Can E-scooters Enhance Active-Mobility Health Outcomes?

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Abstract

Micromobility (μmobility) can improve wellbeing through numerous mechanisms including mobility equity, pollution reduction, urban space reclamation, empowerment, childhood cognitive development, resilience, and sustainability. Active μmobility—most commonly bicycling and walking—additionally improves healthy life expectancy due to increased exercise. Passive μmobility modes such as e-scooters lack the exercise benefit of active modes, negating a primary public health benefit.

Starting from the assumption that due to similar size, speed, and needs, e-scooters trigger safety and infrastructure feedback loops that also benefit bicycling. If this holds, then long-term system interactions may sometimes allow e-scooters to contribute positively to a healthy urban environment.

Drawing from the literature, we sketch causal loops that link μmobility modeshare to safety-in-numbers, infrastructure development, and, ultimately, three health modulators: exercise, mobility safety, and pollution. We investigate some potential scenarios in which e-scooters have the potential to improve urban mobility and health, and call attention to areas where their introduction is most likely have a negative impact.

This exploratory research is not meant to be predictive, but rather to encourage further study of potential system behaviours and their effects on public health, and to stimulate conversation about possible synergies and conflicts.

1 Introduction

Micromobility (μmobility) is showing great promise for providing enhanced mobility while avoiding most of the harms caused by car-centric transportation systems [Miner et al., 2024]. μmobility can improve wellbeing through numerous mechanisms including mobility equity, pollution reduction, urban space reclamation, empowerment, childhood cognitive development, resilience, sustainability. . . [WCA and ECF, 2016; Sheller, 2018; Macmillan et al., 2020] Active μmobility—most commonly bicycling and walking, but also including wheelchairs, handcycles, tricycles, velomobiles, etc—additionally improves healthy life expectancy due to increased exercise, which can easily reduce all-causes mortality by 35% in sedentary people, with a far greater (but harder to quantify) effect upon healthspan (§1.5). Passive μmobility modes such as e-scooters lack the exercise benefit of active modes, negating a primary public health benefit (§1.2).

1.1 Bikes

The popularity of bicycling is modulated primarily by safety and convenience. Safety-in-numbers (SIN) refers to the observation that as the number of bicyclists increases, the risk per trip decreases. And as risk decreases, modeshare increases, creating a safety-numbers feedback loop (§1.3.1). Increased modeshare also drives investments in infrastructure that can affect both safety and convenience, such as secure parking, dealers and mechanics, riding communities, μmobility-specific route improvements, better integration with public transit, and bikeshare system coverage, closing longer-term feedback loops.

1.2 E-scooters

E-scooters have different strengths and weaknesses than bicycles, and thus attract different kinds of users to different kinds of trips [McKenzie, 2019; Curl and Fitt, 2020; Zhu et al., 2020; Zhang et al., 2021; Wang et al., 2023; Roig-Costa et al., 2024]. In reviews by Wang et al. [2023] and Badia and Jenelius [2023], e-scooters replace 25–40% of car trips, generally fewer than 10% of trips by bike, and can both replace and augment public transit depending largely on the distances involved. E-scooters replace a much higher proportion of pedestrian trips (30–60%), making this a crucial direction for future research.

To what extent do e-scooters provide the health benefits of active mobility? Payne et al. [2025] found that stand-up e-scooters bring METs to 1.6. Typical utility bicycling is 4–9 METs, whereas walking is 3.5–5.5 [De Geus et al., 2007; Herrmann et al., 2024] and §1.5. Herrmann et al. [2024] reports a value of 1.8 METs for activities such as “Sitting, fidget feet” and “Standing, light work (filing, talking, assembling)”. This does not preclude e-scooters providing some minor benefit to core stability or balance, but their contribution to cardiovascular health is negligible.

In a study of schoolchildren’s commutes, Pesola et al. [2022] found that cycling provides exercise comparable to walking to bus stops across two Finnish cities. This local result suggests that when e-scooters replace walking for last-mile public transit access, all else being equal, public health outcomes will be harmed. However, Wang et al. [2023] reports on research indicating that e-scooters are frequently used only on one leg or one direction of a public-transit trip, which could potentially encourage healthy multimodal journeys.

It should also be noted that, while e-scooter-share systems appear to provide many of the advantages of bicycles, [Badia and Jenelius, 2023, §5] reviews recent work concluding that due to a high manufacturing investment relative to their service life, and other costs such as fleet rebalancing, they often cause more environmental damage than the modes that they replace.

1.3 Traffic safety

The UK, Germany, Denmark, and the Netherlands kill on the order of one cyclist per 100 million km ridden [Buehler and Pucher, 2021]. Branion-Calles et al. [2020] found somewhat higher rates within seven European cities (unweighted average 2.4 fatalities per 100 million km). At an average moving speed of 14 km/h [De Geus et al., 2007; Rojas-Rueda et al., 2011], this is one death every $\sim$5 million hours of cycling. Bikeshare users ride more slowly—e.g. 10

km/h [Jensen et al., 2010], which would reduce both the risk of fatal collisions per hour and—assuming the lower speeds come from lower effort rather than heavier bikes—the health benefit per hour, although the outsized health benefit of going from no exercise to a small amount could overcome this. If the mean age of a cyclist killed in a collision is ~60 [Evgenikos et al., 2016; Slootmans, 2021], and the life expectancy is ~80, then approximately 200,000 life-hours are lost per 5 million hours of cycling.

The USA is more hostile to cyclists: as of Buehler and Pucher's [2021] analysis, the USA was killing 6 cyclists per 100 million km and rising, with a mean age of 49 [NHTSA, 2025], albeit with a slightly lower baseline life expectancy. These conditions reduce the benefit/cost ratio, but even in the USA the benefits generally outweigh the costs (§1.5).

1.3.1 Safety and Numbers

Empirically, as bicycle use increases, the risk per cyclist decreases—see [Elvik and Goel, 2019] for a comprehensive meta-analysis. One ironic example was accidentally published by Graves et al. [2014] in an article arguing for more helmet use. Their data on 5 intervention and 5 control cities show that in cities that implemented or greatly expanded their bikeshare systems, rates of serious injuries among cyclists dropped by 28% while rates in control cities increased by 2%—although this result was not noticed until [Fishman and Schepers, 2016].

Much safety-in-numbers research includes car, bike, and pedestrian traffic, and examines other factors [Elvik and Goel, 2019], but the simplest form suffices here:

$$\frac{\text{number of collisions}}{\text{baseline number of collisions}} \sim \left(\frac{\text{number of cyclists}}{\text{baseline number of cyclists}}\right)^{\beta}$$

β is the safety-in-numbers exponent. If $\beta = 1$, doubling cycling doubles the number of collisions, leaving risk per trip unchanged. If $\beta < 1$, the number of collisions grows more slowly than the amount of cycling, so the risk per trip is reduced. If $\beta < 0$, then as cycling increases, the absolute number of crashes decreases. Elvik and Goel [2019] include studies that put β as low as -0.14 and as high as 0.87. Over all, they estimate a city-level average of $\beta \approx 0.25$, but on the scale of individual junctions they find $\beta \approx 0.4$. Using $\beta = 0.4$ as a conservative example, if the number of bike-kilometers doubles, the number of collisions increases by a factor of only $2^{\beta} \approx 1.3$, so the risk per km decreases by $1 - \frac{2^{\beta}}{2} = 1 - 2^{\beta-1} \approx 34\%$. If $\beta = 0.25$, then if bicycle use doubles, risk decreases by 40%.

The mechanisms of the safety-in-numbers effect are not completely understood, but the following hypotheses have been tested to varying degrees:

1.3.1.1 More Cyclists → Lower Risk ("Safety-In-Numbers"):

Driver behaviours: As car drivers see more cyclists, they learn to look out for cyclists [Fyhri et al., 2017]. This could result in a rapid change in car-bike conflicts, but minimal change to bike-only crashes.

Infrastructure: More cycling increases pressure to build safe infrastructure such as separated bike lanes [Macmillan and Woodcock, 2017]. This should result in more gradual reduction in car-bike conflicts.

Social effects: As more people bike, drivers are more likely to know someone who bikes, or to be cyclists themselves, increasing awareness and empathy [Aldred, 2016].

Fyhri et al. [2017] used seasonal variation in cyclist numbers to show that drivers better anticipate cyclists as cycling popularity rises, and also that this effect can be masked if new cyclists are inexperienced and behave unpredictably. Elvik and Goel [2019, sec. 5.2] analysed studies that reported the size of the safety-in-numbers effect and the presence of safety infrastructure interventions for both cyclists and pedestrians, and found that while good data were scarce, the SIN effect persisted regardless of infrastructure interventions.

1.3.1.2 Lower Risk → More Cyclists ("Numbers-In-Safety"): The belief that bicycling is dangerous is a primary deterrent [Winters et al., 2011; Claudy and Peterson, 2014; Carstensen et al., 2014; Aldred and Crosweller, 2015; Aldred, 2016; Fishman, 2016; Macmillan and Woodcock, 2017; Campos Ferreira et al., 2022], and similar reasoning has been reported for e-scooters [Almannaa et al., 2021; Badia and Jenelius, 2023; Teixeira et al., 2023]. Thus, as safety improves, so does the number of cyclists [Dill and Carr, 2003; Monsere et al., 2015; Cordeau, 2023; Fosgerau et al., 2023; Pearson et al., 2024; Rérat and Schmassmann, 2024]. The S-I-N relationship could arise via this numbers-in-safety mechanism in at least two ways

Popularity: As the cycling environment becomes safer, fewer people are deterred from bicycling.

Demographic shift: A refinement of the above idea, safety improvements may attract more risk-averse cyclists, lowering the population-wide crash rate [Fyhri et al., 2012; Hoye, 2018]. This would reduce both car-bike and solo crashes, although it could not push $\beta \leq 0$.

Although the health benefits from active transportation usually outweigh the risks (§1.5.1), perceptions, not data, drive daily decisions. Since statistics generally show that bicycling is safe, we can dismiss the hypothesis that the decision not to bike is based on mortality data.

What, then, influences the perception of safety? Infrastructure such as separated bike lanes [Winters and Teschke, 2010; Winters et al., 2011; Fishman et al., 2015; McNeil et al., 2015; Monsere et al., 2015; Willis et al., 2015; Fishman, 2016; Manton et al., 2016; Branion-Calles et al., 2019; Hardinghaus and Weschke, 2022; Fosgerau et al., 2023; Rérat and Schmassmann, 2024], slow car traffic [Hardinghaus and Weschke, 2022], changing emphasis of news reporting [Macmillan et al., 2016], and personal experience [Aldred and Crosweller, 2015; Fishman, 2016; Manton et al., 2016] informed by direct learning from conflicts with motorists:

> Thus in the UK, reported deaths, serious injuries, slight injuries, and self-report injuries might be of the rough magnitude of around 50; 1000; 6000; and 20,000 per billion miles cycled respectively. This research suggests that, per billion miles cycled, one might by contrast expect 25,000,000 'very scary' near miss incidents—a completely different metric and one that can contribute to our understanding of why people apparently over-estimate the risks of cycling. [Aldred and Crosweller, 2015, §3.2.1, p. 381]

It also seems likely that the presence of cyclists serves not just to make the system safer, but also increases the perception of safety through a vote-of-confidence effect.

The presence of arguments and evidence for both causal directions suggests a feedback process. This seems sufficient reason to warrant investigation of potential consequences.

1.3.2 E-scooter safety

Many recent works investigate e-scooter crash characteristics (see, e.g., Kazemzadeh et al. [2023]), but exposure figures are still difficult to acquire. Thus we cannot compare the risk of e-scooter use to that of bicycle use. Anecdotally, they seem to be harder to control, faster, and the small wheels make them more susceptible to pavement damage, but for now little more can be said. For this work, we make the questionable assumption that they are roughly as dangerous as bicycles, and the more justifiable assumption that the collision rate of e-scooters scales proportionally with that of bicycles, which is fairly well understood.

1.4 Convenience

The other dominant factor consistently reported in mode choice is convenience [Claudy and Peterson, 2014; Bachand-Marleau et al., 2012; Fishman et al., 2015; Fishman, 2016; Kabra et al., 2020; Teixeira et al., 2023], and similar motivations are emerging for e-scooters [Almannaa et al., 2021]. Convenience may include such factors as:

- Distance: in many cities, most trips are under 5 kilometres (km), at low speed, and will take a similar amount of time by car, bicycle, or e-scooter. The number of such trips is subject to gradual change, through emergent response to demand or intentionally through new city technologies such as 15-Minute Cities [Moreno et al., 2021]. The convenience of longer trips is more dependent on specialised infrastructure such as access to high-average-speed routes (bike highways) or easy integration with public transportation [Jonkeren et al., 2021].
- Terminal costs: time and cost of parking, walking distance to destination, ability to secure vs. theft…
- Pleasantness of the route for the chosen mode.
- Ability to carry common loads: groceries, children, dogs, recreation equipment…
- For active μmobility in hot climates, availability of showers or changing rooms.
- Availability of everything needed for the use of the vehicle: suitably equipped bicycles (e.g. fenders, racks, cargo boxes) at the location of need, and anything required by law (e.g., lights, helmet).
- Compatibility with other trip infrastructure, such as parking or public transportation.

1.4.1 Shared μmobility services

Whereas ownership requires overcoming various obstacles to purchase (choice, cost, outfitting), logistics (maintenance, storage), and use (restricted to home–[…]–home trips, concerns anent theft), shared-mobility services [Fishman et al., 2015; Fishman, 2016] that are easy to join and that offer dense coverage [Bachand-Marleau et al., 2012; Kabra et al., 2020] can reduce or eliminate these barriers. When combined with μmobility-friendly infrastructure, they can quickly increase ridership. And while they can compete against public transportation and walking, they can also facilitate such trips by reducing last-mile barriers. These options have the potential to reduce trips by car [Cheng et al., 2022; Cordeau, 2023].

Both bike- and e-scooter-shares are available with both docked (the vehicle must be picked up from and returned to a specific location) and dockless (free-floating vehicles to be checked out by anyone and returned anywhere) infrastructure. While the majority of bikeshare systems are docked, many e-scooter-share systems are dockless. Dockless systems allow increased convenience, especially to underserved regions [Qian et al., 2020]. However, they have greater difficulty controlling the emerging problem of vehicles parked in a way that interferes with other mode users (usually pedestrians), and create a greater burden for service vehicles, both for rebalancing and (with electric vehicles) recharging. However, here we ignore this nuance: both bikeshares and e-scooter-shares can be either docked or dockless, and we leave modelling the differences as future work.

1.5 Health

Nieuwenhuijsen [2016] and others have recently tied urban and transport planning with health modulators from the positives such as the creation of wealth and opportunities for efficient use of energy to the negatives such as air and noise pollution, heat islands, limited greenspace, and loss of physical activity. In this work we cannot connect all of these pieces, but look at a subset of health factors modulated by cars and active mobility.

Increasing the number of bicycle trips has numerous direct and indirect health benefits to those who participate. Reducing the number of car trips has numerous, generally indirect, benefits to all members of society. For simplicity our model does not consider most of them explicitly. Some are included implicitly, and the rest would generally increase the potential effect size.

1.5.1 Diseases of inactivity

While lethal cycling collisions are newsworthy, they are rare: the leading causes of death are lifestyle diseases caused primarily by lack of physical activity.[1] The physical and mental health benefits of frequent activity (functional movement, play, exercise...) reduce the prevalence and severity of many—even most—diseases [WHO, 2010; Reimers et al., 2012; USA. DHHS, 2018; Lieberman, 2021; Garcia et al., 2023], arguably including ageing itself. van den Bijgaart et al. [2024] estimated that the social costs of inactivity due to cars might be as much as 20 times greater than other externalities they look at, even before modelling the deterrent effect of car traffic on active mobility (e.g. Anciaes and do Nascimento [2022]).

150–300 minutes/week of moderate exercise decreases all-causes mortality rate by $\sim$30–35% [USA. DHHS, 2018]. This corresponds to increasing life expectancy by $\sim$2–3 years, assuming the habit is maintained for 50 years; see also [Leskinen et al., 2018; Yang, 2019; Lee et al., 2022].

To simplify modelling and make the results more intuitive, rather than lifetime habits affecting odds of dying, we adopt Spiegelhalter's [2012] framework of microlives, in which choices affect life expectancy immediately. Using the numbers above, 1 hour of transportation cycling

[1] The burden of lifestyle diseases due to diet is comparable, but it is beyond the scope of this work.

($\sim$4–7 METs [De Geus et al., 2007; Herrmann et al., 2024]) yields a life expectancy gain of $\sim$2–3 hours.

The greatest gains are at the lowest levels—those going from no activity to a small amount [Powell et al., 2019; Garcia et al., 2023], which amplifies the public-health benefits of lowering barriers to entry for non- or occasional cyclists. But the benefits continue to accrue at higher doses [USA. DHHS, 2018; Lieberman, 2021; Zhao et al., 2021; Lee et al., 2022]. The effects on QALYs, DALYs, LEGPHs, etc. are even greater [Lieberman, 2021] but there are many possible ways to quantify them, so life expectancy should be considered a lower bound on the health gain.

1.5.2 Crash safety comparison

Recalling §1.3: if 5 million hours of bicycle commuting result in the loss of 200,000 life-hours due to fatal collisions, but the recovery of $\sim$15 million life-hours by combating lifestyle-related diseases, then the expected gain is 75 times greater than the loss. This simplistic calculation yields a number roughly consistent with those from more sophisticated analyses [de Hartog et al., 2010; de Jong, 2012; Kelly et al., 2014; Tainio et al., 2016; van den Bijgaart et al., 2024]. Note that this estimate does not yet take into account any system feedbacks.

1.5.3 Pollution

Air pollution from fossil fuels may decrease life expectancy by an average of $\sim$ a year worldwide [Lelieveld et al., 2020], and can be many times more deadly in cities. Not all of this is caused by personal vehicles, so the potential life expectancy gain at optimistic levels of modeshare shift (at least in regions with strong tailpipe emissions laws) might be on the order of minutes per day. However, it applies not just to cyclists but to all residents [Boogaard et al., 2023]. Vehicles also make a significant contribution to non-exhaust particulates [Oroumiyeh and Zhu, 2021; Adamiec et al., 2022], including toxic compounds from e.g. tire and brake dust. Cyclists may consume more car pollution than motorists, but the benefits usually outweigh the risks [de Hartog et al., 2010; Tainio et al., 2016; Cepeda et al., 2017; Zhao et al., 2021]. We note that the health effects of stricter tailpipe emissions controls may be amplified not only by increasing the cost of cars, but also through the feedback loop reducing the air-pollution-exposure disincentive of bicycling, but we leave this as future work.

Mueller et al. [2020] estimates that, in Barcelona, the greatest life expectancy gains that come with shifts from cars to electric μmobility are due to reduced NO_x and noise pollution and mitigating the heat island effect. This seems to represent a pessimistic view on active μmobility, which may be tempered by the fact that the residents of Barcelona are already somewhat more active than those of most cities in, e.g. North America. Furthermore, the heat island effect is probably more important in Barcelona than at higher latitudes. That said, we look forward to incorporating estimators for those health outcomes.

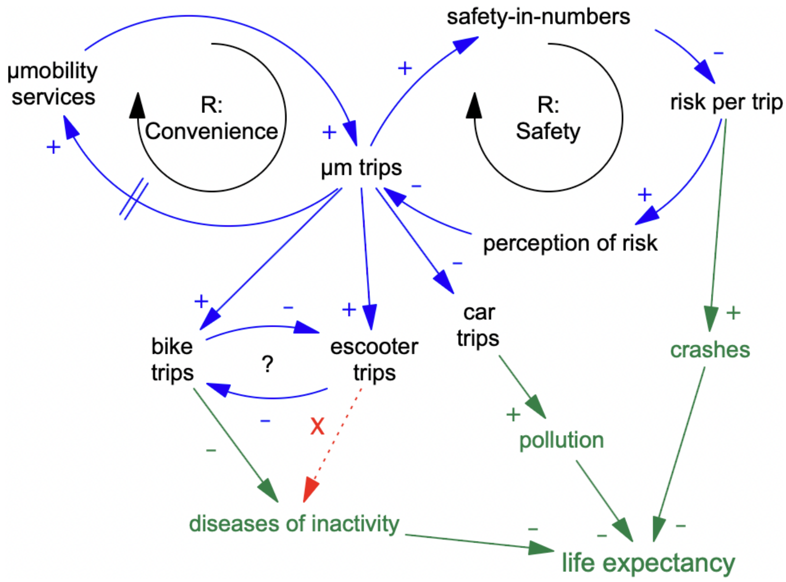

Figure 1: Causal loop diagram and health effects model.

2 Methods

From these pieces, we assemble a causal-loop hypothesis, and link it to changes in life expectancy due to exercise, pollution, and traffic safety.

The model was built and critiqued in Vensim PLE 10.2.2, and analyses were performed in PySD 3.14.2 [Martin-Martinez et al., 2022], on MacOS 15.3.1.

2.1 Assumptions and simplifications

Bikes and e-scooters induce similar urban responses: In particular, we assume that bicycles and e-scooters have a similar effect upon both the safety-in-numbers effect and demand for μmobility infrastructure, and that those changes affect bike and e-scooter ridership similarly. While this is under-studied, it seems plausible due to their similar size, speed, agility, infrastructure needs, and reported concerns.

Infrastructure only affects convenience: This prevents double-counting of safety improvements that are already covered through safety-in-numbers but are due to safety infrastructure. A more detailed model would consider these separately, but the simpler version suffices to investigate possible dynamics.

Constant trips/day: We do not consider the creation of new trips through induced demand. Much of documented induced demand is switching from non-car to car trips rather than the creation of new trips, so this is justified. However, we specifically ignore how mobility-system changes affect the number of trips made by different user groups (e.g. children).

Ignore pedestrians (for now): In environments with many pedestrians, e-scooters pull from walking trips. In more car-centric environments, this effect is minor. However, this im-

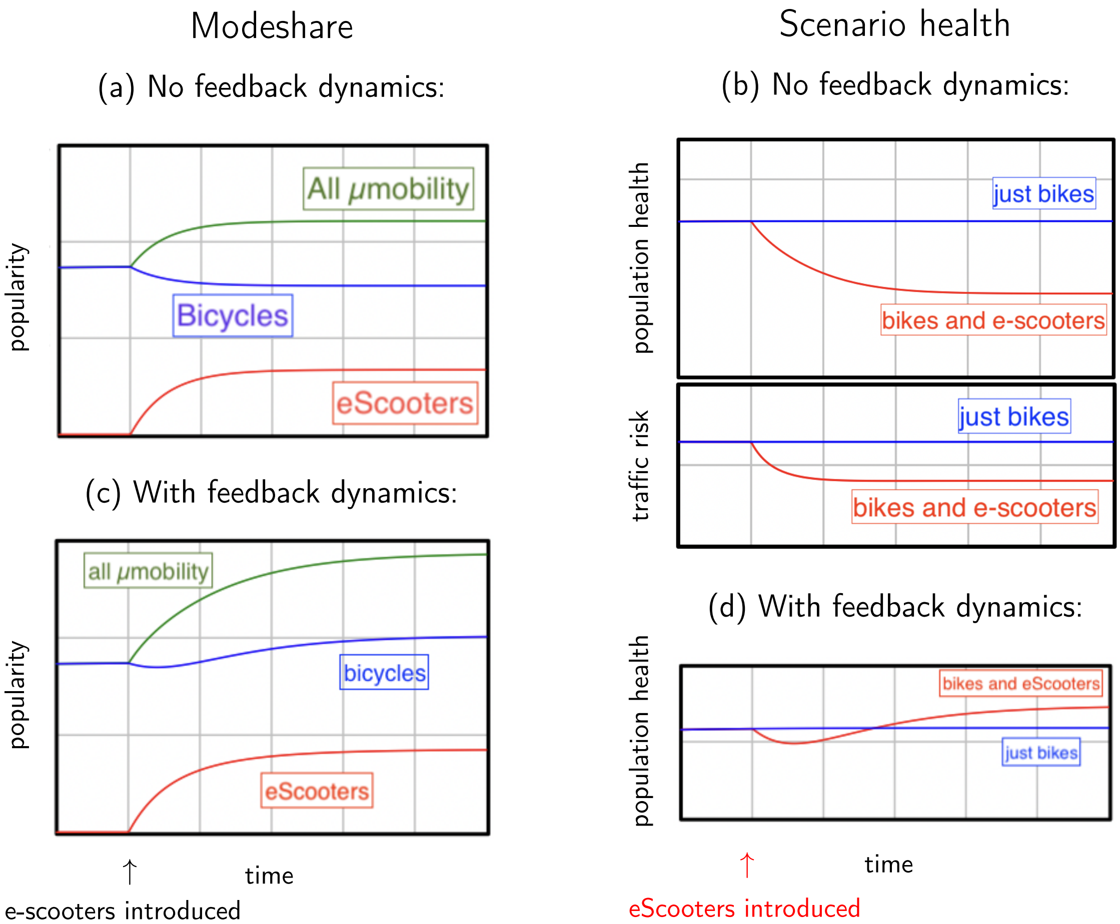

Figure 2: Expected behaviour: *(a–b) Before considering feedback dynamics:* as e-scooters steal trips from bicycles, total μmobility rises but bicycling declines, with the consequent reduction in exercise causing a decline in population health, as well as increased risk per exposure. *(c–d) With feedback dynamics:* Increasing μmobility modeshare decreases crash risk through S-I-N.

portant variable is left for future work.

Crash safety: For now we only consider safety through numbers as described in §1.3.1.1. In particular, safety does not depend on infrastructure, or speed. Correcting these simplifications is future work, but we consider them low-priority because:
- Crash safety does not figure prominently in the final health outcomes.
- We consider other arguments for reducing scooter speed, and wish to separate them from consideration of crash safety.

2.2 Mode choice

Transportation mode is chosen based on:

Convenience: What is the probability that a randomly drawn trip can be easily completed by mode x? We assume that cars are perfectly convenient (which could be modulated by e.g. parking policy, which we leave for future work). μmobility convenience varies in response to μmobility modeshare. The number encapsulates non-safety convenience—not traffic separation, but e.g. secure parking, bike shops, convenient bicycle and e-scooter rental fleets, showers, etc...

Safety: The odds of being deterred by risk tracks the odds of a fatal collision, and that these are the same for bikes and e-scooters. Perceived safety estimated by infrastructure, S-I-N, conflicts and close calls, etc. scales linearly with true risk of death (§1.3.1.2). Car drivers ignore risk.

Speed: We investigate e-scooter speed limits as a policy control. Bicycles are always assumed to move at the average of 14 km/h (§1.3). Car speed limits depend on the amount of car traffic, so as more people switch to μmobility , driving can become faster. This allows a balancing loop, not shown in Fig. 1. Desirability scales linearly with speed.

Utility: Encapsulating vehicle factors such as ability to carry cargo.

2.3 Dynamic hypothesis

The model, sketched in Fig. 1, consists of two reinforcing feedback loops:

Safety:

- **μmobility ridership affects traffic safety:** As μmobility modeshare rises, the per-exposure risk of collisions falls, following §1.3.1.1.
- **Increased safety increases μmobility ridership:** Since risk is consistently one of the most powerful modulators of willingness to bicycle (§**??**), the loop is closed by §1.3.1.2.

Convenience:

- **μmobility facilities boost ridership:** Ridership responds to development of facilities and other infrastructure, as described in §1.4. Facilities of different types are combined into a single term in this simplified model, but may include infrastructure such as bike lanes, parking, mode-specific shops, share stations and vehicles, etc...
- **μmobility users create demand for facilities:** As μmobility modeshare rises, economic incentives encourage the development of appropriate infrastructure [Keynes, 1936].

2.4 Estimating health outcomes

The full list of benefits could include not only the increase in health due to bicycles, but also a reduction in the extensive list of harms caused by cars documented by Miner et al. [2024]. However, for simplicity, we consider only the following health factors:

Exercise: §1.5.1. While the health benefit of exercise is somewhat nonlinear (§1.5), we linearise about a benefit consistent with exercise that meets a majority of typical weekly mobility needs.

Fatal crashes: §1.3.1.1

Pollution: §1.5.3

3 Results

When some bicycle trips are replaced by e-scooter trips, health benefits from active mobility immediately fall. As the increase in e-scooter ridership activates the S-I-N and infrastructure feedback loops, the consequent improvements to μmobility safety and convenience encourage bicycle modeshare to rebound, and under some conditions it can eventually surpass the previous equilibrium. Representative forms are illustrated in Fig. 2 (c–d). This worse-before-better dynamic is sensitive to parameters controlling the relative attractiveness of the different modes, and by the system's responses to increased μmobility use.

Relative attractiveness of different modes is complex and under-studied. In this work we focus on e-scooter speed limit because it is a readily available policy switch already widely applied to e-scooter-share operators. Assumptions are described in 2.1.

3.1 S-I-N feedback loop, no infrastructure improvements

Infrastructure development can be complex. It is simplified to one representative path in our model, which risks ignoring relevant complexity. However, even with that path disabled, the hypothesised effect is observed.

Fig. 3 shows representative health outcomes in which adding e-scooters to the mobility system leads to the deterioration of public health, but can cause a rebound, possibly to a new higher equilibrium. Which case emerges depends on various parameters. Here we show its dependence on the overlap in mode desirability between bikes and e-scooters (how many e-scooter trips would have been made by bike if an e-scooter had not been available?), and the desirability of e-scooters modulated by their speed limit. As described in §1.2, in many studied areas the overlap tends to be around 0.1, showing good potential for e-scooters to improve outcomes in this model (but see §4.1). We guess that this low overlap may be due partially to novelty and could increase over time. We also believe that the overlap can be modulated through policies beyond just speed limits—for example, bicycles fitted with racks or bins can easily carry large quantities of cargo, making them able to replace cars for most local trips, which could further decrease overlap.

The model has converged to equilibrium after 5000 steps. The best health outcomes occur with low overlap between the modes: e-scooters boost S-I-N without a huge impact on bicycle ridership. In this case, making e-scooters more competitive with cars by increasing their speed

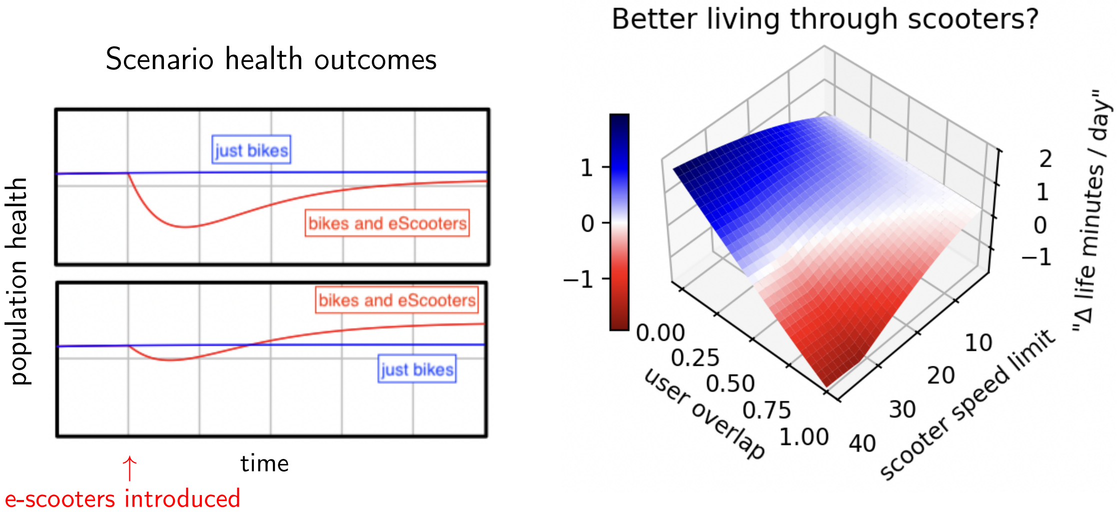

Figure 3: Health outcomes 0: *Left:* Sketches (not to scale) of health outcomes for (blue) just bikes and for (red) bikes+e-scooters, considering only the gain of the "Safety" feedback loop via S-I-N) (no convenience development). *(top):* the introduction of e-scooters permanently reduces public health. *(bottom):* S-I-N amplification leads to more cycling than before. *Right:* Population-wide life expectancy change at timestep 5000, showing the difference between bikes+e-scooters and bikes only, as a function of the overlap between bike and e-scooter utility and the e-scooter speed limit. The z axis is also colour-coded—blue indicates that the introduction of e-scooters increased public health by making bicycling safer; red indicates health worsening *(no relationship to the same colours used to illustrate the scenario health outcomes).*

limit maximises the S-I-N activation. As overlap increases, e-scooters reduce exercise more than they boost bicycle ridership through S-I-N, and here, the greater the e-scooter speed limit, the worse the health outcomes.

3.2 Adding the convenience feedback

Our mode choice model (§2.2) depends on the probability that a randomly drawn trip can be made by a given mode, including factors from routes to availability of a shared vehicle to secure parking, etc. μmobility creates economic incentive for supporting infrastructure, making it more likely that the necessary facilities will be available. The two feedback mechanisms working together can yield much greater gain than S-I-N alone. Fig. 4 shows an example in which just the S-I-N feedback is not enough to drive the system far from status quo, but with convenience infrastructure allowed to adapt to demand, the system enters a persistent growth phase (and has not re-established equilibrium by time 5000).

3.3 Bistability and reversing bicycle death spirals

Population health outcome is a function of the e-scooter speed limit and rate of investment in µmobility infrastructure (not modelled: the relationship between speed and crash probability). We assume that only changes in μmobility use change S-I-N, but infrastructure requires maintenance and upkeep, which depends on sufficient demand. If the number of μmobility users is insufficient to support extant infrastructure or if infrastructure is built too slowly or half-heartedly in response to demand (equivalent to a large infrastructure time constant), then μmobility use enters a death spiral, culminating in a car-centric society with its poor health outcomes. In state-space regions with this dynamic, it is possible that the addition of e-scooters can reverse the trend, pushing the system into its μmobility-friendly equilibrium.

Fig. 5 shows an example of this. Fig. **??** (a) shows "absolute" health outcomes of the car+bike+e-scooter world—compared to an entirely sedentary population—as a function of the infrastructure time constant and the scooter speed limit. Fig. **??** (b) shows the difference in health outcome achieved by adding e-scooters (note the changed axis origins, done for clarity).

Essentially, a higher e-scooter speed limit makes that mode more appealing compared to both cars and bikes. Drawing trips from cars increases the gain of the "Safety" feedback loop via S-I-N, whereas a quick infrastructure build time (small build time constant) increases the gain of the "Convenience" feedback loop. If infrastructure response is slow, then a higher speed limit maximises activation of the S-I-N feedback, leading to the greatest chance of saving the μmobility system from collapse. As infrastructure investment becomes more responsive, the system can be nudged from collapse into growth even with a lower speed limit, which maximises the number of cyclists, improving health. Fig. **??** (d) shows the speed limit for each value of the build time constant that results in the best health outcome at the final timestep.

E-scooters are more likely to harm than to help if infrastructure responds rapidly, but that the damage can be mitigated by lowering their speed limit. They have the greatest potential to help when the build time constant is not so low that e-scooters aren't needed, but not so high that the system is doomed to collapse in any case. Because this scenario involves long convergence

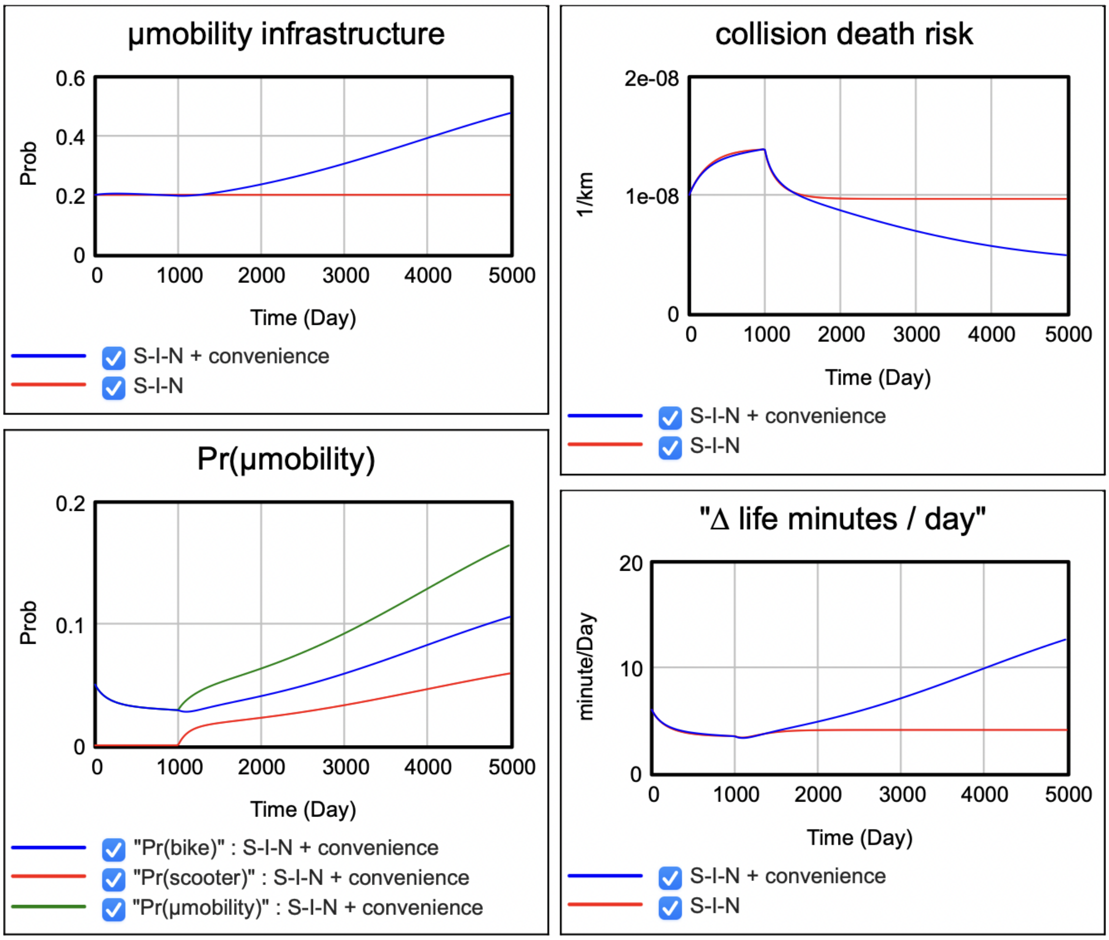

Figure 4: Safety-In-Numbers and Convenience: The system consists of only cars and bikes until equilibrium is reached at time 1000, then e-scooters are introduced. When *μmobility infrastructure* is held constant (“S-I-N”), the S-I-N effect leads to a dip followed by a small increase in cycling in response to the decreased *collision death risk*. When infrastructure is developed in response to demand (“S-I-N + convenience”), the two feedback loops amplify each other, leading to decreasing *collision death risk* and increasing (population-average) Δ *life minutes / day*. Here, the infrastructure time constant is large, so by time=5000 the system has not yet converged.

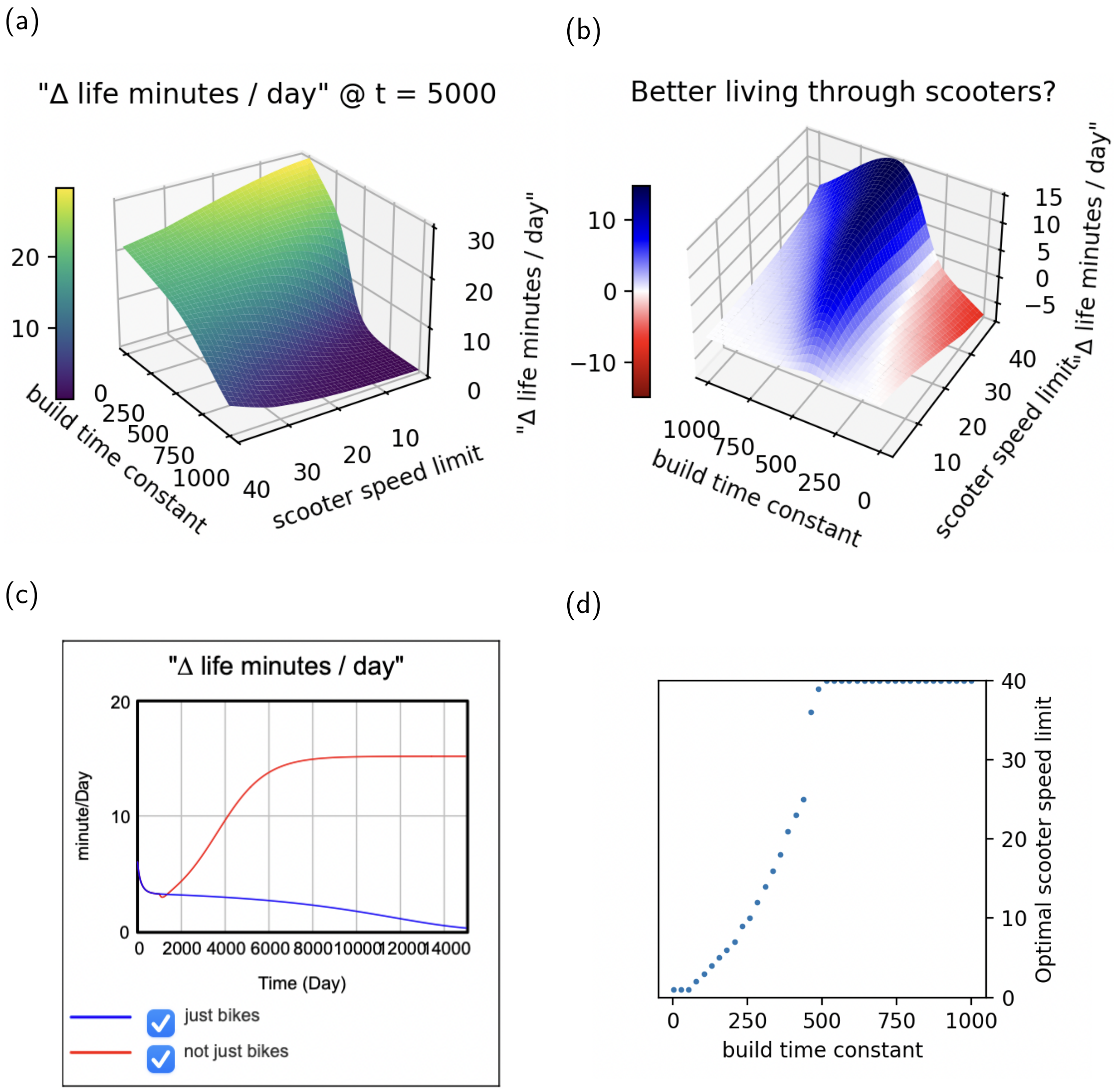

Figure 5: Health outcomes 1: *(a):* Population-wide life expectancy change in minutes/day at timestep 5000 due to predicted μmobility uptake vs. a completely sedentary population, over a range of infrastructure build rates and e-scooter speed limit values. *(b):* Population-wide life expectancy change in minutes/day at timestep 5000, showing the difference between a scenario with e-scooters and without: blue shows regions in policy space where the introduction of e-scooters leads to improved health outcomes vs. just bikes; red indicates reduced population health. *(c):* Bistability: adding scooters (red line, "not just bikes") can rescue a μmobility death spiral. *(d):* For each build time constant, what is the scooter speed limit that leads to the best public health outcome?

times (see, e.g., Fig. **??** (c)), results are shown after 15000 timesteps, and in the parameter-space region closest to the initial unstable equilibrium, the system still hasn't converged.

3.4 Air pollution

We have seen that maximising population health depends on optimising bicycle modeshare, and that nudging people towards e-scooters may or may not help to achieve this. However, population health is also sensitive to the level of air pollution from cars, which (we assume) is reduced equally whether people switch from cars to bikes or to e-scooters (but see [Badia and Jenelius, 2023, §5]). The more people are being killed by air pollution from cars, the more a transition from cars to e-scooters helps, even if at the expense of a transition towards bikes. In Fig. 6 it can be seen that increasing air pollution pushes the optimal policy toward higher speed limits for e-scooters.

Consider adaptive e-scooter speed limits that respond in real time to air pollution levels. This could both serve to tempt people out of cars onto e-scooters on days when reducing car trips is most needed, and could also offer cyclists as-needed access to a form of μmobility that requires less breathing on days when increased pollution exposure is especially harmful—perhaps especially useful to prevent cyclists from reverting to a car on bad-air days. Furthermore, it could make the public more aware of the link between cars and air pollution, and more understanding of strategies to mitigate it.

3.5 Traffic fatalities

As described in §1.3, despite the fact that most people choose not to bicycle due to perceived risk and adapt their choices in response to changes in perceived safety (§1.3.1.2), bicycling fatalities are rare, and we assume that e-scooters are not too different. A representative scenario showing relative effect sizes may be seen in Fig. 7. Definitive numbers on rates of change are difficult to find, but static estimates of risks of traffic death and the benefits of exercise are well established (note that rates of non-fatal injury among cyclists are less well known due to a higher potential for underreporting and misattribution. Although we ignore them here, serious injuries are still serious, and are thought to outnumber fatalities by a factor of $\sim$20 [Aldred and Crosweller, 2015]). Pollution is somewhat less well understood, so that should be considered a ballpark estimate. What is certain is that while changes to the risks from cars affect μmobility mode choice, the absolute risk of death is insignificant next to the risk of death from diseases of inactivity and pollution.

Limiting traffic fatalities is a questionable basis upon which to establish speed limits.

3.6 Fast e-scooters may interfere with active mobility

Modal separation is important for real and perceived safety (§1.3.1.2). What is the effect on a cyclist of having to share a "protected" bike path with much faster vehicles? What if the cyclist is new to biking, or returning to it after 50 years, or is a young child? This area seems to be under-studied, but anecdotally: cyclists react negatively. If this is true, then e-scooter speed limits could have a large effect upon the flow rate into the stock of cyclists.

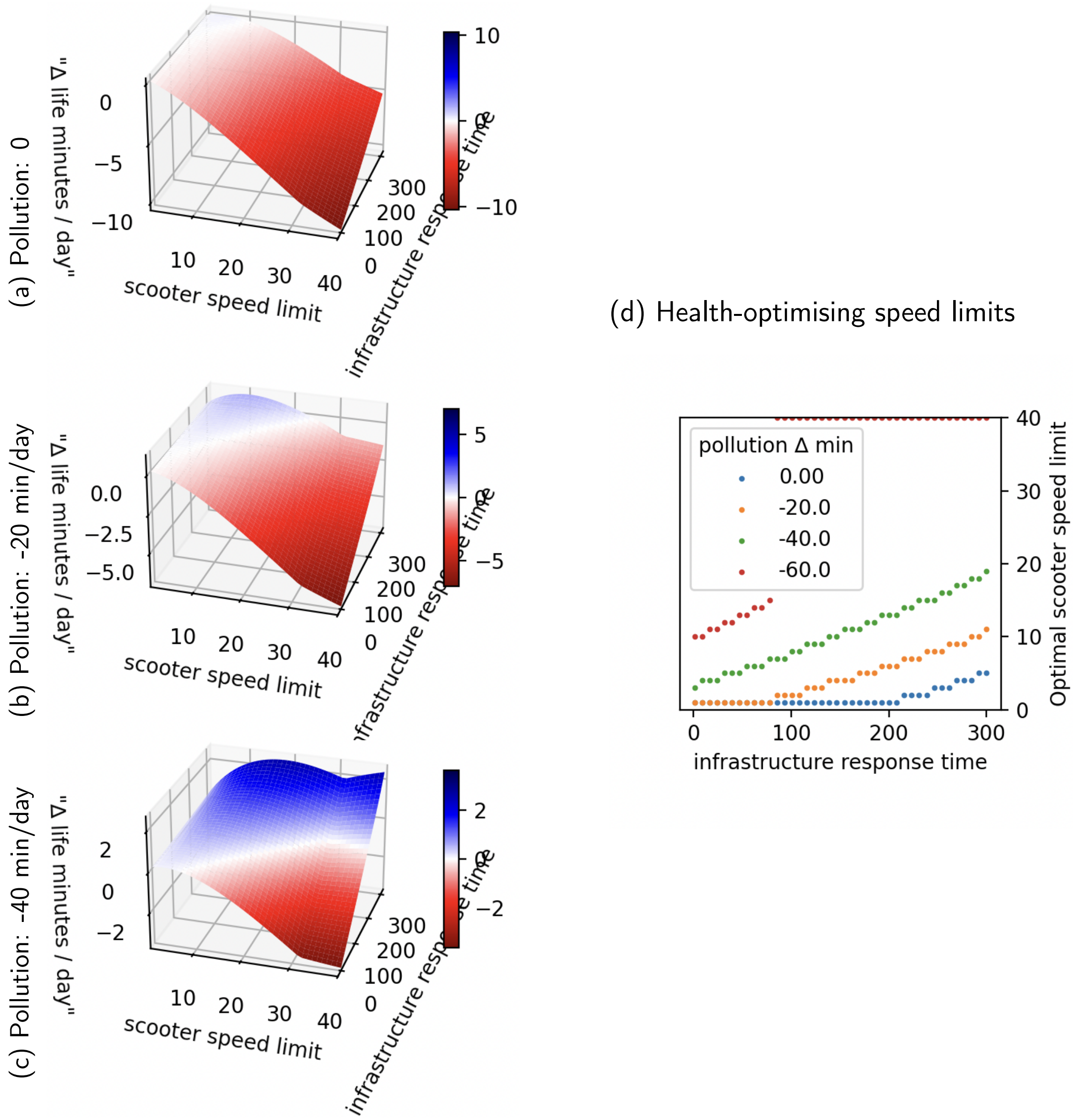

Figure 6: Pollution: Population health can be improved by both increased exercise through active mobility and cleaner air due to fewer car trips. *(a–c):* The greater the pollution burden, the more likely e-scooters are to improve outcomes. Throughout, if the Convenience (infrastructure) feedback loop dominates the dynamics, then limiting e-scooter speeds optimises health. As infrastructure deployment slows, then making e-scooters more desirable (here: faster) can shift trips from cars more quickly. *(d):* Optimal scooter speed limits for four different levels of pollution from cars, given different infrastructure response time constants.

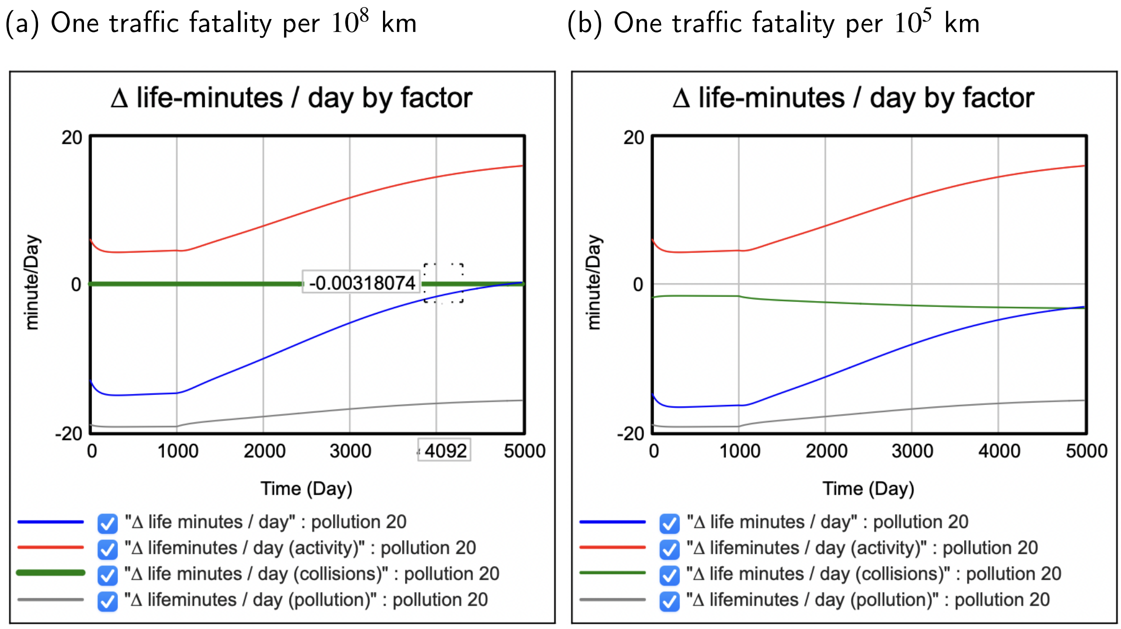

Figure 7: Causes of death: *(a):* With an initial level of pollution costing 20 minutes/day, and with 1 traffic fatality per 100 million km ridden (§1.3), the population-wide cost of μmobility traffic fatalities (green) is 0.001–0.003 minutes/day (the final mode share is 13% of trips by bike and 8% by e-scooter). *(b):* In order to become visible in this comparison, we must imagine that traffic fatalities are 1000 times more likely. Even in the USA, as of [Buehler and Pucher, 2021] the rate was still well below 1 fatality per 10^7 km.

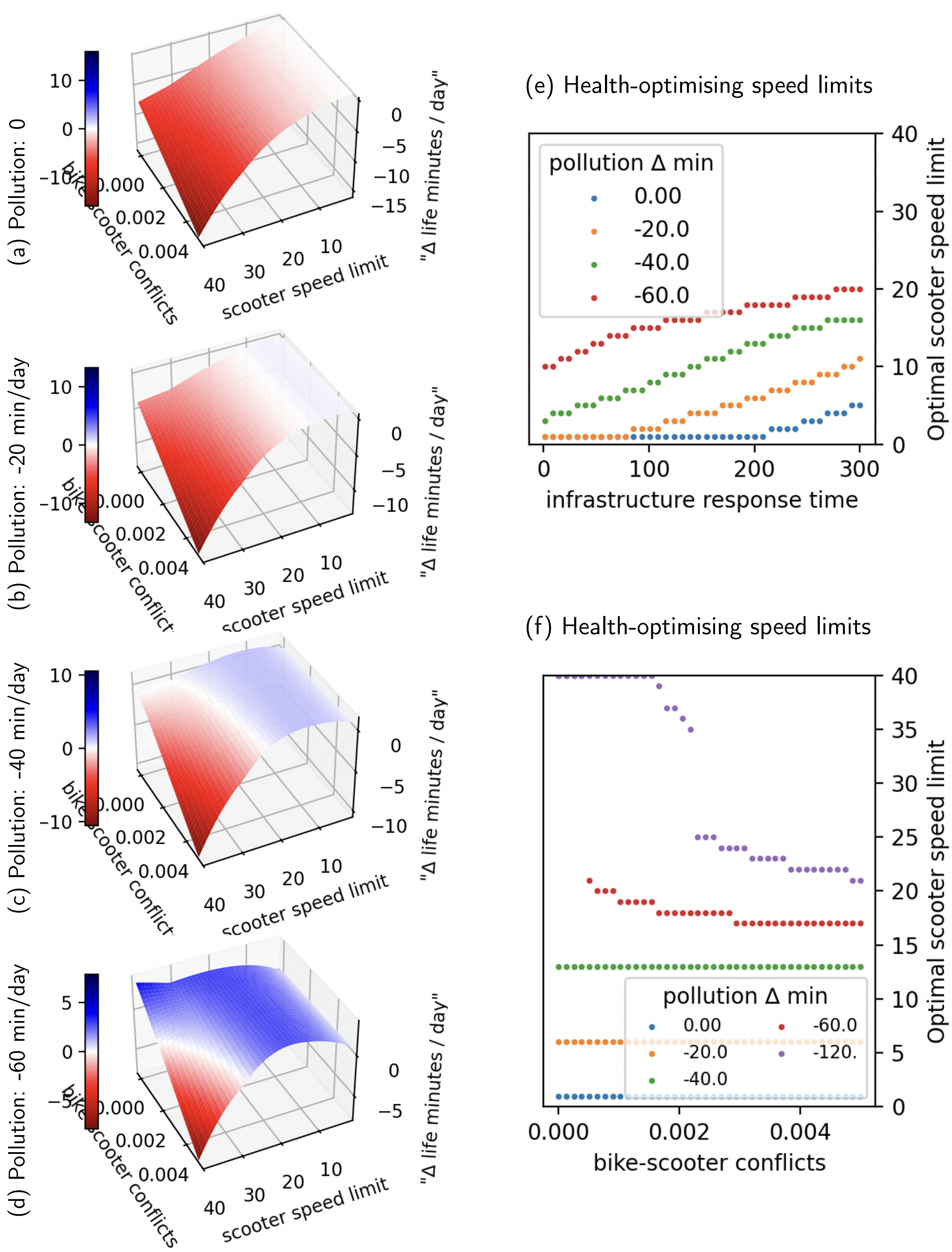

Figure 8: Fast e-scooters disincentivise cyclists: If being passed by a fast e-scooter deters cyclists: *(a–d):* The greater the pollution burden, the more likely e-scooters are to improve outcomes. However, as fast scooters have a greater deterrent effect on cyclists, the benefits of faster e-scooters are increasingly overwhelmed by their reducing cycling, so health is optimised at speed limits closer to that of bicycles. *(e):* as in Fig. 6d. *(f):* Optimal speed limits are sensitive to the magnitude of the fast-e-scooter deterrent effect at higher pollution levels.

Fig. 8 shows the same scenario as Fig. 6, with an additional term in the mode desirability function: “bike-scooter conflicts” represents the magnitude of the cyclist’s negative experience when being passed by a scooter. The greater the speed difference between the e-scooter speed limit and the expected speed of bikes (14 km/h, ignoring the possibility that slower cyclists are doubly likely to be intimidated), and the more e-scooters are in use, the less desirable cycling becomes. Since we know of no research quantifying this effect, the number is unitless, and we explore a range of values. Thus, an e-scooter speed limit of 14 km/h prevents any negative response, but increasing speed limits reduce the number of cyclists, increasing the number of both cars and e-scooters, creating another feedback loop.

Fig. 8 (a–d) show four values for pollution from perfectly clean air to a (hopefully) unrealistically bad city, showing the state-space health benefits or costs of introducing e-scooters. With this negative bike-scooter interaction, only in the most unrealistically polluted environments could high e-scooter speed limits result in significant public-health gains. Health-optimal speed limits as a function of infrastructure response time are shown in Fig. 8 (e)—compare with Fig. 6 (d), and note that while the functional form of the psychological effect size is ad-hoc, for many reasonable choices the best health outcomes may be achieved with scooter speed limits from essentially 0 up to, in the worst case, a speed close to that of bicycles—probably not a surprising result. Health-optimal speed limits vs. the conflict effect size is shown in Fig. 8 (f). *If the hypothesised interaction exists, then establishing the effect size could be invaluable.*

4 Discussion

Car-centric mobility systems create a fascinating array of problems (see, e.g., Anciaes and do Nascimento [2022]; Miner et al. [2024]). Here we have looked at the health burdens from direct opportunity cost due to lack of exercise, and air pollution, ignoring the many other mechanisms by which cars harm societies. μmobility is an effective solution to many of these harms. In a particular, e-scooters are increasingly seen as a way to mitigate many of the problems of cars, with sufficient opportunities for profit to entice private companies to provide them. However, e-scooters run the risk of reducing active mobility, causing significant increases in morbidity/mortality. Not only are bicycles inexpensive, thoroughly tested, made from readily available materials, available for immediate deployment worldwide, but even without their indirect benefits they can reduce all-cause mortality by 35% and increase healthspan and wellbeing even more—dwarfing every other known public-health intervention.

Here, we have focused on the possible consequences of e-scooters for bicycling. In the short term, they can steal trips from bicycles, reducing public health. In the long term, assuming e-scooters and bicycles affect driver awareness (S-I-N) and infrastructure demand similarly, then the short-term health cost may be mitigated by activating feedback loops that improve the bike-friendliness of cities, which may reduce or even reverse the negative impact over time.

The areas of state- and policy-space in which the addition of e-scooters appears to have the greatest potential to increase public health—or merely to do the least harm—are:

High market differentiation: The assumption that introducing e-scooters leads to an increase in μmobility ridership is well borne out by current research (§1.2), but further efforts to nudge or market to different groups for different μmobility modes are likely to enhance the effect. For example, bikes are well-suited to carrying cargo: a rear rack can safely carry a child or a large load of groceries, and a cargo bike can carry more than cars are usually asked to carry.

Health-aware upgrade path: Because of the extreme health benefits, creating an "upgrade path" from passive to active μmobility is invaluable. Measures that decrease the appeal of e-scooters relative to bicycling, such as scooter speed limits that can easily be exceeded by regular cyclists, may be helpful *if the restrictions are chosen in a way that balances feedback loop activation against shorter-term changes to the health environment*. On the other hand, any measure that decreases e-scooters' appeal relative to cars—such as licensing or helmet requirements—are likely to backfire by reducing activation of bike-friendliness feedback loops. The health-optimising policy creates a balance between various health modulators.

Low infrastructure improvement rate: Safety and support infrastructure powerfully encourage increased μmobility use. If the development of such infrastructure is slow, then the primary driver of the transition is S-I-N. If e-scooters can activate this feedback as suggested, then this mechanism dominates the dynamics.

Polluted cities: In an unpolluted environment, transitioning from cars to e-scooters does not result in any *(direct)* public health gain. However, as pollution from cars increases, the pollution-reduction effect of e-scooters becomes significant.

Minimise bike-scooter conflicts: If e-scooters reduce bicycling—either by reducing the perception of safety or by tempting cyclists to switch to e-scooters—then the regions of state- and policy-space in which e-scooters can push towards a net improvement in public health are much smaller, with the greatest gains in the most highly polluted cities. This strongly indicates that in almost all scenarios, every effort should be made to ensure that e-scooters do not deter cyclists. This especially applies to new / inexperienced / young / old / vulnerable users, who constitute much of the potential flow into the stock of regular cyclists. These potential users have an outsized impact to population health due to the nonlinear exercise-health dose-response curve, and may also make an outsized contribution to measures of mobility equity, childhood cognitive development, parental de-burdening, etc…

4.1 Other modes

Other modes are proliferating, but studies of their interactions have largely focused on trips combining μmobility with public transit, or on car-x crashes. Dynamic interactions such as the ones explored here could be crucial in shaping the long-term health, equity, and sustainability outcomes of societies. For example:

Walking: In cities with adequate walking infrastructure, e-scooters steal many walking trips [Badia and Jenelius, 2023; Wang et al., 2023]. The numbers vary by methodology, but since walking is the fundamental mobility mode, e-scooters' negative impact is far greater than reported in this study. An approximation may be made by reducing the speed and carrying capacity of the modelled "bicycles" and increasing the ridership overlap factor (how many e-scooter users would otherwise have taken mode x). These result in qualitative changes to the model—cars become far more desirable, and the speed limits over which scooters can improve public-health outcomes are greatly reduced. However, there are other structural differences—walking does not require walk-shares or walk-shops or walk-parking facilities, but requires only separated lanes, so the infrastructure time constant for walking is large. If the S-I-N effect works, then perhaps e-scooters could still help under some circumstances. Given the magnitude of the consequences, this is the most crucial area for future work.

e-bikes: Two drivetrains are commonly used: independent throttles and pedal force multipliers. The former amount to cleaner motorcycles, but the latter encourage cycling, especially in hilly terrain and among not-yet-fit or older individuals, and thus contribute to exercise [Herrmann et al., 2024]. They can carry loads similarly to bicycles, and indeed many cargo bikes have electric assist. These seem potentially highly beneficial, but create potential similar to e-scooters to create conflicts due to their high potential speed and kinetic energy. Regulating their speed limits probably has much in common with the analysis above, but more research is required.

ICE scooters, motorcycles, etc: In many jurisdictions, internal-combustion-engine (ICE) sit-down scooters are allowed to share μmobility systems. They are capable of high kinetic energies, and additionally are often completely unregulated sources of air and noise pollution. Understanding how these interact with μmobility systemes is vital future work.

Cars: How might public health be affected by policy? imposing geofenced speed limits there? Most of the energy in unconstrained mobility systems is in cars; consequently, they are the source of most of the fatalities as well as most of the negative environmental externalities, and their high cost makes them an amplifier of social inequalities, with numerous additional costs Wilkinson et al. [2019]. Thus, most anything that can be done to make cars seem less appealing seems likely to yield a public-health benefit, at least after transient negative effects of reduced mobility for car-owners pass. The fact that we keep trying to do road safety without regulating the sole cause of road safety problems…

4.2 The true power of speed limits

Rather than viewing speed limits as a means to control kinetic injuries, we have presented an argument that they could be a far more powerful tool when viewed as a means to nudge mode choices, in combination with an understanding of the system's dynamic behaviours and well-being outcomes. In the example presented in this work, when e-scooter speeds are optimised to reduce all-causes mortality, the effect can be far greater than when e-scooter speeds are optimised only for short-term traffic safety (and corporate profit). Furthermore, we argue that *all* policies should be aimed at improving *intrinsic goods* such as wellbeing, and that all-causes mortality or lifespan, while imperfect correlates, can serve as a first step.

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