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A systematic review of empirical and simulation studies evaluating the health impact of transportation interventions

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Graphical Abstract

Urban transportation is an important determinant of health and environmental outcomes, and therefore essential to achieving the United Nation's Sustainable Development Goals. To better understand the health impacts of transportation initiatives, we conducted a systematic review of longitudinal health evaluations involving: a) bus rapid transit (BRT); b) bicycle lanes; c) Open Streets programs; and d) aerial trams/ cable cars. We also synthesized systems-based simulation studies of the health-related consequences of walking, bicycling, aerial tram, bus and BRT use.

Two reviewers screened 3302 unique titles and abstracts identified through a systematic search of MEDLINE (Ovid), Scopus, TRID and LILACS databases. We included 39 studies: 29 longitudinal evaluations and 10 simulation studies. Five studies focused on low-and-middle income contexts. Of the 29 evaluation studies, 19 focused on single component bicycle lane interventions; the rest evaluated multi-component interventions involving: bicycle lanes (n=5), aerial trams (n=1), and combined bicycle lane/ BRT systems (n=4). Bicycle lanes and BRT systems appeared effective at increasing bicycle and BRT mode share, active transport duration, and number of trips using those modes. Of the 10 simulation studies, there were 9 agent-based models and one system dynamics model. Five studies focused on bus/BRT expansions and incentives, three on interventions for active travel, and the rest investigated combinations of public transport and active travel policies. Synergistic effects were observed when multiple policies were implemented, with several studies showing that sizable interventions are required to significantly shift travel mode choices.

Our review indicates that bicycle lanes and BRT systems represent promising initiatives for promoting population health. There is also evidence to suggest that synergistic effects might be achieved through the combined implementation of multiple transportation policies. However, more rigorous evaluation and simulation studies focusing on low- and middle-income countries, aerial trams and Open Streets programs, and a more diverse set of health and health equality outcomes is required.

Keywords: transportation; health; systematic review; natural experiment; complex systems

[insert graphical abstract figure]

Graphical abstract figure legend: This figure represents a word network created by extracting keywords from the paper abstracts included in our systematic review. Each keyword represents a node in the network; its size is proportional to the number of abstracts in which it appears. Keywords are connected if they are found in the same abstract. The colours represent different communities of words as identified using the Louvain method.

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1. INTRODUCTION

Over the course of the last two centuries, the proportion of the world's population residing in cities has increased more than 10 fold, with more than half of all people living in urban areas (United Nations 2014). According to the United Nations (United Nations 2018), especially rapid rates of urbanization are projected to occur in low-and-middle income countries. While the dense intersection of social, natural, and built environments in cities affords numerous health-related benefits, it can also pose serious risks to human health, well-being, and environmental sustainability (Vlahov et al. 2005, Rydin et al. 2012).

Transportation is well recognised as an important feature of urban life and a significant determinant of health and well-being. Beyond the direct associations between transport and traffic accident-related injuries (Litman 2013), transportation may also influence health and well-being via indirect pathways. For instance, transportation serves an important function in facilitating social interaction and access to a wide range of health-related opportunities, including health care services, employment and educational opportunities (Litman 2013). The relationships between transportation and health may also transpire through mediating factors such as physical inactivity, and air and noise pollution arising from an overreliance on motorized forms of transportation (Brunekreef and Holgate 2002, Babisch 2006, Lee et al. 2012). The design of transportation systems, through their capacity to enable or constrain mobility, can also impact a city's economic growth and urban structure (Becerra et al. 2013). As a determinant of health, transport advantage or disadvantage, including inadequate access to transportation infrastructure and services, can exacerbate social segregation (Lucas 2012) and impact health inequalities (Borrell et al. 2013).

The importance of transportation is reflected within the Transformative Commitments of the New Urban Agenda (United Nations 2017) and the United Nation's Agenda for Sustainable Development (UN General Assembly 2015), which features transportation as essential to achieving the 17 Sustainable Development Goals (United Nations 2016). Recognising this call to action, international agencies and cities worldwide have expressed a strong interest in the design and implementation of transportation-based policies and initiatives capable of addressing some of the unique challenges faced by rapidly urbanising cities. Four emerging and innovative policies in urban mobility, that have attracted attention and been implemented in both high and low-and-middle income countries (HIC and LMIC, respectively) include: 1) bus rapid transit (or BRT) in over 160 cities (for example, the Mexico City Metrobús, the Lagos BRT in Nigeria and the Spurbus in Germany) (Becerra et al. 2013, BRT+ Centre of Excellence and EMBARQ 2019); 2) bicycle paths (for example, Santiago's Mapocho Pedaleable in Chile and Denmark's well-known network of paths and bicycle lanes) (Pucher et al. 2010, Becerra et al. 2013); 3) Open Streets programs, which involve the temporary closure of main streets to motorized traffic in order to encourage cycling and other modes of active transport (Kuhlberg et al. 2014, Sarmiento et al. 2017); and 4) aerial trams (i.e, cable cars) designed to connect peripheral hillside neighborhoods or islands with downtown activity nodes (examples include: the Medellín Metrocable in Colombia, the Cable of Constantine in Algeria, and the Roosevelt Island Tramway in New York City) (Alshalalfah et al. 2012).

Despite the growing interest in the health-related impacts of transportation policies, there have been few attempts to evaluate these initiatives. From a public health vantage, it is important to understand what, if any, impact these transportation policies have had on population health and health inequities in both HIC and LMIC. By identifying initiatives that have demonstrated positive public health effects, as well as highlighting gaps in understanding, the synthesis of local and international research can inform decision-making and policy design in cities all over the world.

In addition to health impact evaluations, research employing system-based simulation methods such as agent-based modelling (ABM) and system dynamics (SD) can also be used to elucidate the potential health-related impacts of diverse policies. Large-scale transportation interventions can affect travel behavior, population health, and health inequalities in multiple ways that are hard to anticipate due to the complex and dynamic relations between these policies and the system on which they act. System-based simulation methods are able to capture complex mechanisms not readily accommodated by other analytical approaches, including non-linearity, feedback loops, individual and collective adaptation to changes in environmental and social contexts, self-organization, and emergence (Jayasinghe 2011). Simulation models are often used to assess the health-related impacts of large-scale, complex population-level interventions that are often prohibitively expensive or impractical to trial in the real world (Hammond 2015). For example, elucidating the dynamic mechanisms through which transportation policies impact population health can improve the design of more effective initiatives and reduce the potential for undesirable or unintended consequences. Another advantage of simulation modelling is its capacity to facilitate policy prioritization and planning by affording a platform through which the differential or combined health impact of diverse policies may be compared (Hammond 2015). While there have been a number of systematic reviews of simulation-based methods applied to the study of non-communicable diseases (Nianogo and Arah 2015, Li et al. 2016), there has been no attempt to review models simulating the impact of transportation mode choices and transport-focused initiatives on health outcomes, more broadly.

This systematic review has two broad aims. The first is to summarize existing evidence (longitudinal empirical and simulation-based) on the influence of four innovative transportation policies, programs, and investments (i.e., BRT, bicycle lanes, Open Streets programs, and aerial trams) on health-related behavior and or health outcomes. And second, based on the synthesized evidence, this review will outline key recommendations for future research.

2. METHODS

2.1 Study design

A systematic review of the peer-reviewed literature was conducted with a focus on identifying: 1) primary studies evaluating the influence of BRT, bicycle lanes, Open Streets programs, and aerial trams on health-related behavior and or health outcomes; and 2) system-based simulation studies exploring the links between transportation mode choice, BRT, bicycle lanes, Open Streets programs, and aerial tram policies, and health-related behavior and or health outcomes. The PRISMA checklist was used to ensure methodological rigor (Moher et al. 2009) and the systematic review was registered with the International Prospective Register of Systematic Reviews (PROSPERO No. CRD42018093172). A narrative synthesis was conducted to characterize studies and investigate the health impacts of the four types of applied and simulated policies and projects.

2.2 Search strategy

A search strategy seeking to identify all relevant reviews and primary studies was developed by IS and LMTG, and further refined through consultation with a project working group. Four electronic databases formed the focus of the literature search: MEDLINE (Ovid), Scopus, Transportation Research International Documentation (TRID) and LILACS. These databases were selected because of their coverage of literature from both HIC and LMIC. Using a combination of keywords, MeSH terms, and phrases, a relatively broad search strategy was employed to ensure all relevant studies published from the year 2000 and onwards were identified. The basic search strategy is outlined in Table 1 (please refer to Appendix 1 for details on the complete database-specific search strategies enacted in English, Spanish, and Portuguese). Following the database search, the reference lists of included studies were screened for other unidentified but potentially relevant studies.

Table 1: Simplified search strategy

Domain	**Transportation**
MeSH	"Bicycling" [Mesh: focus] OR
Keywords	(Bike lane* OR bike way* OR bike path* OR bikeway* OR cicloruta* OR bicycl* OR cycling Bus rapid transit OR BRT OR Aerial lift* OR aerial tram* OR cable car* OR metrocable OR gondola lift* OR gondola car* OR cable propelled transit OR (Ciclovia*OR mass event* OR mega event* OR open street*).ti, ab.
	Health
MeSH	"Disease" [Mesh: focus] OR "Health" [Mesh: focus] OR "Urban Health" [Mesh: focus] OR "Public Health" [Mesh: focus] OR "Mortality" [Mesh: focus] OR "Wounds and Injuries" [Mesh: focus] OR
Keywords	(health OR disease* OR behavio* OR injur*OR fatal* OR mortalit*).ti, ab.
	Study design
MeSH	"Non-Randomized Controlled Trials as Topic" [Mesh: focus] OR "Follow-Up Studies" [Mesh: focus] OR "Controlled Before-After Studies" [Mesh: focus] OR
Keywords	(Systematic review* OR quasi-experiment* OR social experiment OR natural experiment* OR difference in difference* OR pre-post OR evaluation OR impact assessment* OR before and after OR Simulation OR systems model* OR agent-based model* OR multi-agent model* OR individual-based model* OR system dynamics).ti, ab.

ti = title; ab = abstract

2.3 Study selection and inclusion criteria

The study selection process included three key steps. First, two reviewers (IS and LMTG) searched all relevant electronic databases in August and September 2017, imported search results into EndNote, removed all reference types other than journal articles and conference proceedings as well as papers in languages other than English, Spanish, or Portuguese. Second, all duplicate records were removed from EndNote using exact match for author and title. The remaining citations were then imported into Covidence (Covidence. 2017), a Cochrane review management platform. Additional duplicate citations identified within Covidence were also removed.

Second, the titles and abstracts of retrieved studies were screened by two pairs of independent reviewers within Covidence and assessed for inclusion within the review. Primary studies were selected for inclusion if they used empirical analyses or system-based simulation methods to evaluate the health impact of Open Streets programs, BRT, bicycle lanes, or aerial tram infrastructure. Health impact was defined broadly to include health outcomes or health-related behaviors such as bus, BRT and aerial tram use, bicycling, walking and more generic physical activity measures. Studies assessing mode share as an outcome were also included if they considered bus, BRT, bicycle and/ or aerial tram use within their definition of mode share. We included these studies because these modes represent active forms of transportation and therefore qualify as health-related behaviors. Systematic reviews were not included, though they were used to help identify potentially relevant studies not identified directly through the search. While no limits were placed on participant demographics, where possible, the search was restricted to studies published in English, Spanish, and Portuguese. The Participants, Interventions, Comparators, Outcomes, and Study design (PICOS) approach was used to assess whether identified studies met the review's inclusion criteria (Table 2). Disagreements related to eligibility were resolved through discussions within reviewer pairs.

Third, full-text manuscripts of all potentially eligible studies were retrieved and screened by IS and LMTG. An interlibrary loan request was made for all manuscripts that could not directly be accessed. Studies that appeared to meet all the inclusion criteria of the review were discussed by the two reviewers and any disagreements were resolved by reflecting on the inclusion criteria and through consultation with the project working group. Systematic reviews and the reference lists of included studies were searched to identify any other potentially relevant papers.

Table 2: PICOS criteria for study inclusion and exclusion

INCLUDE	EXCLUDE
Participants	
Studies including participants of any age group	Animal studies
Interventions	
Studies evaluating the impact of new BRT, Open Streets programs, bicycle paths and /or aerial tram infrastructure on at least one health-related behavior and/ or health outcome. Studies evaluating traffic-free bicycle infrastructure, such as multi-use trails, bridges and boardwalks that report on cycling outcomes separately. Multicomponent interventions, including those implemented across different sites, were included only if the impact of BRT, Open Streets programs, bicycle lanes and/or aerial trams was explicitly evaluated and reported on in at least one of these sites. Systems-based simulation studies exploring the impact of transportation mode choice (including bus, bicycle and/or aerial trams) on at least one health-related behavior and/ or health outcome were included, even if no policy scenarios were simulated.	Studies evaluating light rail transport systems, bicycle boxes, intersection crossings and roundabouts. System-based simulation studies exploring transportation choices that do not include bus, cycling or aerial trams, or do not consider health-related behavior or health outcomes. Simulation studies modeling route choice but not reporting on mode share including at least one of the aforementioned modes, or health-related behaviors or health outcomes.
Comparators	
Evaluations and system-based simulation studies comparing the impact of BRT, bicycle paths, Open Streets programs and aerial tram policies and/or transportation choices including at least one of these modes, on health-related outcomes.	
Outcomes	
Studies that report on at least one health-related behavior or health outcomes, including injury, prevalence and counts of walking or cycling, time and distance walked or cycled (surrogates of physical activity energy expenditure (PAEE)), cycling speed (only if distance and/or time travelled are reported, thus enabling the assessment of PAEE). Studies reporting on mode share including bus, bicycle or aerial trams were also included.	Studies reporting on intermediary outcomes, such as air pollution, intentionality for behavior change or car crashes, without making a link to health-related behavior or health outcomes.
Study design	
Studies published in peer-reviewed journals or as peer-reviewed conference proceedings. Quasi-experimental studies and natural experiments with longitudinal designs. Systems-based simulation studies, such as agent-based models and system dynamics models.	Studies that only collected follow-up data before the intervention was completed or that are cross-sectional in nature. Qualitative studies providing no quantitative assessment of policy effects and simulation studies that are not systems-based (e.g., health impact models). Commentaries and opinion pieces.

2.4 Data extraction and analysis

Two data extraction tools (one for evaluations and another for system-based simulation studies) were developed to capture idiosyncratic aspects of study design and implementation characteristics of policy evaluations and simulation studies. Each tool was independently pilot tested on three studies and amended based on in-depth discussions with the project working group. The refined tool applied to evaluation studies extracted information on: author, year, geography, study type, aims or scope, sample size, participants, policy characteristics, length of follow-up, outcomes, the nature and magnitude of policy effects. The extraction tool applied to simulation-based studies sought to capture information relating to key aims or scope, software, and model specification – including, conceptual models, agent properties, actions and rules, temporal structure and characteristics of the model environment – modelled policy scenarios, outcomes, model parameters, calibration and validation processes, and key findings.

Five independent reviewers working in four pairs (FM & JDM, LMTG & MAM, IS & MAM and LMTG & IS) conducted an in-depth review of all included studies and performed extractions in accordance with the two extraction tools described above. The extractions were compared by each pair and discrepant information relating to any given study was discussed until all conflicts were resolved. Given the heterogeneity in study designs, exposures and outcomes reported by papers included in this review, a meta-analysis was not possible. Instead, a narrative synthesis of information extracted for each of the two extraction tool formats was conducted in accordance with Cochrane recommendations (Higgins et al. 2016).

2.5 Quality assessment

The quality of included studies was assessed using a modified version of the Newcastle-Ottawa Quality Assessment Scale for Cohort Studies (Wells et al. n.d.). Information relating to intervention/ policy characteristics, sampling strategy, representativeness of the target population, comparability of study controls and target populations, nature of outcome assessment, timing and adequacy of follow-up, and rates of attrition was collected from all evaluation studies. Given the absence of tools or guidance relating to quality assessment of system-based simulation studies, we extracted information that we believed would provide a good indication of the quality of a given model's simulated output. This included information concerning sources used to inform model parameters, transparency concerning the equations and assumptions made, the presence of calibration, validation and sensitivity or uncertainty analyses.

3. RESULTS

A total of 4197 records were identified by the search strategy implemented in each of the four databases; MEDLINE(Ovid), Scopus, LILACS and TRID (see Figure 1). Records written in a language other than English, Spanish or Portuguese and those not referenced as journal articles or conference proceedings were removed, as were 439 duplicates. The remaining 3302 citations were screened for inclusion based on title and abstract. Most records (n=3186) did not meet our inclusion criteria. We screened 116 full-text papers (including 15 systematic reviews) and excluded the majority of these (n=90) for the reasons detailed in Figure 1. The identified systematic reviews were all excluded after they were screened for potentially relevant primary studies. A total of 26 studies were identified using the employed search strategy. Thirteen additional studies were identified by: screening excluded systematic reviews (n=2) and reference lists of included studies (n=4), as well as by searching other sources (e.g., reviews and papers identified by the authorship team (n=7)). Ultimately, a total of 39 studies were included in the systematic review, including 29 empirical studies and 10 simulation-oriented papers.

[Insert Figure 1]

FIGURE 1. PRISMA flowchart showing process of study selection

3.1 Empirical studies

Empirical studies included in the review were published between 2005 and 2017 (Table 3). These studies were based in: North America, including the United States (n=11) (Boarnet et al. 2005, Evenson et al. 2005, Burbidge and Goulias 2009, Parker et al. 2011, Chen et al. 2012, Parker et al. 2013, Dill et al. 2014, Brown et al. 2016, Cook et al. 2016, Ferenchak and Marshall 2016, Brown et al. 2016b) and Canada (n=1) (Bhatia et al. 2016); Europe, specifically, the United Kingdom (n=9) (Goodman et al. 2013, Goodman et al. 2013b, Goodman et al. 2014, Heinen et al. 2015, Panter and Ogilvie 2015, Heinen and Ogilvie 2016, Panter et al. 2016, Panter and Ogilvie 2017, Song et al. 2017) and Denmark (n=1) (Jensen 2008); and Australia (n=4) (Greaves et al. 2015, Langdon 2015, Rissel et al. 2015, Heesch et al. 2016). Only three studies were based in LMIC, specifically, Colombia, Mexico and Brazil (Cerdá et al. 2012, Pazin et al. 2016, Chang et al. 2017).

Of the 29 studies, 19 were single-component interventions focused on the implementation of bicycle lanes. The remaining 10 studies evaluated multicomponent interventions. Among these, one study evaluated newly built aerial tram infrastructure which was implemented in combination with other neighborhood improvements including, additional lighting in public spaces, pedestrian bridges and recreational centres (Cerdá et al. 2012). Five studies evaluated the health effects of bicycle lanes which were variously combined with a host of interventions such as light rail and pedestrian infrastructure improvements, the creation of parking facilities and additional lighting (Boarnet et al. 2005, Goodman et al. 2013, Brown et al. 2016, Pazin et al. 2016, Brown et al. 2016b). The remaining studies (n=4) combined BRT and bicycle / pedestrian paths with park-and-ride sites (Heinen et al. 2015, Heinen and Ogilvie 2016, Panter et al. 2016, Chang et al. 2017). Table 3 summarizes the characteristics of included studies.

[Insert Table 3]

All 29 empirical evaluation studies employed a longitudinal study design and included pre- and post-intervention observations. Of these 29 studies, 15 included a control or reference group (Jensen 2008, Cerdá et al. 2012, Chen et al. 2012, Goodman et al. 2013, Parker et al. 2013, Dill et al. 2014, Greaves et al. 2015, Panter and Ogilvie 2015, Rissel et al. 2015, Brown et al. 2016, Heesch et al. 2016, Pazin et al. 2016, Brown et al. 2016b, Panter and Ogilvie 2017, Song et al. 2017). The proportion of studies with a control or reference group did not differ by intervention type; around half of all single component (10 of 19 studies) and multi-component intervention (5 of 10 studies) reported either a control or reference group. Four studies employed a random sampling approach to recruit participants, including three multi-component (Cerdá et al. 2012, Pazin et al. 2016, Chang et al. 2017) and one single component intervention study (Evenson et al. 2005). A further eleven studies attempted to sample the entire study area, including nine single component (Chen et al. 2012, Goodman et al. 2013b, Dill et al. 2014, Goodman et al. 2014, Panter and Ogilvie 2015, Bhatia et al. 2016, Ferenchak and Marshall 2016, Panter and Ogilvie 2017, Song et al. 2017) and two multi-component intervention studies (Goodman et al. 2013, Brown et al. 2016).

Exposure to the transportation intervention was operationalized in several different ways among the 29 empirical studies. Some studies compared geographic locations, specifically, street segments, before and after an intervention (Boarnet et al. 2005, Jensen 2008, Parker et al. 2011, Chen et al. 2012, Parker et al. 2013, Bhatia et al. 2016, Cook et al. 2016, Heesch et al. 2016). Most studies however, considered intervention impacts among people living in a fixed area of influence. These areas of influence were most commonly defined as buffers centred on the focal point of an intervention (Evenson et al. 2005, Burbidge and Goulias 2009, Dill et al. 2014, Panter and Ogilvie 2015, Rissel et al. 2015, Brown et al. 2016b, Chang et al. 2017), although some studies used predefined geographies such as towns (Goodman et al. 2013), block groups (Langdon 2015, Ferenchak and Marshall 2016) and neighborhoods (Cerdá et al. 2012) in and/or surrounding intervention sites. Only 9 studies used a distance-based metric to assess health impacts among people living different distances from an intervention (Goodman et al. 2013b, Goodman et al. 2014, Heinen et al. 2015, Brown et al. 2016, Heinen and Ogilvie 2016, Panter et al. 2016, Pazin et al. 2016, Panter and Ogilvie 2017, Song et al. 2017). We were unable to determine how exposure to the intervention was defined in one study (Greaves et al. 2015).

A total of 183 outcomes relating to 19 unique interventions were assessed by the 29 empirical studies included in our review. Of these, 21 outcomes were described but statistical tests were not conducted (see Appendix 2) (Burbidge and Goulias 2009, Dill et al. 2014, Greaves et al. 2015, Langdon 2015, Song et al. 2017). The 162 outcomes tested for statistical significance varied both with respect to outcome type and the frequency with which they were evaluated (Figure 2A; Appendix 3, Table 1). The four most frequently assessed outcome types included, active travel duration (25%), injury (23%), mode share (i.e., the share of walking, cycling, public transport and or car trips) (22%), and number of active trips (including walking or cycling trips) (11%). Few studies assessed physiological (Brown et al. 2016b), anthropometric (Brown et al. 2016b), and car travel-related outcomes (Greaves et al. 2015, Song et al. 2017). The three studies that evaluated the health effects of interventions in LMIC focused on homicide in Colombia (n=1) (Cerdá et al. 2012), active transit frequency in Mexico and Brazil (n=3 and n=1, respectively) (Pazin et al. 2016, Chang et al. 2017), as well as physical activity (n=4) and active mode share (n=1) in Brazil (Pazin et al. 2016). Appendix 2 provides further information on assessed outcomes and the nature of the associations reported by included studies.

The 19 studies reporting on single-component interventions (all focusing on bicycle lanes; Figure 2B) predominantly reported on injury outcomes (n=37) (Jensen 2008, Chen et al. 2012, Bhatia et al. 2016, Ferenchak and Marshall 2016), active travel duration outcomes (n=30) (Evenson et al. 2005, Burbidge and Goulias 2009, Dill et al. 2014, Goodman et al. 2014, Greaves et al. 2015, Panter and Ogilvie 2015, Cook et al. 2016, Panter and Ogilvie 2017, Song et al. 2017) and active trip outcomes (n=16) (Burbidge and Goulias 2009, Parker et al. 2011, Parker et al. 2013, Dill et al. 2014, Greaves et al. 2015, Rissel et al. 2015, Ferenchak and Marshall 2016, Heesch et al. 2016). Only 6 out of 37 injury outcomes showed statistically significant associations with new bicycle lanes (Jensen 2008, Bhatia et al. 2016, Ferenchak and Marshall 2016), and of these, the majority (n=4, all from the same study) were in the unexpected direction (i.e., the installation of bicycle lanes was positively associated with injuries) (Jensen 2008). The highest number of statistically significant outcomes were observed for active travel duration (i.e., 15 of 30 outcomes) (Evenson et al. 2005, Dill et al. 2014, Goodman et al. 2014, Cook et al. 2016, Panter and Ogilvie 2017, Song et al. 2017). Of these 15 outcomes, 10 showed statistically significant associations in the expected direction, that is, active travel duration increased following the bicycle lane intervention, whereas the inverse was observed in five outcomes. The second highest number of statistically significant associations were observed for active trips (i.e., 8 of 16) (Burbidge and Goulias 2009, Parker et al. 2011, Parker et al. 2013, Greaves et al. 2015, Rissel et al. 2015, Ferenchak and Marshall 2016, Heesch et al. 2016) and active mode share (i.e., 8 of 14) (Goodman et al. 2013b, Cook et al. 2016, Ferenchak and Marshall 2016). Of these, seven active mode share and six active trip outcomes were in the expected direction (i.e., the share of travel made using active modes and the the number of active trips increased following the creation of new bicycle lanes).

Four single component intervention studies assessed the health impacts of living different distances from the site of the intervention. Two of these studies, found positive associations between proximity to cycling infrastructure and the duration of active travel (for 7 of 12 outcomes) (Goodman et al. 2014, Panter and Ogilvie 2017) as well as the share of trips made using active modes (n=4 of 4 outcomes) (Goodman et al. 2013b).

The ten studies reporting on multicomponent interventions (Figure 2C) included a study evaluating the impact of aerial tram infrastructure on homicide (Cerdá et al. 2012), five studies evaluating bicycle lanes, and four studies focused on combined BRT and bicycle lane interventions (Heinen et al. 2015, Heinen and Ogilvie 2016, Panter et al. 2016, Chang et al. 2017). Among the multicomponent interventions, one study (Brown et al. 2016b) uniquely reported on physiological and anthropometric outcomes such kilocalorie expenditure and body mass index. The most frequently reported outcome among multicomponent interventions was active travel mode share with just over half of these outcomes (i.e., 12 of 23) demonstrating a statistically significant and positive association with the installation of bicycle lanes and/ or BRT infrastructure (Heinen et al. 2015, Brown et al. 2016, Heinen and Ogilvie 2016, Pazin et al. 2016).

Of the 10 multicomponent interventions, five investigated whether living different distances from the intervention differentially impacted health outcomes. These five studies found that people living closer to bicycle lanes, with or without an adjoining BRT line, had higher levels of physical activity (for 3 of 6 outcomes) (Pazin et al. 2016), engaged in longer periods of active travel (for 3 of 7 duration outcomes) (Panter et al. 2016, Pazin et al. 2016), and used a higher share of active modes (for 9 of 20 outcomes) (Heinen et al. 2015, Brown et al. 2016, Heinen and Ogilvie 2016, Pazin et al. 2016).

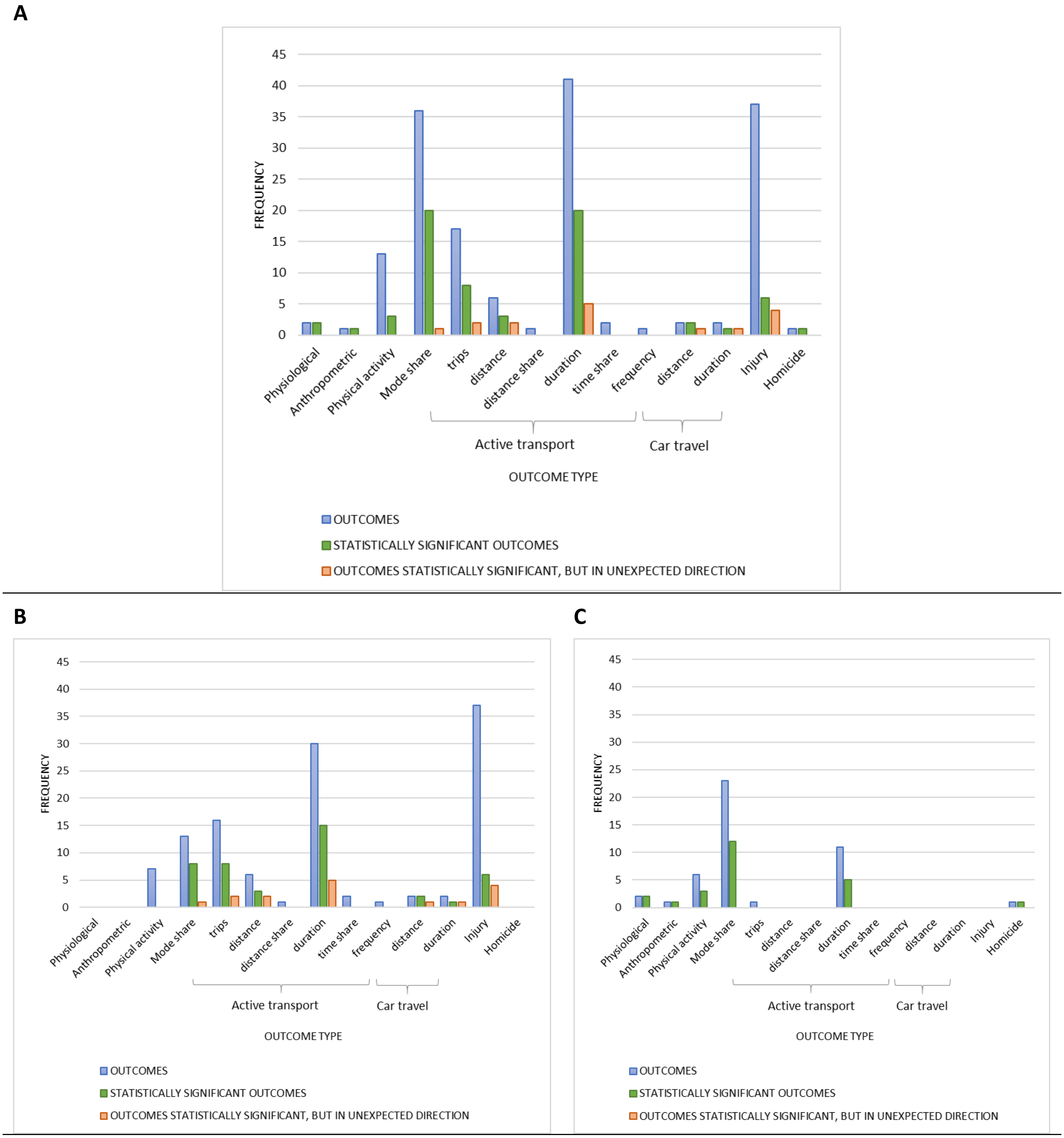

FIGURE 2: Frequency of outcomes, by type, for **A** all included empirical studies (29 studies, 162 distinct outcomes), **B** single component interventions (19 studies, 117 outcomes) focusing on the creation of bicycle lanes, and **C** multicomponent interventions (10 studies, 45 outcomes). The bars in blue represent the total number of outcomes, by type, while the green bars represent the total number of statistically significant outcomes. Of the statistically signficant outcomes, the bar in orange depts the the number of outcomes that were in the unexpected direction for each outcome type.

NB: Figures do not include 21 outcomes reported by 5 studies because these outcomes were not assessed using statistical models

3.2 Simulation studies

The 10 system-based simulation studies (Table 4) included in this review (McDonnell and Zellner 2011, Okushima and Akiyama 2011, Yang and Diez-Roux 2013, Macmillan et al. 2014, Okushima 2015, Yang et al. 2015, Lemoine et al. 2016, Okushima 2016, Zellner et al. 2016, Zou et al. 2016) were published between 2011 and 2016.

Five studies tested the impacts of expanding, improving (e.g., creating exclusive bus lanes or changing the BRT system), or incentivizing public transportation formed the focus of five studies (McDonnell and Zellner 2011, Okushima and Akiyama 2011, Okushima 2015, Lemoine et al. 2016, Zou et al. 2016), three of which were dedicated to BRTs (McDonnell and Zellner 2011, Okushima 2015, Lemoine et al. 2016). Three studies investigated interventions for active travel promotion, such as the creation of cycling infrastructure or implementation of traffic safety measures to promote walking trips to school (Yang and Diez-Roux 2013, Macmillan et al. 2014, Okushima 2016). The remaining two studies investigated combinations of public transport and active travel policies, such as the implementation of transportation cost policies (e.g., public transit fares and parking fees), interventions aimed at changing attitudes towards driving and cycling, and streetscape improvements (Yang et al. 2015, Zellner et al. 2016).

Of the 10 simulation studies, four included active travel as the only health-related outcome (Yang and Diez-Roux 2013, Yang et al. 2015, Lemoine et al. 2016, Okushima 2016). One study also analyzed road traffic injuries and all-cause mortality (Macmillan et al. 2014). The other five studies (McDonnell and Zellner 2011, Okushima and Akiyama 2011, Okushima 2015, Zellner et al. 2016, Zou et al. 2016) reported only on transport-related outcomes, such as mode share, mode-specific travel time or mode shift, featuring either bus and/ or BRTs as one of the investigated modes.

Nine studies (McDonnell and Zellner 2011, Okushima and Akiyama 2011, Yang and Diez-Roux 2013, Okushima 2015, Yang et al. 2015, Lemoine et al. 2016, Okushima 2016, Zellner et al. 2016, Zou et al. 2016) used ABM, and one (Macmillan et al. 2014) used the system dynamics framework. Only two studies modelled cities in LMIC, specifically, Bogota, Colombia (Lemoine et al. 2016), and Beijing, China (Zou et al. 2016), whereas three were based on highly stylized settings (i.e., not grounded in any real location) (McDonnell and Zellner 2011, Yang and Diez-Roux 2013, Yang et al. 2015). All studies explored both the mechanisms driving the behavior of the investigated systems and tested the potential effects of policy interventions.

Of the 10 simulation studies, five included both agent-agent (or, equivalently, persons-persons in the system dynamics model) and agent-environment (persons-environment) interactions in their models (McDonnell and Zellner 2011, Okushima and Akiyama 2011, Yang and Diez-Roux 2013, Macmillan et al. 2014, Yang et al. 2015). Three modelled agent-environment interactions only (Lemoine et al. 2016, Zellner et al. 2016, Zou et al. 2016) and the remaining two included just agent-agent interactions (Okushima 2015, Okushima 2016). In all studies, policy alternatives were considered as new scenarios through the manipulation of exogenous variables (i.e., there were no agents in the model that enacted policy decisions based on changes in the model).

Of the nine ABM studies, eight (McDonnell and Zellner 2011, Okushima and Akiyama 2011, Yang and Diez-Roux 2013, Okushima 2015, Yang et al. 2015, Lemoine et al. 2016, Okushima 2016, Zellner et al. 2016) applied utility functions to represent the agents' decision-making process and one used production ('if-then') rules (Zou et al. 2016). Decisions between modes of transportation were informed by a variety of factors, but most frequently by distance, financial costs and travel time, mode chosen by other persons (such as members of one's friendship network, or those of the community at large), as well as traffic congestion and safety. Mode chosen by other persons, traffic congestion (and, consequently, travel time), and traffic safety were the main mechanisms of interaction between persons and with their environment.

Time steps varied significantly across studies, ranging from just 3 seconds in one study to 1 year in another. Comparatively, there was less variation in the periods modelled, with four studies (McDonnell and Zellner 2011, Yang and Diez-Roux 2013, Lemoine et al. 2016, Zellner et al. 2016) modelling one month or less, and four other studies modelling 10 years or more (Okushima and Akiyama 2011, Macmillan et al. 2014, Okushima 2015, Okushima 2016).

Five of the 10 studies explored economic incentives to encourage the uptake of mass transit and/or discourage the use of cars (Okushima and Akiyama 2011, Okushima 2015, Yang et al. 2015, Zellner et al. 2016, Zou et al. 2016). Evaluated strategies included implementation of congestion fees and green taxes, changes in fuel price and parking fees, and bus fare discounts. The effects of such policies were found to provide significant improvements in health-related outcomes. Improvements of public transport services, including the implementation of BRT systems, were also investigated by five studies (McDonnell and Zellner 2011, Okushima and Akiyama 2011, Okushima 2015, Lemoine et al. 2016, Zellner et al. 2016). Besides the implementation of BRT lanes, other interventions included increasing bus frequency, the introduction of express bus stops, and changes in the system density (coverage). Overall, these studies showed improvements in active travel time and bus share.

Models demonstrated that sizeable modal shift and changes in health outcomes can be achieved from the implementation of multiple, synergistic policies. For instance, Yang et al. (Yang et al. 2015) observed that combinations of decreasing the attitude towards driving, increasing attitudes toward walking, and economic interventions that encourage walking were more effective than any single intervention alone, in increasing walking for all income levels. Similarly, McDonnell and Zellner (McDonnell and Zellner 2011) observed a 14 percentage point increase (21% to 35%) in bus share with the implementation of a BRT system, potentially reaching to an increment of 21 percentage points (i.e., 42% of the mode share) with the additional introduction of off-board ticketing.

[Insert Table 4]

3.3 Quality appraisal

3.3.1 Empirical studies

The studies included in the review employed a range of sampling strategies including, attempts to sample the entire population within a given study area (n=11) (Chen et al. 2012, Goodman et al. 2013, Goodman et al. 2013b, Dill et al. 2014, Goodman et al. 2014, Panter and Ogilvie 2015, Bhatia et al. 2016, Brown et al. 2016, Ferenchak and Marshall 2016, Panter and Ogilvie 2017, Song et al. 2017); random sampling (n=4) (Evenson et al. 2005, Cerdá et al. 2012, Pazin et al. 2016, Chang et al. 2017); non-random or stratified sampling (n=6) (Burbidge and Goulias 2009, Parker et al. 2011, Parker et al. 2013, Langdon 2015, Rissel et al. 2015, Panter et al. 2016); purposive sampling (n=4) (Greaves et al. 2015, Heinen et al. 2015, Heesch et al. 2016, Heinen and Ogilvie 2016); traffic counts (n=2) (Boarnet et al. 2005, Cook et al. 2016). The remaining studies (Jensen 2008, Brown et al. 2016b) provided no description of the sampling strategy used. The representativeness of the recruited participants, as determined by the participant response rate and the sampling strategy used, was unclear for most studies (69%) (Evenson et al. 2005, Jensen 2008, Parker et al. 2011, Goodman et al. 2013b, Dill et al. 2014, Goodman et al. 2014, Greaves et al. 2015, Heinen et al. 2015, Langdon 2015, Panter and Ogilvie 2015, Rissel et al. 2015, Brown et al. 2016, Cook et al. 2016, Heesch et al. 2016, Heinen and Ogilvie

2016, Panter et al. 2016, Brown et al. 2016b, Chang et al. 2017, Panter and Ogilvie 2017, Song et al. 2017), only one study was deemed to have a truly representative sample (Goodman et al. 2013), while the rest were somewhat representative (n=7) (Burbidge and Goulias 2009, Cerdá et al. 2012, Chen et al. 2012, Parker et al. 2013, Bhatia et al. 2016, Ferenchak and Marshall 2016, Pazin et al. 2016) or not very representative (n=1) (Boarnet et al. 2005).

Most studies in the review did not include a control or a comparison group (n=14) (Boarnet et al. 2005, Evenson et al. 2005, Burbidge and Goulias 2009, Parker et al. 2011, Goodman et al. 2013b, Goodman et al. 2014, Heinen et al. 2015, Langdon 2015, Bhatia et al. 2016, Cook et al. 2016, Ferenchak and Marshall 2016, Heinen and Ogilvie 2016, Panter et al. 2016, Chang et al. 2017), of those that did, the extent to which the control and intervention groups were similar at baseline was unclear for eight studies (Jensen 2008, Parker et al. 2013, Greaves et al. 2015, Panter and Ogilvie 2015, Brown et al. 2016, Brown et al. 2016b, Panter and Ogilvie 2017, Song et al. 2017), while the rest featured control and intervention groups that were comparable at baseline, providing either a quantitative characterization of the two groups (n=5) (Cerdá et al. 2012, Chen et al. 2012, Dill et al. 2014, Heesch et al. 2016, Pazin et al. 2016) or general statement to that effect (n=2) (Goodman et al. 2013, Rissel et al. 2015). Included studies featured more self-reported (n=13) (Evenson et al. 2005, Burbidge and Goulias 2009, Goodman et al. 2013, Goodman et al. 2013b, Goodman et al. 2014, Heinen et al. 2015, Panter and Ogilvie 2015, Heinen and Ogilvie 2016, Panter et al. 2016, Pazin et al. 2016, Chang et al. 2017, Panter and Ogilvie 2017, Song et al. 2017) than objectively measured outcomes (n=7) (Boarnet et al. 2005, Jensen 2008, Parker et al. 2011, Cerdá et al. 2012, Parker et al. 2013, Dill et al. 2014, Brown et al. 2016). There were also studies that reported on both self-reported and objective outcomes (n=9) (Chen et al. 2012, Greaves et al. 2015, Langdon 2015, Rissel et al. 2015, Bhatia et al. 2016, Cook et al. 2016, Ferenchak and Marshall 2016, Heesch et al. 2016, Brown et al. 2016b).

The timing and duration of pre- versus post-intervention assessments varied substantively across studies. Pre-intervention assessments were commonly collected over a period spanning an average of 22 months and ranging from 3 months to 5 years. On average, these assessments were conducted 14 months before the intervention and ranged from immediately before to 8 years pre-intervention. Post-intervention assessments were collected on average over a period spanning 17 months and ranging from 5 months to 2.5 years. Intervention effects on outcomes were assessed on average 8.5 months after the intervention though some studies conducted post-intervention assessments immediately after, while others conducted their first assessments 4 years after.

Of the 29 empirical studies, 17 studies experienced loss to follow-up to differing degrees: <30% attrition was reported by 2 studies (Cerdá et al. 2012, Dill et al. 2014), 30-59% by 13 studies (Evenson et al. 2005, Goodman et al. 2013b, Goodman et al. 2014, Greaves et al. 2015, Heinen et al. 2015, Panter and Ogilvie 2015, Rissel et al. 2015, Brown et al. 2016, Heinen and Ogilvie 2016, Panter et al. 2016, Pazin et al. 2016, Brown et al. 2016b, Song et al. 2017), and 60-89% by 2 studies (Burbidge and Goulias 2009, Panter and Ogilvie 2017). Please refer to Appendix 4 for more information about the quality appraisal of included studies.

3.3.2 Simulation studies

Overall, the system-based simulation studies made explicit the models' assumptions and structure. Nine studies provided justifications for all or most of their assumptions (McDonnell and Zellner 2011, Okushima and Akiyama 2011, Yang and Diez-Roux 2013, Macmillan et al. 2014, Okushima 2015, Yang et al. 2015, Okushima 2016, Zellner et al. 2016, Zou et al. 2016). Only one study did not provide justifications for the equations used (McDonnell and Zellner 2011) while the four other studies (Macmillan et al. 2014, Yang et al. 2015, Lemoine et al. 2016, Zellner et al. 2016) provided justifications only for some of the equations. All the 10 system-based simulation studies used empirical sources to inform their parameters.

Calibration and validation procedures and sensitivity or uncertainty analysis were infrequently assessed. Among the four studies with some parameters that could not be informed by empirical data (McDonnell and Zellner 2011, Okushima and Akiyama 2011, Yang and Diez-Roux 2013, Zou et al. 2016), two (McDonnell and Zellner 2011, Okushima and Akiyama 2011) did not calibrate the unknown parameter values and the other two (Yang and Diez-Roux 2013, Zou et al. 2016) used categorical calibration only (i.e., searched for parameter values that produce model results within a range acceptably close to data). Six studies (Okushima and Akiyama 2011, Yang and Diez-Roux 2013, Okushima 2015, Okushima 2016, Zellner et al. 2016, Zou et al. 2016) did not validate the results of baseline scenarios against expected (in purely stylized models) or observed (in models grounded on real locations) outcomes, and only two studies (McDonnell and Zellner 2011, Macmillan et al. 2014) compared outcomes using either qualitative or quantitative means. Five studies (Yang and Diez-Roux 2013, Okushima 2015, Yang et al. 2015, Okushima 2016, Zou et al. 2016) did not conduct either sensitivity or uncertainty analyses, only one conducted both (Macmillan et al. 2014), and the remaining four (McDonnell and Zellner 2011, Okushima and Akiyama 2011, Lemoine et al. 2016, Zellner et al. 2016) ran sensitivity analyses only. Appendix 5 provides more information about the quality appraisal of included simulation studies.

4. DISCUSSION

Of the 39 empirical and system-based simulation studies identified, the majority focused on bicycle lanes and BRT systems. Notably, only one study evaluated aerial trams, and none investigated Open Streets programs. Moreover, most studies (n=24) focused on HIC, while only five studies explored cities in LMIC. In *empirical studies*, bicycle lane interventions were associated with increases in physical activity and active transport. Similarly, BRT systems with an adjacent bicycle lane were found to promote active travel and walking for transport and recreation. The sole aerial tram study reported a significant decrease in homicides following the aerial tram installation. There was also some evidence to suggest that multiple component interventions may be more effective than single component interventions in increasing physical activity. *System-based simulation studies* showed that economic incentives designed to disincentivise car use, and policies designed to improve the public transportation system, can have positive impacts on active travel time and bus share. Consistent with empirical studies evaluating multicomponent interventions, systems-based simulations often reported synergistic effects of multiple interventions and policies.

The *quality of included studies* was mixed. Most empirical studies did not include a control or comparison group and for those that did, it was largely unclear to what extent the control and intervention groups were similar at baseline. Empirical studies also reported a range of sampling approaches. There existed substantive uncertainty about the generalizability of study findings because 21 of the 29 included studies featured populations that were either not representative of the study region or whose representativeness was unclear. System-based simulation studies commonly provided justifications for the assumptions made and the equations used, although several were highly abstract models. Most simulation studies were also informed by empirical data. However, calibration and validation procedures and uncertainty analysis were infrequently conducted, and the periods modelled in a handful of studies appeared relatively short (less than 1 month), which may have impacted study findings.

The most common policy evaluated by empirical studies pertained to *bicycle infrastructure*. These studies generally reported beneficial effects on bicycle mode share and active transport duration and number of trips. Some adverse effects on injuries were documented although these were reported by a single study. However, only one of these longitudinal studies was based in or explored cities in LMIC. Prior reviews have also identified research on bicycle infrastructure in LMIC as important gaps (Fraser and Lock 2010, Yang et al. 2010). Cross-sectional studies focused on LMIC report consistent effects of bicycle lanes on active travel. For example, Florindo et al. found that people living within 500 meters of bicycle paths in Sao Paolo, Brazil were more than twice more likely to engage in cycling for transportation than those who lived further away (Florindo et al. 2018). Another study based in Taiwan, found an association between residents' perceptions of bicycle lanes in their neighborhood and past week cycling for transportation among adults (Liao et al. 2015). Additional longitudinal evaluation studies are needed to determine the impact of the rapid growth in bicycle infrastructures that is occurring in many LMIC, in contexts that are very different from those of HIC.

The second most explored policy focused on *BRT systems*. These studies, mostly focused on HIC, found that BRT systems increase active travel and walking for transport and recreation. There are however over 160 cities around the world with operating BRT systems (BRT+ Centre of Excellence and EMBARQ 2019). Among them are cities from a range of LMIC in Latin America (e.g., Brazil, Colombia, Argentina, Mexico), Asia (e.g., China, India, Taiwan, Vietnam) and the African continent (e.g., Morocco, South Africa, Nigeria, Uganda). While few longitudinal studies have investigated these transport systems in LMIC, cross-sectional analyses suggest that BRT use may positively impact health outcomes. For example, using cross-sectional survey data, Lemoine et al. 2016 found that BRT use in Bogota, Colombia, was associated with around 12 minutes of moderate-to-vigorous physical activity each day (Lemoine et al. 2016). Similarly, Bartels et al. used cross-sectional intercept surveys of BRT passengers in Cape Town, South Africa, and found that BRT-users engaged in significantly longer periods of physical activity per week and were over twice more likely to achieve recommended physical activity guidelines than non-users (Bartels et al. 2016). These findings align closely with the general findings of our review which suggest that BRT interventions represent effective means for increasing physical activity and active travel.

Aerial trams form part of the transit infrastructure, both in LMIC and HIC around the world (Alshalalfah et al. 2012). However, our review of the literature indicates that aerial trams remain relatively under-studied, particularly with respect to their health-related impacts. We found only one longitudinal evaluation of aerial trams and no system-based simulation studies. The sole study included in our review, which capitalized on a natural experiment, found that the construction of the Metrocable (i.e., aerial tram) in Medellin, Colombia, resulted in significant reductions in homicide rates in the neighborhoods surrounding the new aerial tram (Cerdá et al. 2012). Other studies which did not meet the inclusion criteria of our review investigated the impacts of aerial trams on relatively distal outcomes indirectly related to health and health-related behavior, for example, employment access and travel time. One of these studies found that the Metrocable significantly improved access to the central business district and thereby more than doubled employment opportunities for aerial tram users, including low-income groups (Bocarejo et al. 2014). Moreover, in their study of the Mi Teleférico aerial tram in La Paz, Bolivia, Garsous et al. (Garsous et al. 2019) found that users of the aerial tram reduced their travel time by around 20%. Travel time reductions such as these have variously been linked to improved access to health care, employment and education as well as opportunities for leisure-time activities including physical activity (Garsous et al. 2019).

Despite the increasing prominence of *Open Streets programs* in both LMIC and HIC, our review did not identify any longitudinal evaluations of the health impacts of these initiatives. Sarmiento et al. identified 38 Open Streets programs implemented across 11 different countries in 2010, most of which were concentrated in Latin America (Sarmiento et al. 2010). Another review identified Open Streets initiatives hosted in 47 different US cities (Kuhlberg et al. 2014). Furthermore, cross-sectional evidence suggests that Open Streets initiatives can confer meaningful public health benefits. For example, using information synthesized from the Open Streets programs, Sarmiento et al. estimated important potential contributions of Ciclovias to physical activity (Sarmiento et al. 2010, p. S176). Positive associations have also been observed among school children. For example, Triana et al. found that frequent Ciclovia use among Colombian school children was associated with significantly lower levels of sedentary time and higher moderate-to-vigorous physical activity on Sundays, but interestingly, not weekdays (Triana et al. 2019). However, longitudinal evaluations of these important initiatives are necessary.

We observed several points of alignment between the *system-based simulation papers and* the *longitudinal evaluation studies* included in our review. For example, both empirical and simulation studies focused predominantly on estimating the impact of policies encompassing expansions and or improvements in public transport infrastructure (e.g., express bus lanes, creation of BRT system) and service delivery (e.g., increased frequency of buses), or incentives for public transportation (e.g., fare changes) on health. Evidence across both bodies of literature suggests that multi-pronged interventions may be more effective than single-component interventions in shaping some health outcomes. This observation is in keeping with published research (van Sluijs et al. 2007) and Social Ecological Theory which posits that ecological approaches, which seek to enact change at multiple levels of a system, are more effective than those targeted toward just one level (Green et al. 1996, Sallis et al. 2008). However, it was unclear from our systematic review which of the intervention components in a given multi-component study were the drivers of the observed health impacts.

Another important observation was that all simulation studies captured by our review used empirical sources to inform the selection and characterization of model parameters, highlighting the importance of robust empirical studies focused on exploring the influence of transportation policies on health outcomes across a range of contexts, not just HIC. This reliance on empirical data and the fact that most empirical studies we identified were conducted in HIC could explain why most of the simulation-based papers included in our review also explored high-income contexts.

We observed heterogeneity in how studies operationalized people's *exposure to a given transportation intervention*. Some studies compared geographic locations while others considered intervention impacts among people living in an area of intervention influence. These areas were either defined using existing geographic units (e.g., census blocks) or buffers centred on the focal point of an intervention. Only a subset of empirical studies compared the health effects of a given intervention for those living different distances from the intervention site, despite contemporary debates advocating for a pluralistic measurement approach (Laatikainen et al. 2018). Most of these studies reported more significant and positive effects on health outcomes for those living closer to the site of an intervention than those living further away; a finding consistent with existing research (McCormack and Shiell 2011, Djurhuus et al. 2014).

The studies in our review assessed a wide *range of health outcomes*, however, anthropometric/ physiological measures, and mortality outcomes were infrequently reported. Moreover, none of the studies in our review considered disease outcomes such as diabetes, or respiratory and mental health outcomes. And, strikingly, few studies addressed issues of equity by exploring intervention effects using stratified analyses which would have enabled critical insights into health inequalities by socioeconomic status and demographic factors such as race and gender. This relative underrepresentation of *equity-grounded research* has been observed in other reviews of transportation systems in LMIC (Yanez-Pagans et al. 2018) and those investigating built environment influences on physical activity and active transport more broadly (Smith et al. 2017).

The accessibility of transportation is an important predictor of health care access (Syed et al. 2013), and employment, which has been linked to a range of health-related behaviors through its influence on both income and time scarcity (Venn and Strazdins 2017). Importantly, research based in Latin America has shown that patterns in access to BRT, by income, can vary from one city to another. For example, the BRT system in Lima, Peru has been shown to predominantly benefit middle- and higher-SES groups due to the systems limited coverage of areas with high concentrations of poor residents (Oviedo et al. 2019). On the other hand, in Cali, Colombia, the highest levels of access to a new BRT system were observed among middle income groups, while residents of predominantly low and high income neighborhoods had far more limited access (Delmelle and Casas 2012). Such inequalities however are not only observed in LMIC, they have also been reported in HIC such as Australia (Ricciardi et al. 2015), with observed inequalities in access spanning both age and the socioeconomic spectrum. Thus, additional evaluations on the impact of these types of interventions on equity outcomes is sorely needed.

4.1 Limitations

This review should be considered with a few limitations in mind. Our review was necessarily limited through the exclusion of papers that assessed the impacts of BRT, aerial trams, bicycle lanes and Open Streets programs on outcomes that have implications for health, such as accidents, crashes and traffic-related air pollution, but that are not themselves health outcomes. We also excluded studies employing non-longitudinal study designs and other simulation methods such as health impact assessment models, social network analysis, microsimulation or more conceptual/ qualitative models arising from participatory approaches such as group model building. To focus the scope of our review, we also excluded studies evaluating light rail transit systems, as well as those focused specifically on bicycle boxes, intersection crossings or roundabouts as opposed to continuous street segments. Given time and resource constraints we did not contact study authors for clarification where information was missing or unclear. Most of the studies we included in the review were based in HIC which may limit the generalizability of our findings to LMIC. Our assessment of the quality of system-based simulation studies may also be limited given the lack of guidance on how to assess the quality of these types of studies. Finally, several papers included in the review evaluated the same intervention. For example, five different papers, all conducted as part of the iConnect Study, evaluated the same set of bicycle lane interventions implemented in three cities in the United Kingdom (UK) (Goodman et al. 2013b, Goodman et al. 2014, Panter and Ogilvie 2015, Panter and Ogilvie 2017, Song et al. 2017), while four papers evaluated the same combined BRT and bicycle lane intervention in Cambridge, UK (Heinen et al. 2015, Heinen and Ogilvie 2016, Panter et al. 2016, Chang et al. 2017). Given this overlap, our findings represent outcomes for just 19 unique interventions variously evaluated by the 29 empirical studies included in the review.

4.2 Recommendations for future research

The findings of our review highlight several important areas for future research. First, more evaluation and system-based simulation studies are needed to assess the influence of bicycle lanes, BRT systems, aerial trams and Open Streets programs on health outcomes, particularly in LMIC. This is particularly important as differences between HIC and LMIC have been observed in studies investigating associations between built environment characteristics and physical activity, for example (Cleland et al. 2019). In the case of empirical studies, rigorous designs including representative population samples, valid comparison groups, and before and after assessments are needed. On the other hand, the use of evidence to justify model rules and parameters is critical for simulation studies. Second, there also exists a need for studies replicating policy evaluations in different cities to determine the extent to which city-level factors impact the effectiveness of interventions overall and for different population subgroups. These studies may in turn inform simulation-based studies which have the capacity to identify under what conditions a given policy or combinations of policies may be most effective in promoting health outcomes across the socioeconomic and demographic spectrum. Systems-based simulation methods can be especially useful as policy decision-tools, particularly in LMIC where the assessment of large-scale population-level interventions may be prohibitively expensive or impractical to test in the real world (Hammond 2015). These methods can also raise new questions and in turn inform the focus of empirical research and evaluation studies (Diez Roux 2019). To support the use of system-based simulation methods, tools guiding the assessment of quality for these studies represents an important area for future research. Participatory processes such as group model building (Hovmand 2014) which seek to elicit the perspectives of diverse stakeholders, can play an important role in informing the design of simulation models. Moreover, they have the potential to elucidate novel evaluation targets and foster intersectoral and community partnerships which can play an important role in the sustainability and longevity of interventions.

Third, prospective studies, both empirical and simulation-based, focusing on BRT, bicycle lanes, aerial trams and Open Streets programs ought to explore the potential environmental and health co-benefits of these policies. The high expansion of new programs in both HIC and LMIC provide a unique opportunity for natural experiments. For example, studies investigating bicycle lane interventions would be well placed to investigate changes in transport-related air pollution and the respiratory health of city residents alongside and in interaction with changes in mode share and physical activity during transport and leisure time. More studies evaluating the influence of bicycle lanes on injury outcomes are also required. Fourth, studies employing stratified analysis, by for example, gender, income, age and race are required to explore the impact of these transport policies on health disparities across a range of outcomes including anthropometric and physiological measures as well as respiratory and other disease outcomes. Relatedly, to ensure study quality, the design of future system-based simulation studies ought to reflect an alignment between the outcomes of interest and the timeframes being modelled.

Finally, researchers seeking to advance research in this area, particularly in LMIC may benefit from the use of innovative and relatively cost-effective data collection methods such as street imagery (e.g., Google Street View and Bing StreetSide) to capture granular information about the physical environment and behavioral data. Street imagery has widely been tested as a built environment audit tool, including its predictive capacity in documenting relatively small-scale historic changes to the built environment (Candido et al. 2018). There is also evidence to suggest that it can be used to estimate pedestrian counts (Yin et al. 2015), and city-level travel patterns including census-reported mode share (i.e., walking and public transit use, cycling, motorcycle and car use) as well as survey-reported past-month participation in cycling (Goel et al. 2018). Given these features, and with years of historical data available, street imagery may provide an avenue for the conduct of retrospective longitudinal policy evaluations of transport policies, and a promising means of complementing traditional data collection methods, particularly in LMIC.

Researchers can also benefit from using a citizen science approach which “empowers residents to collect diagnostic information about their community environment, prioritize areas of concern, and engage in cross-sector collaboration to generate practical and impactful solutions” (King et al. 2016, p.31). These approaches have successfully been used in Latin American countries to collect neighborhood-level information as well as qualitative data relating to a range of initiatives, including Open Streets programs (King et al. 2016). Other emerging approaches that might be leveraged to advance future studies seeking to monitor the impact of transport policies include drone technology, which has been used to collect data on pedestrian counts (Park and Ewing) and deep learning image analysis, which may afford an especially promising and cost-effective means of estimating local environmental exposures and spatial inequalities in income, education, employment and health, particularly in LMIC (Suel et al. 2019, Weichenthal et al. 2019).

5. CONCLUSION

The literature base encompassing longitudinal evaluations, and system-based simulation studies exploring the health impacts of BRT systems, bicycle lane and aerial tram infrastructure and Open Streets programs varies widely by transportation policy and geographical context. This review contributes to the literature by highlighting several important gaps in knowledge. Specifically, it highlights an underrepresentation of certain types of transportation policies (i.e., aerial trams and Open Streets programs), outcomes (e.g., physiological, anthropometric and health equity measures), and countries (i.e, LMIC) within the literature. By synthesizing the available research, this review also identifies bike lanes and BRT systems as promising transportation initiatives for promoting physical activity and active travel at the population-level. Finally, it provides a series of recommendations for future research designed to bridge critical gaps in understanding, and to support the advancement of the public health agenda through transportation policy.

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