstract, or coverage in full article;
- Paper must be a peer-reviewed journal article in Scopus or Web of Science;
- Paper must be published in English language;
- Paper must be published between 2007–2020. Even though road pricing first appeared in Singapore in the 1970s [38], the recent major contributions in the scientific literature

started around the year 2007. The authors selected the year 2007 as a result of the literature review, which identified 2007 as a turning point in research on road network pricing and its role in travel demand management.

Paper titles and abstracts of identified papers were then reviewed. Articles that were considered out of scope were excluded from primary studies. A total of 165 papers, which mainly dealt with air, rail, sea, or other aspects of transport pricing were excluded based on the review of titles and abstracts. Then, eight papers that were outside the scope of research were excluded after a full text review. Finally, a total of 23 important articles that were not retrieved in the search were manually added, resulting in a pool of 105 articles.

3. Analysis of Bibliographic Results on Road Network Pricing

The fourth and final phase in the SLR framework included analysis of primary articles, synthesis of results, and reporting of findings. This step was guided by the aims and research questions identified at the start of research. The outcomes are reported in terms of statistical analyses and mapping tools that include generation of co-citation analysis.

3.1. Year of Publication Analysis

This analysis showed two distinct periods, namely 2007–2017, and then 2018–2020 (Figure 3). For the period between 2007–2017, the analysis showed low volume of relevant publications (one to four publications per year) including some notable contributions by [11] and [39], where the authors discussed the effectiveness and importance of road network pricing to governments and the public. Implementation strategies and the use of technologies for electronic pricing were also explored [24]. There was high-profile work during that period that attracted the public's interest through case studies from around the world [40]. Towards the end of that period, there was more interest in modelling impacts of road network pricing by using transport modelling tools [7].

Figure 3 shows how the time period between 2018–2020 witnessed a substantial increase in the volume of publications relevant to road network pricing as a travel demand management strategy [17]. Almost 40 percent of the studies on this topic were published in 2020, including case studies on dynamic pricing from London, Singapore, Stockholm, Oregon, New York, and Milan, which have provided appealing results in terms of social welfare benefits [41]. The recent literature in 2020 also emphasised the impacts of road pricing on emissions and pollution [42]; incentivising private vehicle users to shift to public transport [43,44]; the impact of road network pricing on peak hour taxi fares [45]; and trialling of combinations of pricing policies such as parking and congestion pricing [46]. This analysis is directly related to answering **Q-1**. The year of publication analysis also provided insights into the historical development of road pricing and how it evolved over time, as shown in Figure 4.

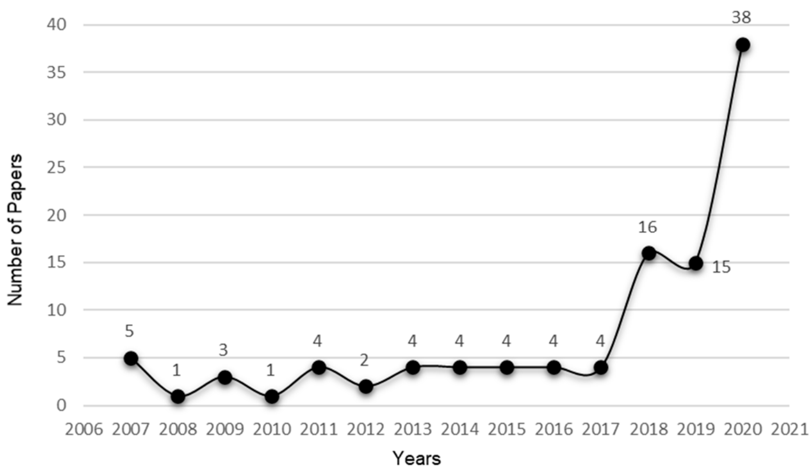

Figure 3. Year of publication analysis.

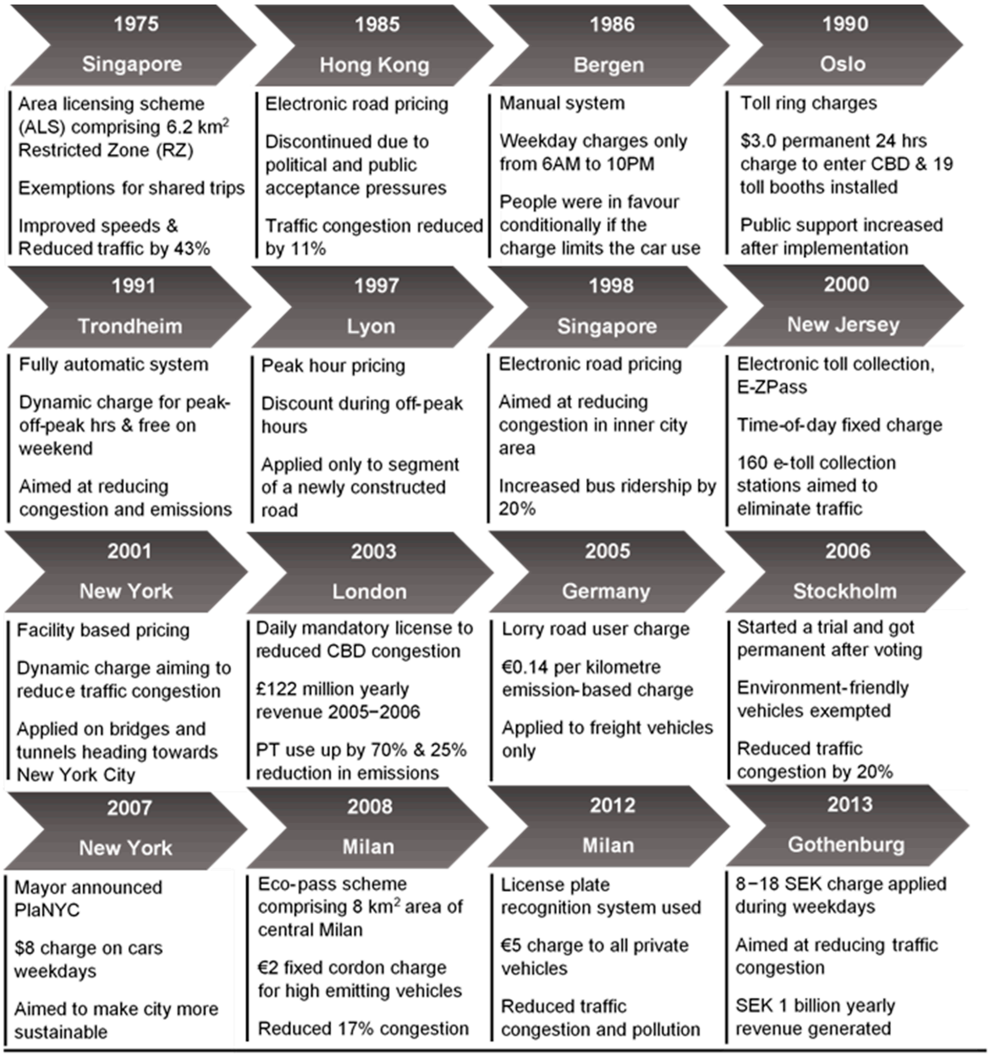

Figure 4. Historical overview of different pricing schemes around the world.

3.2. Geographical Distribution of Research Activity

In this analysis, a bibliographic coupling was undertaken to identify top-ranked geographic areas and their levels of collaboration in terms of joint author publications (Figure 5). The U.S. was ranked highest, followed by China, England, Sweden, Canada, and Australia. The link strength and distance between any two countries represents the volume of articles that are co-authored by researchers from these countries. The U.S. studies have mainly explored implications of congestion pricing, policy, public acceptability, and legislative requirements [6,22,47,48].

In China, where the rate of urbanisation soared during the past decade, road pricing research was given priority in recent times as a strategy to decrease congestion and road-based emissions [49,50]. Studies undertaken in China explored public acceptance and legislation [51]; time varying on-street parking pricing revenue [52]; and optimal road pricing charges [53].

In the UK, studies were conducted around different aspects of dynamic pricing. The research evaluated impacts of London's congestion charging and how to extend it [19]. The scheme, implemented in 2003, was found to generate revenue of £122m in the year 2005/2006, including £100m that was used to improve public transport [3]. Other countries included also had significant publications around dynamic pricing, including Singapore [54], Sweden [55], Australia [7], Germany [56], and the Netherlands [20]. Studies on road network pricing in developing countries were non-existent, which suggests these concepts have not played a significant role in academic and government thinking to date. Opportunities exist in future research to target studies on impacts of road pricing in emerging economies and how government policies and community acceptance can benefit from lessons learned elsewhere. This analysis is directly related to answering both **Q-3** and **Q-4**.

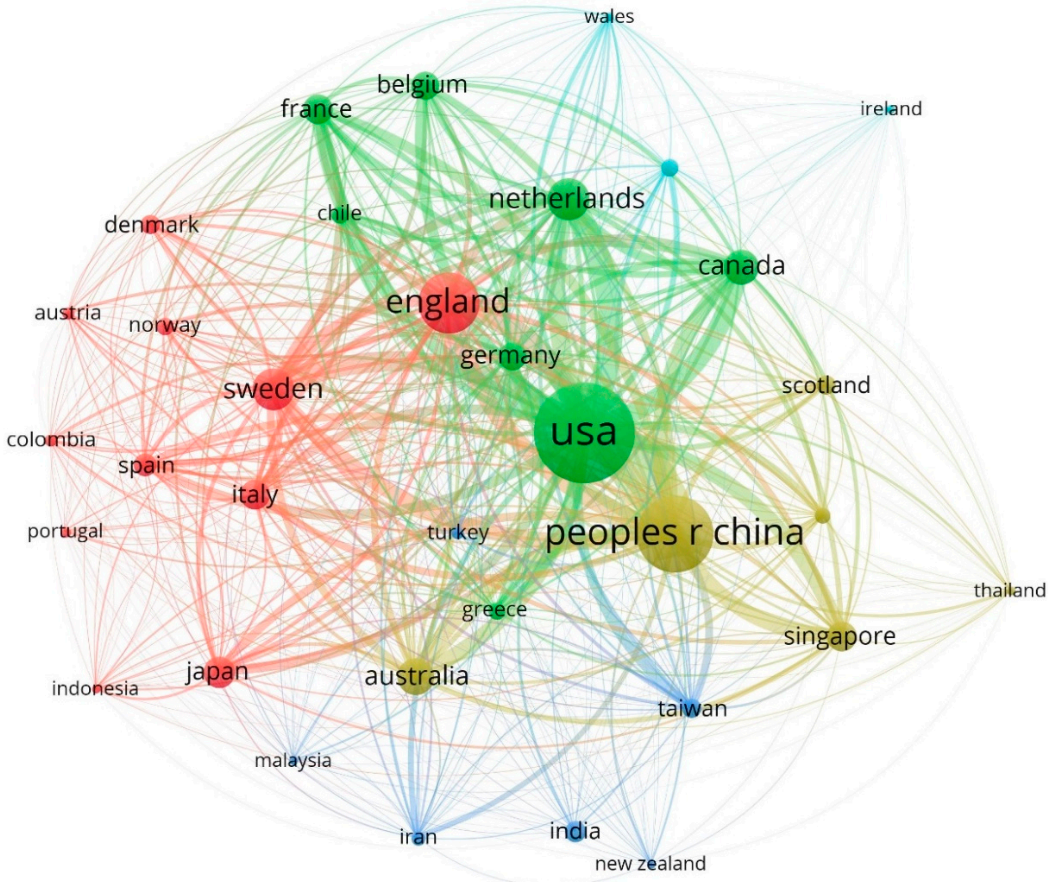

Figure 5. Geographic distribution of research activities.

3.3. Keyword Analysis Using Thematic Maps

The keyword analysis (Figure 6) showed that congestion pricing featured highly, which demonstrates its perceived importance as an effective tool for travel demand management [57]. The convergence of keywords showed the interaction of topics such as acceptability, equity, transport policy, value of travel time, congestion management, and sustainability when considering the value of pricing as an effective strategy to encourage commuters and travellers to adjust their travel behaviour [58]. This analysis captured how studies on mode choice and stated preference were also considered [59] and modelled, e.g., [60,61]. The issue of equity, which has always been considered a critical aspect of road network pricing, also featured in the papers [16]. The literature on the topic shows that equity problems will persist unless the revenue raised from road pricing is used to expand public transport and improve access [62]. The convergence of keywords also showed formations comprising heterogeneity, elastic demand, cost–benefit analysis, and social welfare considerations, which relate to the economic aspects of congestion pricing. The heterogeneity issue is concerned with improving the modelling assumptions by recognising that road users are not homogenous groups of travellers and that income and other characteristics have direct influence on travel behaviour, route, and mode choice [63,64]. Similarly, other studies considered improving the cost–benefit analyses for use in identifying optimal charges for congestion pricing to maximise system performance [65,66].

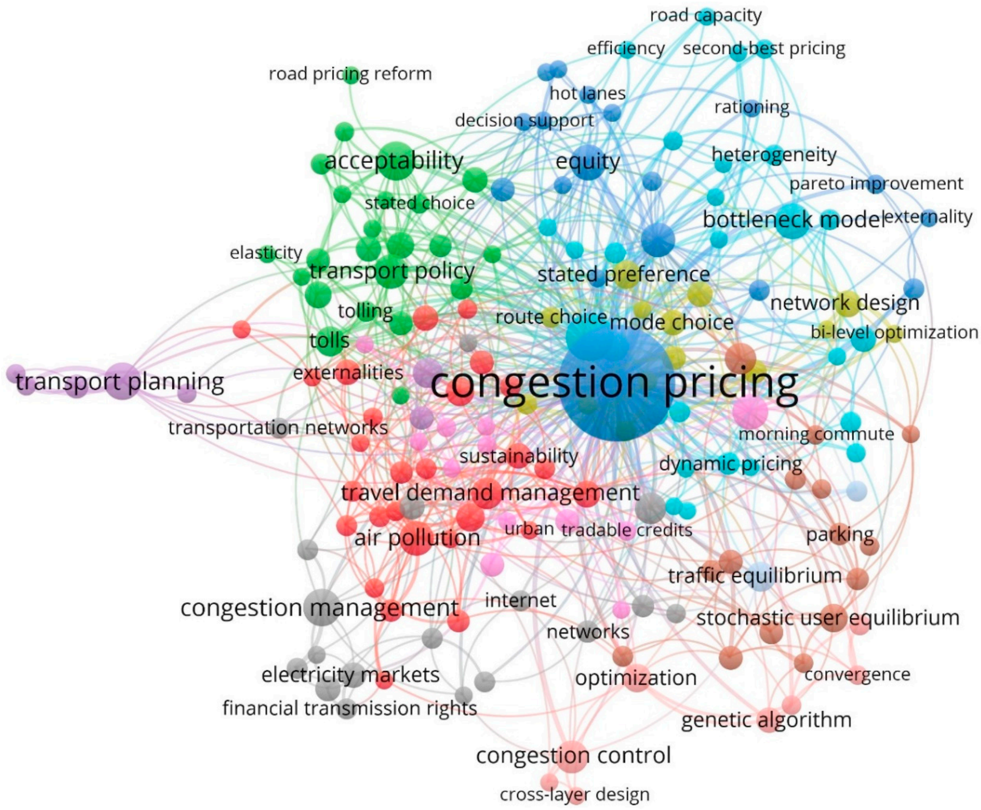

Figure 6. Keyword analysis.

Other formations include mode choice, route choice [67], departure time choice, value of travel time, incentives, and willingness to pay for road pricing [43,49,68,69]. These formations dealt with behavioural research and the factors influencing travellers on using or avoiding areas with road charges. Big data, simulation and modelling, intelligent transport systems, and electronic road pricing were also formations that reflected literature dealing with road pricing technologies. Modern congestion pricing schemes comprise advanced technologies and use of communications and positioning solutions for travel distance/duration calculations [24]. Big data comprising travel flow, speed, route, and mode choice behaviours are used to develop models for simulating impacts of congestion pricing under different pricing scenarios [70,71]. Finally, surveys of stated preferences and discrete choice modelling are formations that reflect literature related to research questions that explored governance, policy implementation, public opinion, and user acceptance [72]. The above keyword analysis is directly related to answering **Q-3**.

3.4. Co-Citation Analysis

The significance of SLR studies, combined with mapping tools, is manifested in identifying linkages between different authors/articles using measures such as: direct citation analysis (frequency of article/author citations); co-authorship (two or more authors collaborating on research [73]); bibliographic coupling (when two primary articles cite common papers in their reference lists [74]), and co-citation analysis (when two primary articles cite common references). Co-citation analysis also evaluates the cognitive structure of a research topic by tracking pairs of papers that are cited at the same time in a primary article. When two authors have higher co-citations in a network, this indicates they have a higher degree of research collaboration. Unlike bibliographic coupling, this analysis is significant because of its forward looking effect [74]. When pairs of papers are repeatedly co-cited, clusters of research themes are formed, showing one or more common themes. The co-citation analysis using VOSviewer [75] resulted in a co-citation network (Figure 7) comprising four distinct research clusters, where the topics within each cluster had strong linkages as well as strong connections with authors/articles from other clusters.

The cluster themes "**Technology, Acceptability, Modelling of Impacts, and Implementation Impacts**" were identified through a comprehensive review of the articles (hence also answering **Q-1**). Node size shows the number of citations, and the connection thickness reflects number of times the articles were co-cited. Co-citation analysis also identified key authors with significant contributions in each cluster (Table 3), hence answering **Q-2**. Only authors with 50 or more citations were included. The four themes identified in the co-citation analysis are discussed next.

Table 3. Key researchers based on citations and link strength in each cluster.

Acceptability	Technology	Modelling of Impacts	Implementation Impacts
David Hensher ◦ Citations 292 ◦ Papers 5	André de Palma ◦ Citations 343 ◦ Papers 2	Nikolas Geroliminis ◦ Citations 230 ◦ Papers 4	Georgina Santos ◦ Citations 494 ◦ Papers 2
Bruce Schaller ◦ Citations 168 ◦ Papers 1	David M. Levinson ◦ Citations 242 ◦ Papers 1	Leonardo J. Basso ◦ Citations 99 ◦ Papers 1	Jonas Eliasson ◦ Citations 151 ◦ Papers 4
Ziyuan Gu ◦ Citations 75 ◦ Papers 3	Andrea Broaddus ◦ Citations 51 ◦ Papers 1	Kara Kockelman ◦ Citations 70 ◦ Papers 3	Martin G. Richards ◦ Citations 81 ◦ Papers 1

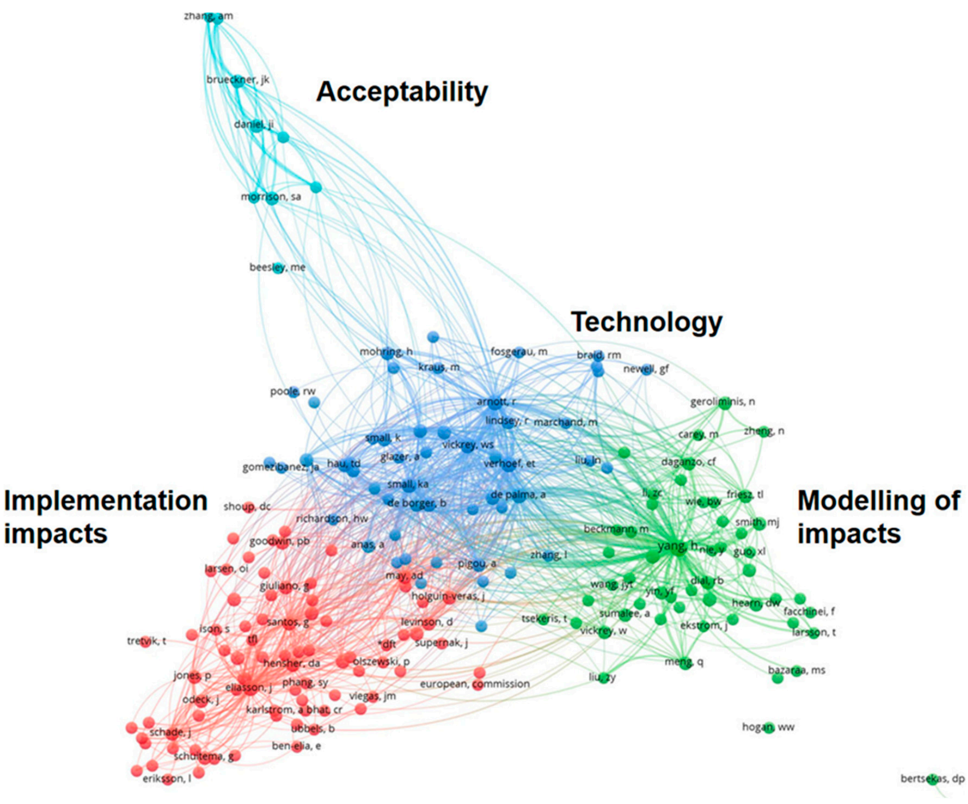

Figure 7. Co-citation analysis.

3.4.1. Implementation Impacts

This theme analysed the social, economic, and environmental impacts of road network pricing. The literature points to several road network pricing instruments that are available to regulators. The most common instrument is congestion charging in urban centres [19], which has been implemented in a number of jurisdictions around the world such as Oregon, Vancouver, New York, London, Stockholm, Gothenburg, Milan, and Singapore [17]. The benefits reported are compelling [9]. In the 12 years since the scheme started in London, traffic congestion was reduced by 10 percent, which included a 34 percent drop in private cars entering the city centre, and a 28 percent increase in the number of cyclists accessing the city [54]. The scheme also reduced emissions by 16 percent within the study area, amounting to a reduction of 30,000 tonnes of carbon monoxide annually. A road safety study also identified that it resulted in reducing traffic collisions by 40 percent over a 10-year period between 2000 and 2010 [76]. London's congestion pricing scheme also raised more than USD 300 million per year in revenue, which was invested in public transport and active transport infrastructure.

Stockholm's congestion pricing scheme reduced peak traffic by 20 percent and increased public transport ridership by 9 percent [77]. In the city's densely populated centre, emissions decreased by 14 percent. The scheme generated an estimated USD 500,000 in daily revenue, which was reinvested in expanding bike lanes and new, dedicated bus lanes. Sweden's Gothenburg scheme was also a success [78] and reduced congestion by 12 percent during peak hours and shifted a large number of private car users to public transport.

Singapore's congestion pricing scheme was established in 1975 [3]. Initially, it was known as an area license system using a flat rate fee. It cut traffic by 45 percent and vehicle crashes by 25 percent [79]. The system was upgraded to electronic road pricing (ERP) in 1998, resulting in a further 15 percent reduction in traffic congestion [80]. More recently, the ERP was found to have reduced congestion by 45 percent and road crashes by 25 percent, as well as reduced traffic volumes entering the central business district by 15 percent [81]. The literature also points to benefits of road pricing based on distance or travel time [48]. This can also be fixed or variable. In New York, the "Move NY" plan proposed to charge taxis based on distance and also time spent within the city [17]. Likewise, in Oregon, a state-wide scheme "OReGo" was introduced, where charging was based on distance. Recently, Singapore's ERP 2.0 (from 2020) commenced using satellite communications for distance charging [54]. These success stories provide unique insights into the pathways for implementation [9,11,82]. These findings demonstrate that road pricing can be effective in reducing congestion, lowering emissions, improving amenity, and addressing inequity in transport taxation systems.

3.4.2. Acceptability

Acceptance of road pricing schemes is critical for their successful deployment and can be a major impediment to deployment [83]. In almost every city where road pricing was implemented, governments faced public resistance [55]. Edinburgh's cordon pricing scheme was rejected by around 75 percent of the voters [41]. Manchester's proposal was also rejected by around 79 percent of the voters [84]. Birmingham faced strong opposition to a proposed pricing scheme [38]. Numerous factors influence public acceptance, including privacy [17], equity [10], scheme understanding [3], complexity of implementation [85], distrust in governments [86], and uncertainty about benefits [47].

The privacy concern is related to sharing personal information in automated payments; camera enforcement systems that are perceived as a major risk for illegal access to personal information; and infringements of privacy [85]. In cities where these concerns were adequately addressed, genuine efforts were made, and appropriate measures were put in place to deal with them [54].

The equity concerns are related to impacts of road pricing on low-income and vulnerable groups who may not be well-served by reliable public transport [87]. These issues are addressed by ensuring equal access to public transport and system design that does not discriminate against people with disability [62].

Another concern with public acceptance is perceived complexity of pricing schemes. Information campaigns about how they work can help increase awareness [86]. Additionally, uncertainty about a scheme's effectiveness in reducing congestion and revenue allocation can reduce public confidence [17]. This can be addressed when generated revenue is directed to improve public and active transport initiatives [88]. Hensher and Li considered factors influencing public support and found the studied schemes generally gained support after deployment [38]. In a similar study by Eliasson, it was shown that public support for Stockholm's congestion charging reached 70 percent after trial [55,86]. Another impacting factor is not taking a holistic view of transport taxation or political acceptance [3,16,89]. Finally, results of a comparative study by Shatanawi et al. revealed that acceptance of congestion pricing differs between cities and countries. Prior knowledge about road pricing was a major factor affecting public acceptance of proposed schemes in cities such as Tunis, Ulaanbaatar, and Damascus; this was contrary to findings for other cities such as Vienna, Athens, Como, and Dresden, where similar schemes were not popular [41].

3.4.3. Modelling of Impacts

This cluster of articles provided significant contributions in development and evaluation of modelling methodologies for evaluating impacts [25,54,90,91]. These studies provide a clear understanding of benefits and limitations [54]. Gu et al. simulated different congestion pricing schemes for Melbourne and showed that proposed pricing scenarios can be effective in reducing congestion. They also found that distance-based pricing distributes the traffic unevenly within a cordon and that combined distance/time pricing can mitigate these impacts [91]. Additionally, in a traffic modelling study for Melbourne, Perera et al. explored different charging schemes, including fixed distance charge, gross vehicle mass charge, and link charges. The findings showed promising emissions benefits [21].

In a study that explored congestion pricing policies in Berlin, agent-based simulation was used to test pricing according to congestion levels [56]. The study showed a 5 percent mode shift from private vehicles to bicycles and a 3 percent mode shift to public transport. In a similar study that simulated impacts of cordon-based congestion charging for New York [58], cordon pricing was simulated by introducing mode choice decisions of travellers, including single occupancy vehicles, shared vehicles/carpools, public transit, taxis, bikes, walking, and biking [58,92]. In a study conducted for Yokohama, a macroscopic cordon-based congestion pricing model was developed for morning peak trips considering equity and reliability [93]. Implementation of an optimal toll reduced duration of peak hours and travel delays, with savings in travel times found to be much higher than the charge paid.

In a study that simulated impacts of commuters' times of departure and mode choice in Toronto, a dynamic assignment model was used and found that pricing significantly reduced total travel time within the network [94]. However, early morning travel time increased due to induced demand related to travellers who changed their route to avoid a higher charge. After a time-dependent charge was applied, travel times were reduced [5]. In a study on dynamic pricing, an agent-based model showed that congestion pricing provided incentives to use public transport, which in turn impacted mode shift and departure time choices [95].

Zheng and Geroliminis also studied impacts of parking restrictions. Two dynamic parking pricing strategies were developed to determine pricing for on-street and multi-storey parking. The pricing strategies had positive impacts on promoting a mode shift from private vehicles to buses [96]. Similarly, in a study that investigated the impact of a newly implemented parking pricing scheme in Nanning, China, it was shown that parking turnover increased in the long run, with parking demand found to be inelastic during peak periods [52]. In another study conducted in Sydney, Gu et al. demonstrated impacts of reactive and pro-active parking pricing and suggested that free or under-priced parking should be eliminated [25].

Finally, recent studies also looked at some future scenarios such as pricing of shared autonomous vehicles (AVs). Simoni et al. used MATSim to study different traffic congestion pricing scenarios to evaluate the impacts of shared autonomous vehicles (SAVs) in Austin. A total of 45,000 travellers (agents) were modelled, representing a 5 percent sample of the population. It was found that in all pricing scenarios, traffic congestion was significantly reduced. A distance-based road pricing scheme was found to be more effective in both the base and SAV scenarios, while a link-based scheme was found to be more suited for AV scenarios [48]. In another study, Lee and Kockelman explored the impact of pricing on traffic flow considering drivers with different value-of-travel-time (VOTT). It was found that a combination of tolling and automated vehicles could significantly reduce congestion. Drivers with higher VOTT had more willingness to pay, while low VOTT drivers took longer paths to reach their destination to avoid charges [68].

3.4.4. Technology for Electronic Road Pricing Schemes

The fast pace of developments in ERP technologies has enabled deployment of a number of automated schemes around the world [97]. In particular, the automation has allowed for free-flow charging without the need to stop and pay charges. These technologies comprise three key components including automated vehicle identification systems used to determine the identity of the vehicle and track its movement along the road network to be able to apply the correct charges [24]. Most systems today use radio-frequency identification based on gantry communication with vehicle transponders through dedicated short range communications (DSRC) [98]. The use of automatic number plate recognition (ANPR) is also common for vehicle identification [18]. The advantage of ANPR is that it avoids the need for in-vehicle devices, but it suffers from high error rates under severe weather conditions [98]. ERP technologies also include automated vehicle classification to classify different types of vehicles, including laser profilers that identify shapes of different vehicles and distinguish vehicle types for ease of charging. The ERP systems also include transaction processing and violation enforcement systems comprising back-office technologies that maintain customer accounts and issue infringement notices as needed. ANPR systems are typically used to capture images of vehicles where a transponder was missing or when the user's account did not have a sufficient balance. Singapore's congestion pricing used DSRC technology for communication between gantries and in-vehicle devices [54], while London and Stockholm relied on ANPR. In the German heavy goods vehicle charge scheme, digital tachographs and smart cards were used to calculate the distance [99]. For distance-based road pricing, GPS is typically used for vehicle tracking and has been reported to be reliable [100]. The accuracy of the technologies varies with weather conditions, device resolution, and signal quality. Modern DSRC systems have an accuracy of 99 percent but suffer from inclement weather or when vehicle number plates cannot be read. Satellite systems can deliver wider coverage, but they suffer from resolution/accuracy issues compared to other technologies [100]. Microwave-based systems have also been found to be accurate for vehicle recognition [18].

3.5. Re-Imagining Urban Transport Amid and Post COVID-19: The Role of Road Pricing in Shaping a Resilient Urban Future

The coronavirus pandemic has had a significant impact on cities all over the world. Building on the momentum of the shift to more sustainable practices will be one of the many challenges of recovery—and transportation will be a particular challenge. The pandemic, in particular, has shown how vulnerable public transport can be in the face of extreme stresses. As people try to maintain physical distancing and avoid crowded areas, public transport patronage has suffered and may continue to suffer for the next few years until the pandemic is contained. Thousands of journeys will have to be completed by other means every day. Congestion on the roads will worsen if people abandon public transportation in favour of driving. According to recent data, this may have already begun in major cities around the world, with recovery of public transportation trips lagging behind recovery of private vehicle trips. An example is shown in Figure 8 for Sydney, Australia, which shows that driving has already bounced back and has now exceeded the baseline traffic conditions of January 2020, while public transport and walking have both lagged behind in recovery This situation is not unique to Sydney and is being experienced by many cities around the world. There is considerable agreement in the literature that congestion will increase and persist if driving becomes a new habit, and many cities would risk losing on the past momentum and achievements in shifting travellers away from private vehicles.

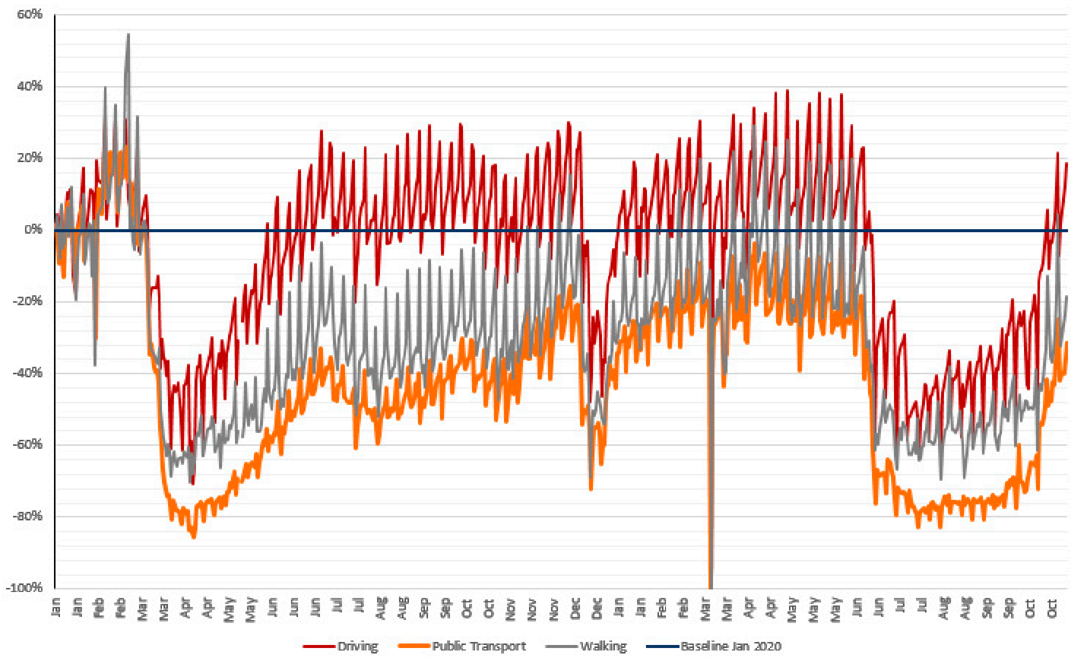

Figure 8. Changes in trips for Sydney, Australia, measured by changes in trip routing requests. Source: Authors provided based on data from Apple Maps COVID-19 Mobility Trends.

Given also the increasing renewed interest in road pricing because of changes in government policies, sensitivity to environmental issues, and the need to meet emissions reduction targets, as well as the rapid developments in vehicle electrification and the forecast reduction in fuel excise revenue, it is anticipated that road pricing will become increasingly important as a transport policy tool to manage private vehicle travel amid and post COVID-19.

3.6. Gaps in Knowledge and Future Research Directions

The analyses provided in this paper show that road network pricing schemes were generally found to result in reductions in traffic congestion and environmental emissions [14,59,71,101,102]. These analyses, however, point to a number of gaps that provide a transparent framework for appropriately positioning new research activities. Analysis of the reviewed literature shows gaps that include the need for investigations into improved mode and route choice models for estimating the impacts of road pricing [56,58,103]. Other areas for future research focus on modelling and simulation, including exploration of relaxing inelastic transport demands in extreme peak hours [50,66] by providing travellers other modes of travel (e.g., public transport) and diverting vehicle traffic to multi-modal forms of transport. In addition, there is a need to assess user heterogeneity by considering multi-class users [44,60,63,104], and differentiating user groups with varying socio-economic characteristics and values of travel time [6,64,87]. Future research should also explore optimisation of the balance between the two main pricing indicators, i.e., distance and time, in formulating a pricing policy [91,105]. Finally, and given the pandemic situation in 2020 and the decline in public transport patronage, there are already signs of increased road congestion with more people choosing to use their private vehicles instead. If this trend persists, congestion will worsen, and emissions will increase, in which case the justification for road pricing would be more pressing than ever before. More research is needed over the coming years to understand the drivers of travel change amid and after the pandemic with a particular emphasis on determining the role of pricing in curbing the demand for private vehicle travel. To conclude this section of the paper, Table 4 presents a summary of how the paper responded to the research questions.

Table 4. Sections of paper responding to research questions.

Research Question	Relevant Sections	Discussion Points
Q-1	Sections 3.1 and 3.4	Year of publication analysis and co-citation analysis
Q-2	Section 3.4	Co-citation analysis
Q-3	Sections 3.2 and 3.3	Geographical distribution and keyword analysis
Q-4	Section 3.5	Gaps in knowledge

4. Conclusions and Implications for Research and Practice

This paper provided a rigorous systematic review of empirical evidence on road network pricing and its effectiveness as a travel demand management strategy. The article also provided a comprehensive overview of research topics and their historical development over time, including methodologies used for analysis and modelling of impacts. Influential contributions that shaped the discipline were also acknowledged and debated using bibliometric analyses. The article classified the literature into four distinct categories and consolidated evidence on the benefits of road network pricing as a travel demand management strategy. The evidence-based approach helped to undertake unbiased aggregation of empirical results through review of academic contributions and identification of trends that might emerge in this field of research. The key contributions of this work are summarised below:

- This work has helped to identify the challenges and opportunities facing road network pricing in post-pandemic cities. The reviewed literature showed that road network pricing is increasingly becoming the focus of ignited deliberation on transport taxation reform and rethinking of approaches that raise revenue to maintain and upgrade the infrastructure required to support a city's mobility needs. Today's transport infrastructure funding models, which are grounded in raising revenue from vehicle registrations, fuel excise, and license fees, are inequitable. Revenue from these schemes will not be sufficient to meet future infrastructure expenditure requirements. They will also face increased pressure as transportation revenues decline as consumers shift to electric vehicles and fuel-efficient vehicles.
- Road network pricing should be viewed as an integral part of a broader taxation reform that would eliminate or restructure other transport taxes, such as vehicle registration fees that are unrelated to the amount of travel. Road pricing schemes should also provide incentives to avoid driving in congested areas and encourage travellers to choose more sustainable modes of transport. The revenue generated by the user fees would be used to fund initiatives that would increase public transport usage, maintain and operate roads and transportation services, and improve travel options. The importance and urgency of implementing road pricing as a solution to reduce emissions, particularly in congested urban areas, will become more prominent.
- This article identified several gaps in the literature and provided a clear framework for appropriately positioning future research directions. The pandemic has also presented some significant challenges for cities, as driving has increased as a result of the pandemic. More research is needed in the future to better understand the drivers of travel change and to investigate the role of pricing in reducing traffic congestion and emissions post pandemic.

Finally, one general limitation of SLR studies is that "positive" results are more likely to be published than "negative" results. This is heavily influenced by the viewpoints and perspectives of the authors who write the article. Unless meaningful independent determinations are included to address this limitation, "publication bias" can lead to systematic partiality in SLR studies. This was addressed in this study by including a review of grey literature and conference proceedings, as well as consultations with other key researchers, which resulted in 'snowballing' a number of relevant articles that were not automatically retrieved in the search results.

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