Chapter 11: Cycling, climate change and air pollution

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Abstract

Cycling is considered a healthy and sustainable form of getting from A to B. The net effects of the various forms of cycling and e-biking on mobility-related air pollutant emissions are complex. This chapter synthesizes research on the potential of cycling and e-biking to reduce (and contribute) to air pollutant emissions from mode shift away from motorised transport. Life cycle analysis of greenhouse gas emissions from production, use and end-of-life of active and motorised vehicles is used to compare the most common urban transport modes and determine whether cycling and e-biking reduce overall emissions or not. By doing so the Chapter provides a summary of research on cycling as a low carbon and clean mobility option in context of the climate emergency and the air quality crisis in cities.

Keywords

Transport emissions, Mode shift, Active mobility, E-bikes, Climate change mitigation, Urban transport, Rural transport, Life cycle analysis

- *Brand, C., Dekker, H.-J., & Behrendt, F. (2022). Cycling, climate change and air pollution. Advances in Transport Policy and Planning: Academic Press. Volume 10: Cycling.*

- *DOI: https://doi.org/10.1016/bs.atpp.2022.04.010*

1 Introduction

> *"A cycle is silent, emits no fumes, takes up little road space and when it collides with another cyclist or pedestrian, injuries are usually slight. Many Cambridge car owners use cycles for local journeys."* Cambridge traffic plan, 1950.

Yes, things have changed since the 1950s when the Cambridge traffic census showed that cycle traffic was sometimes three times greater than motor traffic. Today, cycling has largely been marginalised in favour of the 'motor car'. But cycling is still cleaner, quieter and more space-efficient than cars – whether the bicycles are electric or not. Personal cars are responsible for a large part of transport emissions. In the UK, for example, carbon dioxide (CO_2)[1] emissions from car travel are responsible for 61% of the sector's emissions (Philips et al., 2022), and despite increasing sales of hybrid, and electric vehicles, average tailpipe emissions of new cars are still increasing in large part due to increased sales of larger and heavier cars such as sports utility vehicles (SUVs). There is also a growing consensus that the technological switch to electric cars may not solve this sufficiently or fast enough to meet our climate goals (Brand, 2021). Replacing car trips by more sustainable modes is therefore one of the most effective ways to reduce transport emissions.

To put this into context, transport today accounts for 21% of global carbon emissions (IEA, 2021) and 29% of European carbon emissions (ICCT, 2021). It is now the largest emitting sector in many developed countries. While Europe and North America dominate historic transport emissions, much of the projected growth in emissions is in Asia. Even if current and committed policies were to succeed, transport's carbon emissions would still grow almost 20% by 2050 (ITF, 2021). Highly ambitious policies could cut these emissions by 70% (ITF, 2021) – but not to zero.

Modal shifts away from carbon-intensive to low-carbon modes of travel hold considerable potential to mitigate carbon emissions from transport (Cuenot et al., 2012). One of the more promising ways to reduce transport CO_2 emissions is to promote and invest in 'active travel' (i.e. walking, cycling, e-biking) while 'demoting' motorized modes that rely on fossil energy sources (Scheepers et al., 2014, ECF, 2011, de Nazelle et al., 2010, Goodman et al., 2012, Sælensminde, 2004, Quarmby et al., 2019, Keall et al., 2018, Bearman and Singleton, 2014, Neves and Brand, 2019, Woodcock et al., 2018, Frank et al., 2010). Out of all the various forms of active travel, cycling and e-biking have arguably the biggest potentials to reduce emissions, particularly in urban areas. While 'conventional' cycling has been around for more than two centuries, e-bikes are rising quickly in popularity, including shared schemes, and these electrical vehicles have the potential to replace short-to medium-distance trips, also in sub-urban and rural settings.

To better understand the emission-reduction impacts of cycling, it is important to assess the key determinants of (and changes in) travel pollutant emissions and include a detailed, comparative analysis of the distribution and composition of emissions by transport mode (e.g., bike, car, van, public transport, e-bike) and journey purpose across a wide range of

[1] Carbon dioxide accounts for roughly 99% of the direct transport carbon dioxide equivalent (CO_2-eq) emissions, based on a 100-year global warming potential.

contexts (e.g., intra-urban, inter-urban, rural). With the increasing popularity of electrified forms of cycling that have zero emissions at point of use, it is also important to assess the main *sources* of emissions (e.g., from vehicle use, energy supply or vehicle manufacturing). We focus here on emissions of greenhouse gases and the key local air pollutants relevant to public health, i.e. particulate matter and nitrogen oxides. Other impacts of substituting car travel for cycling such as less noise pollution, better use of space in cities, (de)congestion, increased crash risks, and more active lifestyles are of course also important but are outside the scope of the Chapter.

This Chapter first compares impacts of the key urban transport modes on a per passenger-km basis using a life cycle analysis (LCA) approach. For cycling, this includes conventional bikes and e-bikes in both private and shared settings for moving people and their goods – freight transport and last-mile logistics are not covered here. It then synthesizes the evidence on mode substitution as a key determinant of cycling's environmental impact. Given a set of emission factors (which can be determined with a LCA analysis) we can compare the environmental impact of different modes. This in turn allows us to calculate what degree of mode shift needs to occur to result in a certain net reduction of emissions. For example, if e-biking predominantly replaces walking trips, we can assume that the environmental impact of this shift will be negative (i.e. a relative increase in emissions and impact). Ideally, cycling and e-biking replace trips by private cars running by fossil fuels.

2 Travel emissions: how do 'cycling' and 'cyclists' compare?

2.1 Determinants and distribution of emissions

Travel emissions are determined by transport mode choice and usage, which in turn are influenced by journey purpose (e.g. commuting, visiting friends and family, shopping), individual and household characteristics (e.g. location, socio-economic status, car ownership, type of car, bike access, perceptions related to the safety, convenience and social status associated with active travel), land use and built environment factors (which impact journey lengths and trip rates), accessibility to public transport, jobs and services, and meteorological conditions (Carlsson-Kanyama and Linden, 1999, Stead, 1999, Timmermans et al., 2003, Cameron et al., 2003, Brand and Preston, 2010, Ko et al., 2011, Brand and Boardman, 2008, Nicolas and David, 2009, Adams, 2010, Alvanides, 2014, Bearman and Singleton, 2014, Anable and Brand, 2019, Götschi et al., 2017).

Mobility-related pollutant emissions are highly variable and distributed highly unequally across a wide range of contexts (Ko et al., 2011, Brand and Boardman, 2008, Büchs and Schnepf, 2013, Preston et al., 2013, Susilo and Stead, 2009). In many cases the prevalence of cycling is low, implying that measurement and detection of statistically significant effects of cycling on mobility-related carbon emissions are a major challenge (Brand et al., 2014). Some people travel a lot, especially by motorized means, while others do not travel at all on a given day (Brand et al., 2013). A major European study found that the top 10% of survey participants were responsible for 59% of carbon emissions from daily travel, and that those with better car access, higher incomes and poor bus accessibility producing higher emissions overall (Brand et al., 2021a). This is important for targeting mitigation efforts at the highest emitters while not increasing emissions of the lowest. The latter might however be desirable from a mobility justice perspective in that travelling more might allow these groups to access otherwise unavailable job opportunities or other services. If active modes are not chosen for this, overall emissions might increase somewhat, which would need to be offset by further reductions among the highest emitters.

2.2 Life cycle emissions of private and shared bikes

Life cycle assessment (LCA) is a way to study the environmental impact of (in this case) transport modes from cradle to grave. A typical LCA of transport mode emissions take into account the emissions generated by making the vehicle, using it, fuelling/charging it and any end-of-life treatment. In the production phase the materials from which the vehicle is made are considered, as well as the energy expended during production. The use phase can be the most complex, involving not just the direct emissions but also – in the case of shared operations – indirect emissions from service operations caused by the collection, charging, and redistribution of shared e-bikes, often done by internal combustion engines vehicles.

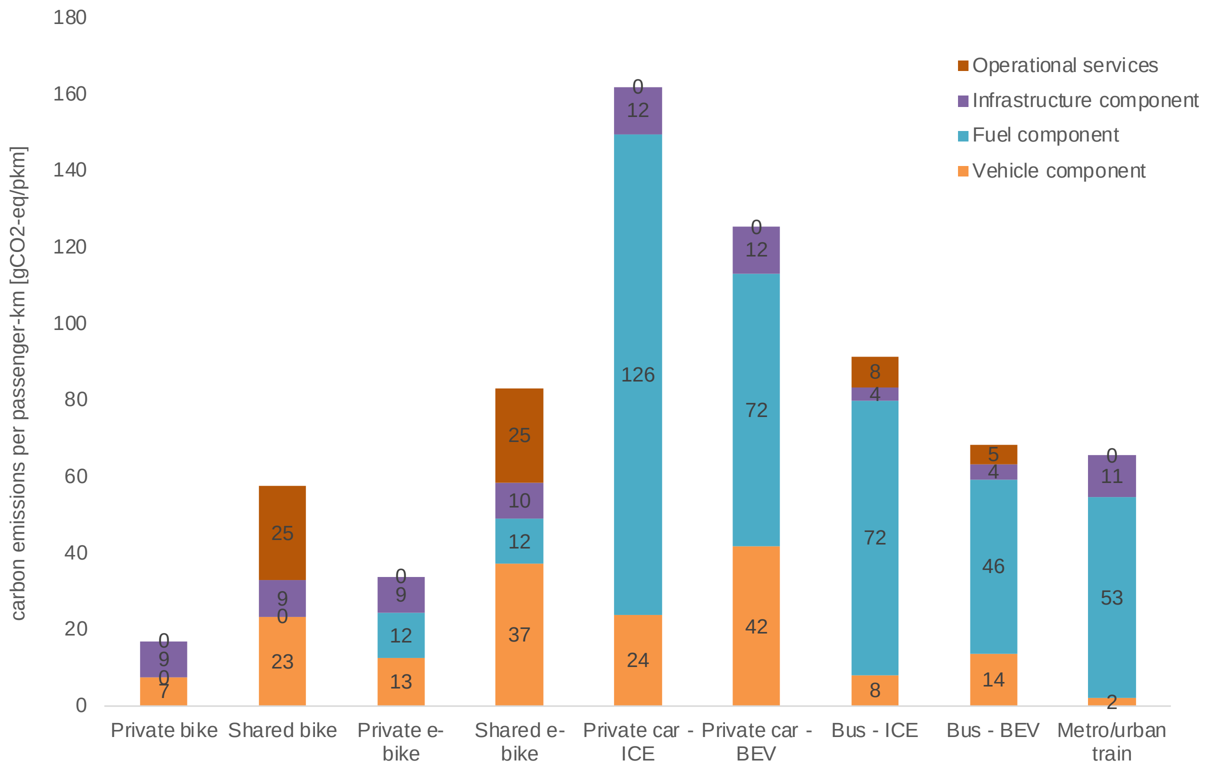
While cycling and e-biking cannot be considered a 'zero-carbon emissions' mode of transport due to the amount of carbon produced from vehicle manufacturing and energy supply, life cycle emissions from cycling can be more than 30 times lower for each trip than driving a fossil fuel car, and about ten times lower than driving an electric one (Brand et al., 2021a). Table 1 gives an overview found in the literature of average rates of carbon emissions (in grams of carbon dioxide equivalent, CO_2-eq, per passenger-km, or pkm) for the main modes of urban transport. The main reasons for variation in the values for 'conventional bicycle' are due to different accounting methods: for example, some studies include an infrastructure component or emissions from changes to dietary intake, both of which can be larger than the vehicle manufacturing component (OECD/ITF, 2020). Emissions from public transport depend mainly on the mode (bus, light rail, or metro) and different occupancy rates in the study areas. Urban rail typically has lower average emission rates than buses, with OECD/ITF (2020) providing 'global averages' of 66 gCO_2-eq per pkm for metro/urban train and 91 gCO_2-eq per pkm for bus. Note these can be substantially lower in public transport systems that run on low carbon electricity, such as Norway, Denmark and France. In Paris, for instance, life cycle emissions can be as low as 7 gCO_2-eq per pkm for metro and 9 gCO_2-eq per pkm for suburban rail (de Bortoli, 2021). The variation in car emission rates is as expected, as they vary by the fuel mix and age of the car fleet, car size and weight, occupancy rates (which vary by trip purpose) and trip speeds (slower speeds in urban areas mean higher per-km emissions).

Table 1: Average life cycle GHG emissions for key transport modes, private ownership and use, excluding infrastructure component

Avg. life cycle GHG emissions (in grams of CO_2-eq per pkm)	*Conventional bicycle*	*E-bike*	*Urban public transport*	*Car*
Cherry 2007	5	22	48	306
Blondel et al. 2011	21	22	101	271
Weiss et al. 2015	5	25	110	240
OECD/ITF 2020	7	24	67	149
Brand et al. 2021	5	15	65	190
De Bortoli 2021 (data for Paris)	11	18	7 (metro), 125 (diesel bus)	202

Figure 1 provides a 'central estimate' of average GHG emissions broken down into the main LCA components. LCA GHG emissions depend on the materials used in vehicle manufacturing, the propulsion technologies and their energy vectors, ridership characteristics, the frequency with which infrastructure (e.g. roads, railways, bike lanes) is used, as well as operational practices. Using central estimates with regards to vehicle lifetimes, electricity generation mix, and vehicle occupancy rates, the data in Figure 1 suggest that private bikes and e-bikes that are regularly used have the lowest life-cycle GHG emissions per kilometre travelled. This is the result of low material requirements per vehicle, no external energy required for vehicle operation in the case of private bikes, energy efficient use of electricity for e-bikes and no energy needed for operational services. Crucially, the difference between the vehicle component for private and shared (e-)bikes is due to different vehicle lifetimes assumed in the comparative analysis. Interestingly, infrastructure-related GHG emissions are most relevant for individual vehicles requiring the use of significant amounts of lane km of roads, including parking (i.e. for private cars). We used a single, reputable source (OECD/ITF, 2020: see Annex A for methodological details and data sources) for comparing modes as the inherent uncertainties in LCA studies make a direct comparison across modes difficult. We discuss below how the emission performance for each LCA component can be improved.

Figure 1: Life cycle GHG emissions of urban transport modes by LCA component, in gCO_2-eq/pkm (central estimates)



Notes: ICE=internal combustion engine vehicle; BEV=battery electric vehicle. Source: adapted from OECD/ITF (2020) assessment tool, using central estimates with regards to vehicle lifetimes, electricity generation mix, and vehicle occupancy rates.

2.3 Private or shared: which is lower carbon over the life cycle?

While the majority of bikeshare systems employ conventional bicycles, the number of e-bicycle sharing schemes (e-BSS) have been growing worldwide. Galatoulas et al. (2020) have provided an inventory showing that in 2018, 23% of the newly launched bike-sharing systems used (at least in parts) e-bikes; in 2019 that number was 32%. In the decade prior to 2018 the share of e-bike systems never exceeded 11%. Of all e-BSSs, 59% are European, 27% in the Americas, and 13% in Asia (outside these regions only Australia and Egypt have an e-BSS). However, many of the European systems are quite small in scale (mean fleet size of 166 vehicles), whereas systems introduced in North America or Asia are generally larger (mean fleet size 465). In terms of dockless vs. station based systems, it is hard to draw generalizations. For instance, many systems launched in North America in 2018 were dockless, but this dropped sharply in 2019, whereas in Europe, dockless systems seem to be on the rise. As of November 2019, the largest e-BSSs outside China were located in Madrid, Brussels, Amsterdam, and Milan.

However, life cycle assessments of these systems are rare. While a growing number of studies on shared e-scooters is appearing (see e.g. de Bortoli, 2021), bikeshare systems are rarely studied from this environmental perspective. OECD/ITF (2020) provided a range of estimates about the impact of both private and shared (e-)bikes. While privately-owned e-bikes have a slightly higher environmental impact than conventional bicycles, both have the lowest life-cycle energy requirements of all vehicles (OECD/ITF, 2020). Elliot et al. (2018) estimated that e-bikes in New Zealand generated 20 gCO_2-eq/pkm. Similarly, OECD/ITF found that conventional bikes generated 7 g CO_2-eq/pkm and private e-bikes 24 gCO_2-eq/pkm (both excluding infrastructure component). But the literature is fairly clear that life cycle carbon emissions are higher for current shared systems: shared systems with conventional bicycles can emit 48 g CO_2-eq/pkm while a shared e-bike system produces 74 g CO_2-eq/pkm (OECD/ITF, 2020). This is not to say that shared systems can have lower emissions rates. Indeed, a well balanced, well used system can have lower per-pkm emissions than an underused one that requires lots of relocation of bikes. A range of actions can improve the environmental performance of shared services, including:

- Use low carbon materials in vehicle manufacturing (steel is better than aluminium);
- Design solutions that extend vehicle life, and;
- Improvements in operations due to lower servicing requirements per kilometre of service.

2.3.1 Vehicle production and end-of life treatment

Emissions from bike manufacture are a major part of vehicle life cycle emissions (de Bortoli, 2021). OECD/ITF (2020) put the share of production in total emissions at around 50% for private and shared e-bikes, with similar figures for *shared* conventional bikes. Central estimates (and % shares) reported in OECD/ITF (2020) were:

- 7 gCO_2-eq/pkm out of a total of 7 g for private bikes (100%);
- 13 gCO_2-eq/pkm out of a total of 24 g for private e-bikes (51%);
- 23 gCO_2-eq/pkm out of a total of 48 g for shared bikes (49%), and;
- 37 gCO_2-eq/pkm out of a total of 74 g for shared e-bikes (50%).

Elliot et al. (2018) found a higher share of production emissions at over 87% of total GHG emissions of e-bikes in New Zealand, which is largely due to the approximately 80% share of renewable electricity generation in New Zealand – much higher than the global average figure underpinning the OECD/ITF data. Note none of the above figures include the infrastructure component, which has been estimated at around 9-10 gCO_2-eq/pkm for both conventional and e-bikes (OECD/ITF, 2020).

In terms of end-of-life treatment, emissions have been shown to be relatively small. Elliot et al. (2018), for example, found that end-of-life contributes about 4% to total GHG emissions.

The economic lifetime and annual distance travelled of a vehicle are important considerations here: the longer a vehicle can be used the lower the per-pkm emissions associated with production and end of life treatment. For private bikes and e-bikes, OECD/ITF (2020) assumed mean lifetimes of 5.6 years (taking into account a 30% reduction in the typical lifetime of 8 years due to theft, accidents, and vandalism) and an annual distance travelled of 2,400 km per vehicle. For shared bikes and e-bikes OECD/ITF assumed a vehicle lifetime of just 2.0 years (taking into account a 60% reduction in lifetime due to tampering, vandalism, loss and damage, etc.) with an annual distance travelled of 2,900 km per vehicle.

2.3.2 Transportation and delivery to point of purchase

Vehicle transportation and delivery is generally a small component of total emissions. In the case of New Zealand, relatively close to production in China, Elliot et al. (2018) found it contributed only 1% to the total impact. OECD/ITF (2020) likewise found that the transport of shared e-bikes contributed around 3 gCO_2-eq/pkm out of 74 gCO_2-eq/pkm (4% of total emissions), with similar percentages for other types of bicycles. Vehicle transportation is therefore less actionable than other aspects of the vehicle life cycle (other than perhaps creating local production facilities in the US and Europe).

2.3.3 Emissions from energy/fuel supply to the vehicle

Neither cycling nor using e-bikes incurs direct emissions at point of use. But using e-bikes implies there are emissions associated with supplying the energy used in charging. The associated GHG and local air pollution emissions depend heavily on the electricity generation mix, with OECD/ITF (2020) providing a central estimate of 12 gCO_2-eq/pkm (assuming a global average generation mix that includes large shares of fossil fuel generation). Of course, very low carbon electricity as produced today in Norway, France or Costa Rica (to name but a few leaders here), or called for by future scenarios transitioning electricity production away from fossil to renewable sources, would reduce this to near zero. However, higher carbon electricity as in Poland or India would roughly double this value. Elliot et al. (2018) showed how New Zealand's relatively green energy production (80% renewables) can minimize charging impact. As a result, the use phase of e-bikes in the country contributes less than 10% to total impact, whereas for conventional fossil fuelled cars this is over 90%.

While shared e-bike systems are on the rise, they are very new phenomena and charging practices are not clear in the literature. To avoid emissions associated with collection for recharging, docked bikeshare systems that double as charging stations are a promising solution. The bike-share operator PBSC Urban Solutions has taken a stance against swappable batteries and prefers to use docks that start charging as soon as a user puts the bike into the dock (PBSC Urban Solutions, 2019). This system requires 4 hours for a full charge, but 30 minutes of charging is enough for 12km of riding. Dockless bikeshare systems need other solutions and, like free-floating e-scooters, typically require operators to manually swap batteries, which can be highly polluting if conventional fossil fuel vehicles are used for this (OECD/ITF, 2020). Apart from emissions associated with collection for recharging, there might still be emissions from collection in order to redistribute the bikes to match the demand.

2.3.4 Emissions from energy/fuel supply to the user

Does cycling and e-biking lead to increased dietary intake and associated net carbon emissions? The evidence is inconclusive on whether day-to-day active travel (as opposed to performance/sport activity) significantly increases overall dietary intake when compared to motorized travel. When people burn more calories through exercise they don't typically consume as many extra calories in their diet (Elder and Roberts, 2007). Related to this, the effects of an increase in active travel on health outcomes such as BMI (essentially body weight) are inconclusive. One longitudinal study in the Netherlands reported no significant effects (Kroesen and De Vos, 2020) while another longitudinal study in European cities showed a significant, if small, effect of a decrease in BMI for those who travelled actively (Dons et al., 2018). A study using consumption data obtained from a consumer survey found that a 10% rise in active transport share was associated with a 1% *drop* in food-related emissions, which may be related to overall health awareness or concerns as well as impacts on well-being and mental health (Ivanova et al., 2018). Another recent study by Mizdrak et al. (2020) made the *explicit assumption* that increased energy expenditure is directly compensated with increased energy intake, while acknowledging that this is an unproven assumption. More speculative, a surplus intake of calories is common in Western societies, resulting in weight gain over the years. This would at least speak for there not being an immediate need to compensate for extra calorie expenditure – people who do daily moderate physical activity from cycling just get a little fitter and loose weight.

2.3.5 Operational impact of shared systems: rebalancing, collection and redistribution

Private (e-)bikes have no operational impact since they are used, stored and charged individually by private individuals. However, shared (e-)bike systems do have operational costs since they require rebalancing (and recharging in the case of e-bikes). Rebalancing is especially problematic in hilly cities where people tend to leave bicycles downhill, forcing daily redistribution by van – although this applies less so for e-bikes. Rebalancing is a major source of emissions associated with shared mobility systems. OECD/ITF (2020) estimates the number for operational services of bike-share systems at 25 gCO_2-eq/pkm. This is 51% of total emissions associated with shared bikes, and 34% for shared e-bikes. Service operation can therefore be a significant contributor to environmental impacts of bicycle-share systems. Changes in operational practices, in particular the minimisation of the ratio of servicing vehicle km to (e-)bike km (achievable with increases in the average number of e-bikes per service vehicle trip or the reduction of service trip distances, or both) can lead to net reductions in GHG emissions (OECD/ITF, 2020).

There are other strategies to encourage users to help with the rebalancing of bikes in shared bicycle systems. Zürich operator Bond (previously smide), for instance, indicates 'bonus zones' where users receive free user minutes if they park their bikes there; this incentivises trips into under supplied areas. The same applies to parking the bikes at a charging station (Guidon et al., 2019). In the Polish Tricity area (Gdánsk, Gdynia, Sopot), a hybrid system was applied where users were allowed to park bikes outside public transit stops for an extra fee but received a bonus if they parked them at a docking station (Bieliński and Ważna, 2020).

2.4 Summary: cycling and e-biking are the lowest carbon emitters on a life cycle basis

There is a growing body of evidence that both e-bikes and conventional bicycles (when privately owned) have significantly lower life-cycle GHG emissions per passenger-km than most road-based urban transport vehicles; they are also comparable with efficient rail-based systems such as metro, light rail and urban rail that run on low carbon electricity such as in Paris (de Bortoli, 2021). Yet the verdict on the exact magnitude of how much better e-bikes are is still out, as this will depend on future optimization of technologies, system management, and the share of low carbon electricity in recharging. Given their typically higher average trip distance, and their ability to carry loads, e-bikes and e-cargo bikes have significant potential to replace more and/or different trips than conventional bikes, also in intra-urban and rural areas. Perhaps surprisingly, life cycle GHG emissions can be higher for current generation of shared systems, which can be comparable to efficient, diesel-based urban bus services. However, the potential for improvements is significant here.

3 Mode shift: what are potential and observed emission reductions from shifting to cycling?

3.1 Which trips and trip purposes are amenable to mode shift?

For most journey purposes cycling covers short to medium length trips. Most studies focus on these 'short' (up to 5 km) to 'medium' (up to 20 km) length trips, as they are amenable to at least a partial modal shift towards active travel (Beckx et al., 2013, Carse et al., 2013, de Nazelle et al., 2010, Goodman et al., 2014, Keall et al., 2018, Neves and Brand, 2019, Vagane, 2007). Travel diary data from thousands of survey participants across seven European cities reported *mean* trip lengths of 1.1 km for walking, 4.8 km for cycling and 9.4 km for e-biking (Castro et al., 2019), with relatively wide distributions that suggest that some people travelled a lot further than the mean values suggest. Typically, the majority of trips in this range is made by car or bus (U.S. Department of Transportation, 2017, Beckx et al., 2013, Keall et al., 2018, Neves and Brand, 2019, JRC, 2013).

E-bikes in particular have significant substitution potential, some call them a 'game changer', as e-bikers have been found to take longer trips by e-bike and bicycle, compared to cyclists. E-bikes work better in hilly areas, allow for more luggage to be carried, and generally increase travel speed. As a result e-bikes have a larger potential for mode substitution away from cars (Castro et al., 2019, Mason et al., 2015, Kroesen, 2017, McQueen et al., 2020, Fyhri and Beate Sundfør, 2020).

So, what is the potential for reductions in carbon emissions due to mode substitution? In the UK, for instance, about 3 out of 5 car trips are under 8 km (5 miles), producing 21% of car CO_2 emissions (BEIS, 2019, DfT, 2018) – largely for commuting, shopping and personal business purposes. 'Medium' length trips of between 8 km and 16 km produce a further 18% of car CO_2, with longer trips of between 16 km and 25 km adding a further 8% of car

CO_2. If we assume that a trip duration of one hour is a reasonable 'threshold' (i.e. maximum) for regular trips by e-bikes, the corresponding max. distance is about 25km. So overall, trips up to 25 km in length could be substituted by cycling or e-biking. These represent about 40-50% of car CO_2, or about 30-40% of passenger transport CO_2 emissions. In contrast, the 40-50% of mileage and carbon emissions from all person transport that come from long distance travel (i.e. over 100km) are 'out of reach' for mode substitution to cycling (van Goeverden et al., 2016).

3.2 Potential effects: 'what if' scenario and potential impacts studies

Much of the work on climate change emissions impacts of cycling has been based on analyses of the *potential* for emissions mitigation (Yang et al., 2018) or the generation of 'what if' scenarios that explore the likely impacts of hypothetical increases in cycling (Goodman et al., 2019, Lovelace et al., 2011, Woodcock et al., 2018, Tainio et al., 2017). The potential effects depend largely on the study contexts, the ambitions of the underlying 'what-if' assumptions, and geographic scales.

Global scale

Mason et al. (2015) developed a 'high shift cycling scenario' and found that a 11% combined cycling/e-bike share of urban passenger travel distance worldwide by 2030 would cut CO_2 emissions from urban transport by about 7%, rising to a 14% combined cycling/e-bike share and a near 11% reduction by 2050. E-bikes played a critical role in the scenario. The study highlighted a range of issues that must be addressed for e-bikes to succeed as a mass transportation mode in many countries, including safety and (upfront) cost. Governments should encourage and subsidize low-powered, speed-limited e-bike usage while placing direct restrictions on high-polluting gasoline cars and motorbikes (Mason et al., 2015).

European scale

The European Cyclists' Federation (ECF) estimated that the carbon emissions benefits of an annual distance cycled of 146 billion kilometres for the EU28 (Steenberghen et al., 2017) amounts to about 16 million tons of CO_2 avoided each year (ECF, 2018). Using more conservative assumptions about mode substitution, trip generation and default emissions rates for motorized transport contained in the WHO's Health Economic Assessment Tool for walking and cycling (Götschi et al., 2020), this level of cycling amounts to about 12 million tons of CO_2 emissions avoided each year (source: own calculation using the online tool). To put these figures into context, total CO_2 emissions from cars in the EU were about 520 million tons in 2015 (T&E, 2018). Therefore, existing cycling activity makes a modest contribution to climate change mitigation in Europe.

National scale

A study in the UK (Stott, 2020) estimated that if cycling's popularity returned to 1940s levels (when the average Brit cycled six times further per year than today) and these trips replaced car journeys, that would create a net saving of 7.7 million tons of CO_2 per year in the UK alone. To put these figures into context, total carbon emissions from cars and taxis in the UK were 68 million tons in 2019 (DfT, 2021). Hence, the potential net savings from cycling at 1940s levels amount to about 11% of annual GHG emissions from cars.

It has also been estimated that e-bikes, if used to replace car travel, have the 'physical capability' (simulated as how far people are capable of travelling, based on physical ability, travel patterns and infrastructure provision at fine spatial scale) to cut car CO_2 emissions in England by up to 50% (about 30 million tons of CO_2 per year) (Philips et al., 2022). The greatest opportunities were found to be in rural and sub-urban settings: city dwellers already have many low-carbon travel options, so the greatest impact would be on encouraging e-bike use outside urban areas (Philips et al., 2022). In Denmark, Germany, Switzerland and the Netherlands, they already know this (Hansen and Nielsen, 2014).

In Sweden, Winslott Hinselius and Svensson (2017) found that a 14-20% reduction of transport-related emissions can be achieved, or 272-394 $kgCO_2$ saved per e-bike per year. Fyhri et al. (2017) studied a case in Oslo, Norway, and found a reduction of 87-144 kg of CO_2 per year. Bucher et al. (2019) argue that a wide uptake of e-bikes for commuting in Switzerland could reduce emissions from diesel and gasoline by 10-20%.

All of the above studies stress that these potential shifts will require a mixture of push and pull measures: segregated cycling infrastructure can help, as can measures raising the cost or convenience of driving.

Regional and city scale

McQueen et al. (2020) found that in Portland, Oregon, a 15% e-bike mode share (by distance travelled) would reduce car trip mode share from 85% to 75%, leading to a 12% reduction in CO_2 emissions and averaging 225 $kgCO_2$ saved per e-bike per year.

Individual scale

Brand et al. (2021a) estimated that an average person in European cities who 'shifted travel modes' from car to bike decreased life cycle CO_2 emissions by 3.2 $kgCO_2$/day – equivalent to the emissions from driving a car for 10km, eating a serving of lamb or chocolate, or sending 800 emails. Scaling this up to twice a week, 50 weeks a year gives an estimate of 320 $kgCO_2$/year, or about a quarter of the average per capita car emissions in Europe of about 1 ton of CO_2/year (T&E, 2018).

Many studies to date have focused on commuting. Life cycle CO_2 emissions from social, shopping, personal business and recreational journeys have been shown to be more strongly associated to car use, and that shopping and personal business trips were found to be significantly shorter, therefore increasing the potential for mode shift to cycling (Brand et al., 2021a, Brand et al., 2014, Brand et al., 2021b).

3.3 Observed effects: cross-sectional and longitudinal studies

Empirical evidence of observed mode shifts is rarer, methodologically challenging and often limited to smaller scale studies focusing on a single city or urban areas. For instance, a longitudinal panel study of 50 participants in the Cardiff, Wales area showed that, taking into account individual travel patterns and constraints, cycling can realistically substitute for between 41% and 69% of 'short' car trips up to 5 km, saving between 5% and 10% of CO_2 emissions from car travel. This was on top of 5% of 'avoided' emissions from cars due to existing walking and cycling.

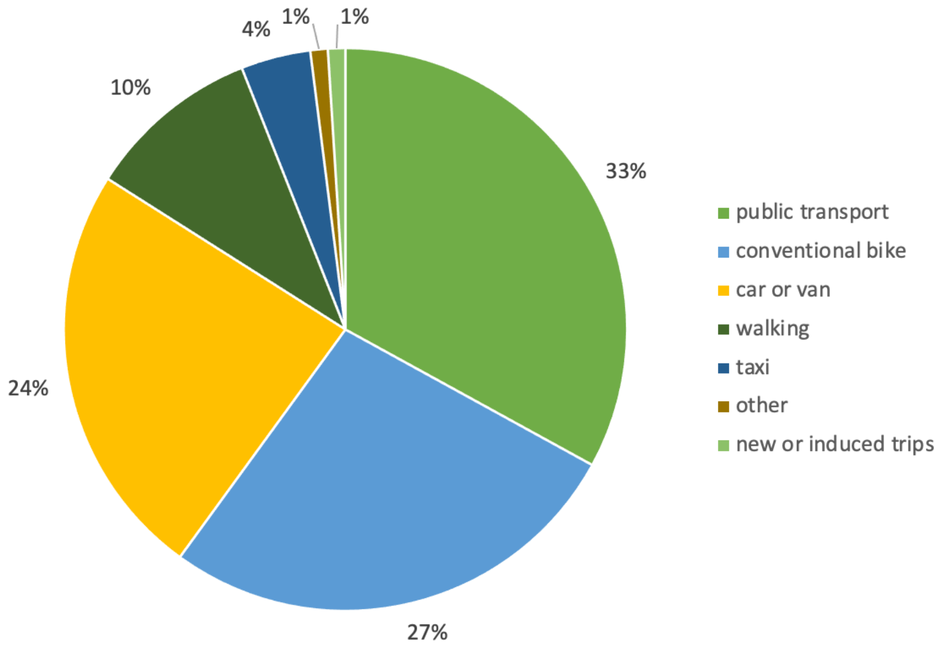
In a recent study of daily travel behaviour (i.e. all trips recorded on a given weekday) of more than 3,500 participants across seven European cities, 'cyclists' had 84 percent lower life cycle CO_2 emissions from all daily travel than 'non-cyclists' (Brand et al., 2021a). The study also found that mobility-related life cycle CO_2 emissions were 14% *lower* for those participants who cycled one trip per day more, and 62% *lower* for those who used a car or van for one trip a day less (while keeping everything else constant).

A separate analysis using longitudinal panel data of nearly 2,000 urban dwellers found that increases in cycling significantly lowered carbon footprints, even in urban European contexts with a high incidence of cycling (Brand et al., 2021b). The study found that an increase in cycling at follow-up *independently* lowered mobility-related lifecycle CO_2 emissions, thus suggesting that active travel substituted for motorized travel and did not constitute additional, induced travel. It estimated that those who switch one trip per day from car driving to cycling – and do this regularly for about 200 days a year – reduce their carbon footprint by about 0.5 tonnes over a year, representing a substantial share of average per capita CO_2 emissions and equivalent of a one-way flight from London to New York. If just one in five urban residents permanently changed their travel behaviour in this way, the study estimated that it would cut emissions from all car travel in Europe by about 8% (Brand et al., 2021b).

Bigazzi and Wong (2020) conducted a meta-analysis of 24 studies on e-bike mode substitution. They concluded that generalizations are hard to make since local substitution patterns vary significantly. **Overall, however, the median mode substitution that could be gleaned from this literature is that 33% of e-bike trips replace public transit, 27% conventional bicycle, 24% cars and 10% walking** (see also Figure 2). Kroesen (2017) and Sun et al. (2020) found that in the high-cycling context of the Netherlands, many e-bike trips replaced trips by conventional bike rather than car trips. However, Ling et al. (2015) point out that these might for instance be senior citizens who were no longer comfortable cycling and would have switched to a car had they not chosen e-bikes. We therefore have to consider that one potential positive impact from the uptake of e-bikes is keeping existing cyclists on the bike longer. Senior citizens who might shift to more climate-impacting motorized modes can continue cycling longer when they employ e-bikes (Leger et al., 2019, Jones et al., 2016). It might also convince more women to take up cycling (Wild et al., 2021).

There are a few case studies from Sweden, which are worthwhile to consider since they are European but do not have the relatively high cycling levels of the Netherlands and Denmark. Winslott Hinselius and Svensson (2017) show that in Sweden e-bikes predominantly replace car trips. As expected, a larger share of conventional bicycle and public transit trips were replaced in urban areas than in rural contexts, but in both rural and urban contexts the net environmental impact of e-bike uptake is a reduction of CO_2 emissions.

Figure 2: Median mode substitution to e-biking based on meta-analysis of 24 studies



Source: Bigazzi and Wong (2020)

One randomized controlled trial of 98 Swedish drivers investigated the effect of using e-bikes on modal choice, number of trips, distance travelled, and perceptions of e-bikes as a substitute for the car (Söderberg f.k.a. Andersson et al., 2021). The study found that those people who were given an e-bike increased cycling by 1 trip and 6.5 km per day and person, which led to a 25% increase in total cycling, with the increase due to a reduction in car use by 1 trip and 14 km per person and day; a decrease in car mileage of 37%. This overall reduction in car travel is higher than in studies conducted by Kroesen (2017) in the Netherlands (28%) or Cairns et al. (2017) in Brighton (20%). This can partly be explained by the fact that car levels in these cases were already lower to begin with than in the case in Skövde, Sweden. Interestingly, study participants reported that e-bikes reduce barriers linked to time, distance, and physical exertion, especially in hilly areas. The study further claimed that e-bike use was related to hedonic, rational, and altruistic gains by individuals. These factors can explain why e-bikes may have a larger appeal to car drivers than conventional cyclists.

3.4 What about mode shift from bike sharing systems?

The potential for BSS to reduce emissions is more complicated than for private ownership of e-bikes. The existing literature has a strong focus on the dominant conventional bike sharing systems and has yet to grapple with more recently introduced e-BSS. In car-dominant cities in the US or Australia, research suggests a reduction of car kilometres travelled as the result of the introduction of these systems. However, in a European context, cities tend to have higher levels of public transit and active transport. As Fishman et al. (2014) illustrated for London, car kilometres actually rose as a result of the introduction of bicycle share systems as few car trips were substituted while many new kilometres were added by the trucks driving around to rebalance bicycles. Luo et al. (2019) studied dockless vs. docked BSS in the US and concluded that dock-less BSS are problematic in this regard, as they may require at least 34% of car trips to be replaced by shared bike trips for a net positive impact, which is higher than most systems currently achieve. In contrast, docked systems may have more potential to decrease GHG emissions because they require fewer car trips to be substituted to have positive net emission effects (Luo et al., 2019).

The mode substitution effects of e-BSS have only recently been investigated. Specific mode substitution data for an e-bike sharing system exists for the Tricity area in Poland. Bieliński and Ważna (2020) found that shared e-bikes did not, in the majority of cases, substitute car trips, but rather acted as replacements for public transit trips or as first mile/last mile trips to public transit stops (replacing walking). Because the area is somewhat hilly, the municipal government chose e-bikes rather than conventional bicycles in the hopes of substituting car trips or encouraging e-bike use as feeder transport for public transit – successfully, as 39% of respondents to the questionnaire in this study used it in this way. All the same, as in other studies on bike-share systems or e-bikes, the e-Bike Sharing System was far more likely to replace public transit trips than car trips.

3.5 Local air pollution effects

So far we have largely focussed on the climate change mitigation effects of using conventional bikes or e-bikes and any mode shift from motorised mobility. Human health damages from local air pollution caused by road traffic are significant, in particular in urban areas where most people live and/or work (House of Commons, 2018). Urban transport is also one of the reasons why many urban areas are in breach of air pollution regulatory limits. Road transport is often the principal source of pollution, though domestic and background emissions also contribute to the problem (Hitchcock et al., 2014). Current regulatory breaches in many countries relate to nitrogen dioxide (NO_2), generated from emissions of nitrogen oxides (NO_X), and particulate matter, the latter both in its coarser PM_{10} form (particles with an average diameter of 10 micrometres or less) and the fine $PM_{2.5}$ form (2.5 micrometres or less). NO_X is mainly a by-product of fuel combustion, whilst PM results from fuel combustion as well as road, brake and tyre wear (Grigoratos and Martini, 2015, Grigoratos and Martini, 2014).

As with GHG emissions, neither conventional bikes nor e-bikes produce any tailpipe emissions of NO_X and PM. However, they produce very small amounts of PM from road, brake and tyre wear. Similar to life cycle emissons of the global air pollutant CO_2, their use is also responsible for air pollutant emissions from electricity generation, as well as vehicle manufacturing, maintenance and disposal. These occur generally at some distance from highly populated areas, hence health impacts are somewhat reduced by dispersion and dilution over distance and time (as compared to carbon emissions, which contribute to climate change independent from where they occur).

The literature on local air pollution effects is sparse when compared to climate emissions effects. Much of the evidence suggests that when compared to cars and vans, non-tailpipe air pollutant emissions for e-biking are several times lower per kilometer than for motorcycles and cars, have comparable emission rates to buses and higher emission rates than bicycles (Cherry et al. 2009). This is mainly because in-use emission rates are proportional to the vehicle weights – up to the power of four in case of road abrasion emissons. Comparing emissions of the main air pollutants and environmental health impacts (primary $PM_{2.5}$) from the use of conventional vehicles (CVs) and electric vehicles (EVs) in 34 major cities in China, Ji et al. (Ji et al. 2012) found that e-bikes yield lower environmental health impacts per passenger-km than the three CVs investigated: gasoline cars (2×), diesel cars (10×), and diesel buses (5×).

In terms of health impacts of air pollution from mode shift to cycling, it is important to compare to the emissions rates of the substituted modes (i.e. car or bus). In terms of $PM_{2.5}$ and NO_X emissions, Brand and Hunt (2018) showed substantial differences between petrol, diesel and electric vehicles, particularly for NO_X where conventional diesel cars emit nearly six times more per km than conventional petrol cars. Battery electric vehicles (BEV) do not emit any NO_X when in use. $PM_{2.5}$ (and PM_{10}, not shown) emissions are more equally distributed, although there are clear differences as well, with non-diesel cars and vans emitting two thirds of the fleet average, and less than half of diesel cars and vans. BEV have zero exhaust emissions and contribute the lowest PM emissions of these vehicle types. As mentioned above, they do contribute a small but important share of non-exhaust emissions of particulate matter due to tyre, brake and road surface wear (Grigoratos and Martini, 2014, Ntziachristos and Boulter, 2016, Timmers and Achten, 2016, Loeb, 2017, Williams et al., 2018).[2] BEV are estimated to emit 5-19% less PM_{10} from non-exhaust sources per km than internal combustion engine vehicles (ICEVs) across vehicle classes (OECD, 2020). However, BEV do not necessarily emit less $PM_{2.5}$ than ICEVs. Although lightweight BEVs emit an estimated 11-13% less $PM_{2.5}$ than ICEV equivalents, heavier weight BEVs emit an estimated 3-8% more $PM_{2.5}$ than ICEVs (OECD, 2020). In the absence of targeted policies to reduce non-exhaust emissions, consumer preferences for greater autonomy and larger vehicle size could therefore drive an increase in $PM_{2.5}$ emissions in future years with the uptake of heavier BEVs. This also means that in order to reduce air pollution policy should favour a shift away from BEVs to cycling.

4 Implications for policy and planning

Realizing the significant potential for mode shift

The evidence presented above shows that private bikes and e-bikes that are regularly used have the lowest life-cycle GHG emissions per pkm. It also shows that cycling and e-biking substitutes, at least in parts, for motorized travel, and that increases in cycling are not just additional, induced travel or due to route substitution (which can be the case for new infrastructure developments where new routes show significant uptake of cycling). This means that, even if not all car trips could be substituted by cycling and other forms of active travel, the potential for decreasing emissions is considerable and, as shown above, range between 5% (real world observation, cycling, conservative) and 50% (capability-based e-bike scenario).

Policy interventions that target mode shift and behaviour change have been shown to achieve emissions reductions closer to the bottom than the top of that range (Grischkat et al., 2014, Semenescu et al., 2020), so policy ambition needs to rise sharply and involve a raft

[2] Non-exhaust emissions from road vehicles are in general terms enhanced by increased vehicle weight. Timmers and Achten (2016), for instance, acknowledge the benefits of regenerative brakes on electric vehicles and made a conservative estimate of zero brake-wear emissions for electric vehicles. Hence, their claim that electric vehicle particulate matter emissions are comparable to those of conventional vehicles was based upon the greater tyre and road surface wear, and resuspension associated with a greater vehicle weight.

of bold 'push' and 'pull' measures that transform the mobility system and wean us off motorized mobility and 'car dependency' (OECD/ITF, 2021). Clearly, given the shorter distances covered by cyclists, land use and urban planning are critical – with car restraint and limiting or pricing car parking being important in addition to making cycling and other active travel options the better, more reliable and more convenient options for short (and medium) length journeys. Urban density and accessibility to jobs and services by active modes are important. This is exemplified by the growing number of city and local authorities that pursue urban planning around the concepts of the 15-minute city (Moreno et al., 2021) or the 20-minute neighbourhood (Nieuwenhuijsen and Khreis, 2016, Tranter and Tolley, 2020).

Minimise the impacts of shared systems and make it easier to own and use a private vehicle

Private cycling and e-biking perform better in terms of life cycle emissions than shared vehicles, which is largely due to the much lower economic lifetime of vehicles in shared systems – one study showed the lifetime mileage of shared bikes to be 2.4 times lower than for private bikes (OECD/ITF, 2020). Incidentally this is also the case for shared and private e-scooters. Yet, the use of shared vehicles should be encouraged where space is at a premium, resources are limited and private ownership may be beyond the means of potential users, particularly in areas of 'transport poverty' (Pabayo et al., 2012). Policymakers should therefore consider measures that minimise the impacts of shared systems by, for instance, decreasing the impact of servicing and operations (e.g. redistribution with zero emission vehicles) and increasing the longevity of the vehicle (and battery).

While subsidies for purchasing e-bikes are already in place in some EU countries and cities, this could be extended and/or marketed more, and could be more balanced in relation to measures that encourage uptake of electric cars. Apart from safe and convenient infrastructure, and safe traffic conditions, policy measures specific to e-bikes are:

1. secure storage facilities;
2. covered parking facilities as well as bike path winter maintenance;
3. including space for e-bike parking in building regulations;
4. converting existing car parking into bicycle parking facilities, and;
5. charging of e-bikes should be made as convenient as possible. This is particularly important for people's home and work locations, but also for all other trip destinations such as education, shopping or leisure.

Expand the scope to rural and sub-urban settings

People living in urban areas tend to have access to a range of low-carbon travel options and infrastructure. There is a risk that increased levels of cycling may decrease public transport ridership and walking more than car use. The above studies have shown, however, that cycling and e-biking in cities does indeed shift modes away from cars and reduce daily carbon emissions. Yet, a potentially greater impact would be on encouraging e-bike use outside urban areas. E-bikes offer an opportunity to substitute for fossil-fuel motorised mobility on 'longer' journeys (defined here as in the 8-25 km range, based on mean speeds of 25 km/h and up to 1 hour travel time) but this may need a range of policy and planning 'carrots' (in particular, safe and high-quality infrastructure and financial support to reduce the up-front costs) and ‘sticks’ (restraint/no access for motorised mobility, reduced traffic speed via road design, speed limits/enforcement) to mirror the success of countries such as the Netherlands, Switzerland and Germany, which have had some success in increasing rural e-biking, largely due to developing decent rural and intercity route systems.

5 Summary conclusion

Cycling and e-biking have been shown to have significant if limited carbon reduction benefits for short to medium length trips across a range of urban settings. The effects are more pronounced when cycling provision is coupled with car restraint policies. What is less clear (in terms of empirical evidence) is the role it can play in reducing carbon emissions from inter-urban and rural travel, and how soon the effects materialise. The relatively high emissions from the operation (rebalancing, recharging logistics) of current shared systems suggests we need to develop, implement and evaluate more balanced (e-)bike sharing systems and assess how they perform in environmental terms. Achieving high levels of mode shift away from cars is hugely contextual, so we need more robust evidence on the ‘why’, ‘how’ and ‘in what circumstances’ mode shift has been achieved in real world settings. What is also less clear is the potential of multimodal substitution; for instance, what are the conditions and policies needed to shift a 50km car trip to work to a multimodal trip involving a 10km e-bike ride, a 35km train journey and a 5km shared ebike trip? There are also a number of mobility modes ‘between car and bike’ that might be interesting to study – L-category or micro-mobility modes that are still marginal today but could play a role in meeting mobility needs of certain segments of the population (Héran and Bigo, 2020). An improved knowledge of the effects of active travel will provide a more robust evidence base to underpin climate change mitigation strategies and pathways at the local, national (CCC, 2020) and international (IEA, 2020) levels.

Nearly half of the fall in daily carbon emissions during global lockdowns in 2020 came from reductions in transport emissions (Le Quéré et al., 2020). The pandemic forced countries around the world to adapt to reduce the spread of the virus. Cycling and walking have been the ‘big winners’ in many countries, including the US and Europe. This is despite cycle commuters being very likely to work from home. Cycling and e-biking has offered an alternative to public transport and driving (shared, taxi, etc.) that keeps social distancing intact. It has helped people to stay safe during the pandemic and it could help reduce emissions as confinement is eased, particularly as the high prices of used and new electric vehicles are likely to put many potential buyers off for now. Electric cars have a range of mobility justice issues (Henderson, 2020) and cannot reduce GHG emissions fast enough on their own (IEA, 2021, Brand et al., 2020). Even if all *new* cars were electric from now on, it would still take 15-20 years to replace the world’s fossil fuel car fleet (Keith et al., 2019).

So, the race is on. Cycling and e-biking can contribute to tackling the climate emergency and urban air quality crisis *earlier* than electric cars while also providing affordable, more equitable, reliable, clean, healthy and congestion-busting transportation.

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