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Healthy climate, healthy bodies: Optimal fuel taxation and physical activity

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Passenger transport has significant externalities, including carbon emissions and air pollution. Public health research has identified additional social gains from active travel, due to the health benefits of physical exercise. Per mile, these benefits greatly exceed the external costs from car use. We introduce active travel into an optimal fuel taxation model and characterize analytically the second-best optimal fuel tax. We find that accounting for active travel benefits increases the optimal fuel tax by 44% in the USA and 38% in the UK. Fuel taxes should be implemented jointly with other policies aimed at increasing the uptake of active travel.

1 | INTRODUCTION

Transport policies need to balance the economic gains from passenger vehicle use with a large number of significant externalities, including air pollution, accidents, congestion and climate change. For example, in the USA and the UK, the transport sector is the largest contributor of greenhouse-gas emissions (Hockstad and Hanel 2018; Gabbatiss 2018). Increased active travel such as cycling and walking—even to the nearest public transport stop—can reduce these externalities, especially in urban areas. In addition, the physical exercise involved in active travel is highly beneficial for public health, especially given high rates of inactivity and obesity in many societies. Previous scenario-based modelling in public health research has indicated that the health benefits of active travel exceed those from abating emissions and air pollution of private vehicles (Woodcock *et al.* 2009; De Hartog *et al.* 2010). For example, Woodcock *et al.* (2009) find that an increased active travel scenario would avoid 530 premature deaths per million population in London annually, while a low-carbon motor vehicles scenario would save only 17.

Surprisingly, economists have yet to examine the significance of the health benefits from active travel for optimal regulation of urban transport. While they can be assumed to know that exercise is good for health in general, most citizens are not aware of the full extent to which it

provides health benefits (Fredriksson *et al.* 2018). Furthermore, the effectiveness of simple interventions such as reminders or initial payments to attend a gym (Calzolari and Nardotto 2017; Charness and Gneezy 2009) and evidence of overspending on gym contracts (DellaVigna and Malmendier 2006) point to self-control problems and an underappreciation of the health benefits of exercise. One might think that health benefits of active travel are a local phenomenon, which has limited relevance for transport policy at the macro level. It is, however, yet to be determined how fuel taxes, or more targeted instruments, should be set to reap these health benefits in addition to mitigating the externalities of car use.

In this paper, we examine a novel economic effect by adding an active travel mode to a model of transport externalities from car use. Households respond to higher fuel taxes by buying more fuel-efficient cars and reducing car travel, but do not fully internalize the health benefits of switching to active travel modes. We confirm that on a per mile basis, the monetary value of the health benefits from active travel exceeds the social costs of unregulated externalities of carbon emissions, air pollution, congestion and accidents by up to two orders of magnitude. First-best policy would thus involve a large subsidy to promote active travel (at least absent health policy to increase activity levels in general). Without such subsidies, we derive the second-best optimal fuel tax that corrects for the externalities and the unrealized health benefits. We examine the difference for the tax rule, and quantify the appropriate tax rate when including or excluding health benefits from active travel.

Our main finding is that the optimal tax increases by 44% in the USA, and 38% in the UK, when health benefits from physical exercise are included. The second-best optimal fuel tax for the USA is $12.92 per gallon, and $8.99 per gallon without physical inactivity costs, while the current[1] rate in the USA is $0.50 per gallon (US Energy Information Administration 2023). The optimal fuel tax for the UK is $6.31 per gallon, which is higher than the current rate of $3.82 per gallon (RAC 2023). Without physical activity costs, the second-best optimal tax would be $4.56 per gallon.[2]

Our main contribution is to show that the health benefits from active travel are so significant that they should change the second-best fuel tax—the most archetypal, widely used, and very effective instrument of transport regulation. To be clear, other transport policies such as congestion charges, adequate walking and cycling pathways, and parking fees will be better suited to promoting active travel than fuel taxes (see the final subsection of Section 3, on first-best policies). Furthermore, they can better address concerns about the negative impacts that increasing fuel prices have on low-income households, as they can be differentiated between locations. Analysing which mix of fuel- or mileage-based taxes and more local instruments, such as urban infrastructure overhaul, are feasible to best achieve sustainable mobility (Banister 2008) requires geographical context and is beyond scope of our approach.

This paper builds on three distinct strands of the literature.

First, a large body studies optimal levels of fuel taxes, and which externalities should be addressed by them (van Essen *et al.* 2019). In addition to generating government revenue, fuel taxes are typically used for the purpose of reducing most forms of non-priced costs of transport—for example, the externalities of carbon dioxide and particulate matter, or reducing congestion by raising the cost of driving. Parry and Small (2005) derive the optimal gasoline taxes for the USA and the UK, accounting for congestion, accidents, carbon emissions and air pollution, and Antón-Sarabia and Hernández-Trillo (2014) apply this framework to Mexico. Sterner (2012) compares the optimality of fuel taxes in Europe and the USA, concluding that fuel taxes vary considerably between countries. They are inefficiently low in most European countries (Santos 2017). Yet the optimal fuel tax literature has so far not considered the health benefits from active travel.

Second, the field of public health, starting with Woodcock *et al.* (2009), has identified high social benefits from active travel over and above the benefits from abating emissions and air pollution of private vehicles (De Hartog *et al.* 2010; Wolkinger *et al.* 2018). To the majority of the

population, increasing physical activity outweighs the negative impacts of increased exposure to air pollution (Tainio *et al.* 2016). This is due to the overwhelmingly sedentary lifestyles in both the UK and the USA, making physical inactivity a leading risk factor for 6 of the 10 largest causes of death worldwide (World Health Organization 2019). Most UK adults do not exercise regularly (37% never, 16% less than once a week, 57% admit they never do activity strenuous enough to be out of breath; European Commission 2018). This leads to significant costs, including higher rates of disease incidence, lower quality of life, loss of income, excess healthcare costs, and productivity losses in the workplace. Meeting the minimum recommendations of 150 minutes of moderate-intensity physical activity per week can reduce the risk of cognitive impairment and dementia, depression, hypertension, several kinds of cancer, type 2 diabetes, and cardiovascular disease (Davies *et al.* 2019). We build on the valuation methods in public health to quantify the welfare cost of travel that is inactive.

Third, behavioural public economics research has elaborated on the important role of 'internalities' in various domains of public policy (Allcott and Sunstein 2015). An 'internality' occurs when an individual imposes a significant cost on herself due to behavioural failures, broadly understood as being prevented from acting according to her true motivation. As these private costs are imposed only or mainly on oneself—which is true for lack of physical activity—they fall outside the definition of an externality. Nonetheless, governments regulate internalities when scientific evidence substantiates them. Internality taxes have been applied to the market for smoking (Gruber and Kőszegi 2004), gym memberships and exercise (in the form of subsidies; DellaVigna and Malmendier 2006), sugary drinks (Allcott *et al.* 2019a,b) and the energy and automobile market (Allcott and Wozny 2014; Allcott and Sunstein 2015), where they also interact with environmental externalities. In the latter case, the interaction leads to a behavioural–environmental second-best problem (Shogren and Taylor 2008).[3] 'Sin taxes'—surcharges on prices of goods of which people consume too much because of internalities—have been modelled as either simple extensions of a Pigouvian tax (O'Donoghue and Rabin 2006) or complex interactions between taxes and individuals' heuristics and decisions, to achieve an optimal outcome in second-best settings (Allcott *et al.* 2014).

However, this body of literature has not considered the internality of physical inactivity in urban transport. Walking, cycling and switching to public transport are considered ways in which people can achieve 'appropriate' levels of physical activity as prescribed by public health guidelines (Gibson-Moore 2019; Office of the Surgeon General 2015). People generally undervalue the contribution of physical exercise to their long-term health (Zamir and Teichman 2014). There are two behavioural biases behind this undervaluation, which lead to insufficient levels of exercise and further health impacts: imperfect information and insufficient self-control (Allcott *et al.* 2019b). This reinforces the case for building active travel into commuting routines.

Our contribution is threefold. First, we introduce a physical-activity-related health internality into an established framework of transport decisions (Parry and Small 2005), and use this behavioural–environmental framework to provide an analytical solution for the second-best optimal fuel tax. Second, we provide an updated quantification of the external costs of travel provided by Parry and Small (2005), considering recent research and global climate policy goals, and complement this with a quantification of the health benefits of active travel. For example, updating the carbon price estimates increases the contribution of fuel pollution to the optimal fuel tax by two orders of magnitude. Congestion costs have also risen more significantly than accident costs since the year 2000. In the USA, though not in the UK, the Ramsey tax component contributes more than the individual externalities to the optimal fuel tax. Third, in terms of policy implications, we contribute to evaluating fuel taxes as opposed to other policies. We confirm that raising the propensity of consumers to switch to active travel modes can impact greatly the appropriate fuel tax: the demand for vehicle miles travelled (VMT) is so inelastic that increasing the appropriate

elasticities to their upper bound found in the literature raises the fuel tax by up to 58% for the UK and 78% for the USA.

To be clear, our paper does not aim for a complete characterization of first-best policy instruments to address the underappreciation of physical activity, including information provision, commitment devices and direct monetary incentives by health providers. Rather, our contribution is more modest: insofar as there remains uninternalized valuation of physical activity from direct attempts to reduce it, we show how it affects optimal transport policy through fuel taxation.[4]

While local policies are attractive for addressing specific transport externalities, we focus on fuel taxes to show that the health benefits of active travel matter even for getting the macro level of optimal transport regulation right. Fuel taxes have some advantages over more specific transport policies. First, they can be implemented with relatively small administrative costs compared to other policies, since most countries already have fuel taxes in place and levels would only have to be adjusted accordingly. Second, fuel taxes have a proven track record of reducing carbon emissions (Bento *et al.* 2009; Sterner 2012; OECD 2019; Bretschger and Grieg 2020). Third, they generate government revenue—which remains true if more electric vehicles in the future will prompt a switch from fuel- to mileage-based road taxes. This revenue could be used either for green spending, for instance on low-carbon transport infrastructure, or for compensating households that are especially affected by the tax (Bento *et al.* 2009). Both measures could make the public more supportive of fuel- or mileage-based taxation (Klenert *et al.* 2018).

The analysis is organized as follows. Section 2 describes the analytical model, which includes the standard externalities of road transport and the behavioural failure of ignoring health benefits. We derive an analytical result for the optimal fuel tax. Section 3 explains our choice of parametrisation for quantifying second-best fuel taxes and drawing implications for first-best options. Section 4 presents the quantitative results on fuel tax levels, and traces sensitivity and welfare effects. Section 5 discusses limitations of our analysis and explains the context of our result on fuel taxes in transport economics and policy. Section 6 concludes with policy implications.

2 | ANALYTICAL FRAMEWORK

2.1 | Model

To explore how the fuel tax might be adjusted optimally to account for health benefits of public transport, we extend Parry and Small (2005) to include active travel decisions and associated health benefits. We take advantage of the fact that in certain settings, internalities can be treated as extensions of externalities (O'Donoghue and Rabin 2006).

We consider a representative agent with the utility function

$$U = u(\psi(C, M, T^{in}, T^{ac}, G), N) - \varphi(P) - \delta(A) + \xi(Q), \qquad (1)$$

where C is the quantity of numeraire consumption, M is total distance travelled, T^{in} and T^{ac} are total time travelled using active and inactive modes respectively, G is exogenous government spending, and N is leisure, with $U_C, U_M, U_G, U_N > 0$ and $U_{T^{in}}, U_{T^{ac}} < 0$, where the subscript denotes a partial derivative. The level of pollution is denoted by P, while A captures accidents, and health is denoted by Q. As in Parry and Small (2005), we assume that $u(\cdot)$ and $\psi(\cdot)$ are quasi-concave, and $\varphi(\cdot)$ and $\delta(\cdot)$ are convex. The functions $\varphi(\cdot)$ and $\delta(\cdot)$ capture the disutility from pollution and accidents, respectively. We add the concave function $\xi(\cdot)$, which captures the positive utility from health Q.[5]

Total travel M can be separated into two components, inactive travel M^{in} and active travel M^{ac}:

$$M = M^{in} + M^{ac}. \qquad (2)$$

Inactive travel denotes travel using modes that require very little physical activity, most importantly using the car. Active travel instead captures walking and cycling. We also consider public transport as an active mode of travel, as it typically requires the individual to walk or bike to the bus stop, tram stop or train station, in some cases providing up to 30% of daily exercise recommendations (Besser and Dannenberg 2005). As such, active travel requires spending S, which will be specified further below. Inactive travel distance M^{in} requires fuel F, and other travel inputs H: $M^{in} = \chi(F, H)$. In line with Parry and Small (2005), we assume that M^{in} is homogeneous of degree one with respect to its inputs. This specification allows for multiple channels of substitution. For instance, as fuel prices increase, the agent can decide to: (i) reduce total distance travelled M; (ii) spend more on other inactive travel inputs, H, such as purchasing a vehicle with higher fuel economy; or (iii) increase active travel distance M^{ac}.

The agent spends time T^{in} in inactive travel. For a given distance M^{in}, this time is increasing in the amount of congestion on roads, which we take as an increasing function of the population average inactive miles travelled, $\overline{M}^{in}$:

$$T^{in} = \pi^{in}(\overline{M}^{in})\, M^{in}, \qquad (3)$$

where $\pi^{in}_{\overline{M}^{in}} > 0$. Here, π^{in} is equal to the inverse of the speed of inactive travel, which we assume the agent takes as exogenous. In equilibrium, $\overline{M}^{in} = M^{in}$. For active travel, we abstract from congestion,[6] and model time travelled as directly proportional to distance:

$$T^{ac} = \pi^{ac} M^{ac}, \qquad (4)$$

with π^{ac} the inverse of speed from active mobility. Only inactive travel contributes to pollution, in the form of both carbon dioxide emissions and local air pollution. Carbon emissions are directly proportional to fuel use. To capture local air pollution effects, inactive miles travelled offer a better proxy (Hitchcock et al. 2014).[7] This allows us to write

$$P = P^f(\overline{F}) + P^m(\overline{M}^{in}), \qquad (5)$$

with $P^f_{\overline{F}} > 0$ and $P^m_{\overline{M}^{in}} > 0$. We also assume that the agent will take pollution as given; she will not internalize the effect of travel decisions on the population averages $\overline{F}$ and $\overline{M}^{in}$.

Both active and inactive travel are subject to accident risk. We assume that agents internalize own accident risk and separate accident costs associated with active and inactive travel. For inactive travel, accident costs are increasing with the amount of travel. As travel increases, the agent also imposes an 'accident externality' upon other users: the higher average travel $\overline{M}^{in}$, the more likely a road user will be involved in an accident. For active travel, we similarly assume that higher travel increases the number of, and thereby costs of, accidents. Yet roads that are busier with cars tend to be more dangerous to both cyclists and pedestrians. Conversely, there exists a so-called 'safety in numbers' effect: more cyclists on the road tend to make cycling safer overall (Elvik and Bjørnskau 2017; Kahlmeier et al. 2017). Hence we assume that the accident costs associated with active travel are increasing in the average amount of inactive travel $\overline{M}^{in}$, and decreasing in average active travel $\overline{M}^{ac}$. This gives

$$A = A^{in}(M^{in}, \overline{M}^{in}) + A^{ac}(M^{ac}, \overline{M}^{in}, \overline{M}^{ac}), \tag{6}$$

with $A^{in}_{M^{in}} > 0$ and $A^{in}_{\overline{M}^{in}} > 0$. Likewise, $A^{ac}_{M^{ac}} > 0$ and $A^{ac}_{\overline{M}^{in}} > 0$, while $A^{ac}_{\overline{M}^{ac}} < 0$.

We assume that active travel is conducive to health. To capture this, we write health as a function of active travel:

$$Q = Q(M^{ac}, O), \tag{7}$$

where O are other forms of exercise,[8] with $Q_{M^{ac}} > 0$ and $Q_O > 0$. We assume that the agent considers only a constant share $\omega \in [0, 1]$ of Q as relevant in her optimization problem. Instead of considering actual health Q, she considers 'perceived health' Q^{per}:

$$Q^{per} = \omega Q + \tilde{Q}, \tag{8}$$

where the agent considers $\tilde{Q}$ as outside of her control, while in reality, $\tilde{Q} = (1 - \omega)Q$. Whenever $\omega < 1$, equation (8) represents the notion that the individual underestimates the effect of exercise on health. This underestimation is consistent with substantive evidence that individuals do not fully appreciate the positive effects of activity-related health (see the subsubsection 'Rate of health internalization, ω' in Section 3), and is also underscored by the existence of policy interventions encouraging healthy behaviours.[9]

With equation (8), we adopt a specification of limited attention proposed by DellaVigna (2009), which assumes that the direct benefit of completing travel (in active mode, M^{ac}) is 'visible', while the health benefit Q from active travel is 'opaque'. This seems justified as many citizens are largely unaware of the high health benefits of even short walks (Fredriksson *et al.* 2018; Bennett *et al.* 2009). Alternatively, the unrealized health benefits from active travel could represent a case of time-inconsistent preferences (Laibson 1997; O'Donoghue and Rabin 1999), where citizens highly value their health, but repeatedly postpone undertaking exercise (DellaVigna and Malmendier 2006). This can be captured by an equivalent formulation of equation (8) in our *static* model, as the assumption of time-inconsistent preferences implies that an activity level less than desirable in the long term is pursued at any point in time.

The agent's budget constraint is given by

$$C + (p^f + t^f)F + p^h H + p^o O + S = w(1 - t^l)L, \tag{9}$$

where $p^f + t^f$ is the consumer price of fuel, p^h is the price of other inactive travel inputs, and p^o is the price of other forms of exercise.[10] In addition, active travel requires the agent to spend on items such as a bicycle or public transport. We denote by S any such spending on active travel (with normalized price), with $S = S(M^{ac})$, $S(0) = 0$ and $S_{M^{ac}} > 0$. Finally, we denote the gross wage rate by w, and the labour tax rate by t^l. The total amount of time available is given by $\overline{L}$, which is allocated to labour L, leisure N, and time spent travelling T^{in} and T^{ac}, such that

$$L + N + T^{in} + T^{ac} = \overline{L}. \tag{10}$$

In the remainder of this paper, we assume that all prices are exogenous and constant. The fuel tax t^f will be set by the policymaker. The proceeds of the fuel tax will be used to fund government spending G. The labour tax will in turn be set such that the government budget constraint is binding:

$$G = t^f F + t^l w L. \tag{11}$$

Throughout, we assume that there exists a unique and interior equilibrium, where the agent chooses strictly positive levels of C, F, H, M^{ac}, O and L, and that G is such that $t^l > 0$.

2.2 | Second-best fuel tax

In the setup above, an increase in fuel use is associated with carbon emissions. Additionally, higher fuel use increases the number of miles travelled, which increases local pollution, as well as congestion and accident risk. All these effects are not internalized by the representative agent, who takes them as given. On their own, these externalities already justify the introduction of a positive 'externality tax' on fuel. Such a tax will be welfare-improving, as it forces the agent to internalize (part of) the externality. In addition to the externalities, our framework also features an 'internality': whenever $\omega < 1$, the agent underestimates the extent to which higher levels of active travel deliver positive health benefits. Consequently, the choices of M^{ac} and O, and resulting Q, may be suboptimally low.

Our aim is to quantify how the consideration of these health benefits of active travel affects the welfare-maximizing (optimal) fuel tax. For this purpose, we derive the solution for the optimal fuel tax t^{f*}, and calibrate its value. We present the full derivation of t^{f*} in Online Appendix A, where we obtain the result

$$
t^{f*} = Z^{P_{\overline{F}}} + \left[Z^{P_{\overline{M}^{in}}} + Z^C + Z^{A_{\overline{M}^{in}}} \right] \left(\frac{-\mathrm{d}M^{in}/\mathrm{d}t^f}{-\mathrm{d}F/\mathrm{d}t^f} \right) + Z^{A_{\overline{M}^{ac}}} \left(\frac{-\mathrm{d}M^{ac}/\mathrm{d}t^f}{-\mathrm{d}F/\mathrm{d}t^f} \right) \tag{12}
$$
$$
- (1 - \omega)\tilde{Z}^Q \left(\frac{-\mathrm{d}Q/\mathrm{d}t^f}{-\mathrm{d}F/\mathrm{d}t^f} \right) - wt^l \left(\frac{-\mathrm{d}L/\mathrm{d}t^f}{-\mathrm{d}F/\mathrm{d}t^f} \right).
$$

Here, we define

$$
Z^{P_{\overline{F}}} \equiv \frac{\varphi_P}{\mu_I} \, P_{\overline{F}}^f, \quad Z^{P_{\overline{M}^{in}}} \equiv \frac{\varphi_P}{\mu_I} \, P_{\overline{M}^{in}}^m, \quad Z^C \equiv \Gamma^{in} \pi_{\overline{M}^{in}}^{in} M^{in},
$$

and

$$
Z^{A_{\overline{M}^{in}}} \equiv \frac{\delta_A}{\mu_I} \left[A_{\overline{M}^{in}}^{in} + A_{\overline{M}^{in}}^{ac} \right], \quad Z^{A_{\overline{M}^{ac}}} \equiv \frac{\delta_A}{\mu_I} \, A_{\overline{M}^{ac}}^{ac}, \quad \tilde{Z}^Q \equiv \frac{\xi_Q}{\mu_I},
$$

with $\Gamma^{in} \equiv w(1 - t^l) - \psi_{T^{in}}/\psi_C$.

Equation (12) characterizes the optimal fuel tax. This tax is equal to the sum of uninternalized costs associated with fuel use. The first term in equation (12), $Z^{P_{\overline{F}}}$, is the direct pollution externality of fuel use. It is equal to the marginal cost of pollution φ_P, multiplied by the effect of additional fuel use on pollution $P_{\overline{F}}^f$, and converted to consumption units using the shadow value of income μ_I.

Next, higher fuel use is associated with more inactive miles travelled. The marginal externality cost of inactive miles travelled is captured by $Z^{P_{\overline{M}^{in}}} + Z^C + Z^{A_{\overline{M}^{in}}}$, the cost associated with increased air pollution, congestion and accidents, respectively.[11] The contribution of these costs to the magnitude of the optimal fuel tax depends on the marginal effect of a fuel tax increase on miles travelled relative to the marginal effect on fuel use. If the reduction in fuel use due to higher fuel taxes is associated with a small reduction in miles travelled $\left(\text{small } \left(-\mathrm{d}M^{in}/\mathrm{d}t^f \right) / \left(-\mathrm{d}F/\mathrm{d}t^f \right)\right)$, then only a small portion of the externality costs associated with miles travelled can (implicitly) be attributed to fuel use.

Likewise, fuel taxes may lead to changes in active travel distance, which is associated with accident externalities, with cost $Z^{A_{\overline{M}^{ac}}}$. The contribution of those costs to the optimal fuel tax then depends on the relative response of active travel to fuel taxes: $\left(-\,\mathrm{d}\overline{M}^{ac}/\mathrm{d}t^f\right)/\left(-\,\mathrm{d}F/\mathrm{d}t^f\right)$.

Our main effect of interest is $(1-\omega)\tilde{Z}^Q\left(\mathrm{d}Q/\mathrm{d}t^f\right)/\left(-\,\mathrm{d}F/\mathrm{d}t^f\right)$: the adjustment of the optimal fuel tax to the health internality. Here, $\tilde{Z}^Q$ is the marginal value of additional health, with $(1-\omega)$ the uninternalized portion; see subsubsections 'Cost of inactivity, Z^Q' and 'Rate of health internalization, ω' in the first subsection of Section 2. As can be seen from equation (12), a high value of $\tilde{Z}^Q$ does not automatically imply that once health internalities are accounted for, the optimal fuel tax is adjusted much; this is the case only if the fuel tax is an effective tool to increase health Q. Following equation (7), fuel taxes can affect health through two channels: by changing active travel M^{ac}, or through other forms of exercise O. The interpretation of the final term is similar. Fuel taxes may also affect labour supply. Even though the agent takes into account that higher labour supply increases income, she does not internalize the positive effect of increased labour on the government budget. This effect is equal to the wage, multiplied by the labour tax rate wt^l. Its contribution to the optimal fuel tax is larger when the increase in labour supply in response to higher fuel taxes is higher.

In the next section, we quantify the optimal tax t^f and the effect of considering the health benefits of active travel on it. To facilitate this quantification, we further manipulate equation (12) to

$$t^{f*} = \frac{MEC}{1+MEB} + \frac{t^l\left(p^f+t^f\right)}{1-t^l}\,\frac{\varepsilon^c_{LL}\left(1-\eta^{M^{in}I}\right)}{-\eta^{FF}} \qquad (13)$$
$$+\,\frac{t^l}{1-t^l}\left[\varepsilon_{LL}-\varepsilon^c_{LL}\left(1-\eta^{M^{in}I}\right)\right]Z^C\beta^{M^{in}}\,\frac{M^{in}}{F},$$

with ε^c_{LL} and ε_{LL} the compensated and uncompensated labour supply elasticity (and MEC, MEB defined below). Akin to Parry and Small (2005), this optimal tax is separated into three components.

The first component of equation (13) is the 'adjusted Pigouvian tax', equal to the marginal external cost associated to fuel use, corrected by the marginal excess burden of labour taxation. The marginal external cost (MEC) of fuel use is given by

$$MEC \equiv Z^{P_{\overline{F}}} + \left[Z^C + Z^{A_{\overline{M}^{in}}} + Z^{P_{\overline{M}^{in}}}\right]\beta^{M^{in}}\,\frac{M^{in}}{F} \qquad (14)$$
$$+\left[Z^{A_{\overline{M}^{ac}}} - (1-\omega)(1-\varsigma)Z^Q\right]\beta^{M^{ac}}\,\frac{M^{ac}}{F},$$

with $Z^Q \equiv (\xi_Q/\mu_I)Q_{M^{ac}}$ the marginal value of active travel through induced changes in health. This latter term is corrected by a factor $(1-\varsigma)$, which captures the unrealized share of health benefit from increased active travel due to crowding out of other exercise O:

$$\varsigma \equiv -\frac{Q_O}{Q_{M^{ac}}}\left[\frac{\mathrm{d}O/\mathrm{d}t^f}{\mathrm{d}M^{ac}/\mathrm{d}t^f}\right].$$

We use the following ratios of fuel and income price elasticities to capture the indirect benefits of fuel taxes through inactive and active distance travelled and health:[12]

$$\beta^{M^{in}} \equiv \frac{\eta^{M^{in}F}}{\eta^{FF}}, \quad \beta^{M^{ac}} \equiv \frac{\eta^{M^{ac}F}}{\eta^{FF}}, \qquad (15)$$

with η^{XF} the fuel price elasticity of $X \in \{F, M^{in}, M^{ac}\}$, and $\eta^{M^{in}I}$ the income elasticity of inactive travel. The marginal excess burden (MEB) is commonly defined as

$$MEB \equiv \frac{\left(t^l / \left(1 - t^l\right)\right) \varepsilon_{LL}}{1 - \left(t^l / \left(1 - t^l\right)\right) \varepsilon_{LL}}. \tag{16}$$

The second component of equation (13) is the 'Ramsey tax': fuel taxes raise revenues, which are used to finance government spending. This component commands a positive tax on fuel even in the absence of external costs. The third component is the 'congestion feedback': a reduction in travel due to fuel taxation reduces congestion, freeing up time for labour. This creates a positive welfare effect as long as labour is taxed at a positive rate ($t^l > 0$), and as such increases the optimal fuel tax.

3 | FUEL TAX COMPONENTS

In this section, we explain how we choose the parameter values for the quantification of the optimal fuel tax. We specify a central value and a plausible range. Table 1 summarizes the main parameter values, and Figure 1 provides a graphical representation of the social costs Z expressed in 2022 USD. We compare our parametrization of social cost to Parry and Small (2005), and state the implications for first-best policy. We base our values on the most recent available publications or official datasets.

Table 1 and Figure 1 highlight that the social cost of inactivity is one to two orders of magnitude larger than that of the second-largest social cost: congestion. While this difference is

TABLE 1 Parameter Values Used for Optimal Fuel Tax Calculation and Sensitivity Analyses

Parameter		USA		UK	
		Central value	Range	Central value	Range
Baseline fuel efficiency	$M^{in,0}/F^0$	24		28	
Fuel pollution (CO$_2$), per gallon	$Z^{P_{\overline{F}}}$	160	[74, 347.5]	150	[69, 323]
Distance pollution (air), per mile	Z^{P_M}	5.4	[1.2, 10.7]	4.3	[1.2, 9.6]
Congestion, per mile	Z^C	11.9	[3.6, 16.7]	6	[0.1, 8.7]
Accidents, inactive, per mile	$Z^{A}_{\overline{M}^{in}}$	7.6	[2.4, 21.5]	1.9	[1.2, 2.7]
Accidents, active, per mile	$Z^{A}_{\overline{M}^{ac}}$	6.3	[1.8, 17.9]	1.9	[1.4, 3.1]
Inactivity, per mile	Z^Q	825	[481.1, 1192.7]	291.3	[174.4, 815.4]
Rate of health internalization	ω	0.5	[0.3, 0.7]	0.5	[0.3, 0.7]
Fuel price elasticity	η^{FF}	−0.36	[−0.21, −0.75]	−0.48	[−0.3, −0.9]
VMT-fuel price elasticity	$\eta^{M^{in}F}$	−0.25	[−0.05, −0.3]	−0.35	[−0.2, −0.5]
Income elasticity of inactive travel	$\eta^{M^{in}I}$	0.4	[0.02, 0.6]	0.61	[0.3, 0.8]
Cross-elasticity of active travel	$\eta^{M^{ac}F}$	0.19	[0.06, 0.31]	0.19	[0.06, 0.31]
Current tax rate on gasoline[a]	t_f^0	50.2	n.a.	381.7	n.a.

Notes: [a] Includes VAT for the UK but not the USA.
All values apart from fuel efficiency are provided in 2022 USD cents using the end 2022 exchange rates 1 GBP = 1.21 USD, and either per mile or per US gallon. Baseline fuel efficiency is provided in miles travelled per US gallon. $M^{in,0}$ and F^0 denote intensive miles travelled and fuel used at the initial gasoline tax rate. Justification for the social cost values is given in the subsubsections 'External cost of carbon emissions (fuel pollution), $Z^{P_{\overline{F}}}$' to 'Rate of health internalization, ω' in the first subsection of Section 3.
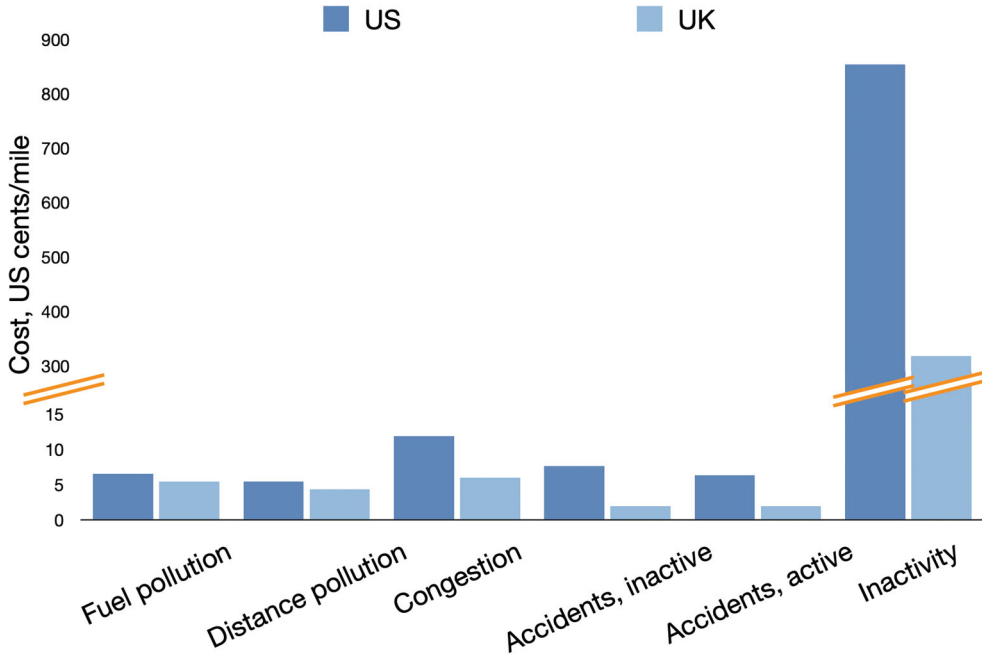
FIGURE 1 Social costs of personal car travel in US cents per mile in 2022 prices, fuel pollution in US cents per gallon; own calculations. *Notes*: Distance pollution comprises local air pollution; fuel pollution accounts for climate damages.

in part due to the difference in travel time between motorized transport and walking or cycling, it signals the potential importance of health benefits for optimal fuel taxes.

3.1 | Parametrization

3.1.1 | Baseline fuel efficiency and elasticities

- *Baseline fuel efficiency and taxes*. We set $M^{in,0}/F^0$ according to average fuel efficiency of the UK and US vehicle fleets. The US average was 24 miles per gallon in 2016 (Federal Highway Administration 2018), and the UK average was 28 miles per gallon (Department for Transport (DfT) 2018b). These values have not changed substantially since 2016, as more energy-efficient cars are counterbalanced by the greater adoption of sports utility vehicles in both countries. The difference in fuel efficiency is due to a smaller average size of the UK private vehicle fleet, and a higher proportion of diesel cars, which have a higher average fuel economy. The social cost estimates of carbon emission and air pollution per mile account for the fleet composition. Baseline (current) fuel tax levels are calculated differently for the two countries. For the UK, it is the sum of the fuel, excise and value-added taxes. For the USA, it is the average over the different federal and state taxes.

- *Fuel price elasticities*. Based on Dieler *et al.* (2015) and Litman (2013), we choose a fuel price elasticity $\eta^{FF} = -0.38$ for the USA as a central estimate. This is slightly less elastic than the UK value -0.45, where there are more public transport options. The elasticities of inactive miles travelled (VMT) with respect to fuel price $\eta^{M^{in}F}$ are calibrated at -0.25 in the USA, and -0.35 in the UK.[13]

    To our knowledge, very few direct estimates of the cross-elasticity of active travel (walking and cycling), with respect to the fuel price $\eta^{M^{ac}F}$, exist. Instead, we utilize primarily estimates

of the cross-elasticity of public transport with respect to fuel price (Litman 2019). The use of public transit requires getting to and from stations, often on foot or by an alternative active mode, and certain public transit investments have been found to be an effective way of increasing active travel (Reis *et al.* 2016). We adopt a range 0.06–0.31 for $\eta^{M^{ac}F}$, with central value 0.185 for both the USA and the UK. We conduct a further sensitivity analysis for the UK, where we increase the possible range of $\eta^{M^{ac}F}$ by an additional standard deviation (see Section B.2 of the Online Appendix).

- *Income elasticity of inactive travel*. The elasticity of inactive travel demand with respect to income, $\eta^{M^{in}I}$, is calibrated at 0.4 (0.02–0.6) for the USA, and 0.605 (0.3–0.8) in the UK. We use long-term elasticities where possible to allow for mode shifts and other behaviour changes. Further details and a full list of references on fuel price and income elasticities can be found in Section B.2 of the Online Appendix.

- *Labour supply elasticities*. For the compensated and uncompensated labour supply elasticities, ε^c_{LL} and ε_{LL}, we adopt the same values as Parry and Small (2005). These estimates fall in between the more recent estimates by Bargain *et al.* (2011) and Erosa *et al.* (2016).

3.1.2 | External cost of carbon emissions (fuel pollution), $Z^{P_{\overline{F}}}$

The external costs of fuel use are the cost of carbon emissions and associated climate damages. We derive our central estimate and range of plausible values from a large body of literature (see Section B.3 of the Online Appendix for a full overview). We multiply the value of climate change costs per tonne of CO_2 emitted by the amount of CO_2 emitted per gallon of fuel burnt, weighted by fuel type consumption in both countries (diesel/gasoline) to derive an average value of fuel pollution costs per gallon of fuel.[14] With a social cost of carbon \$158 per tCO_2 and range \$73–343 per tCO_2, the central estimate for the USA is 160 cents per gallon, with range 74–348 cents per gallon. The central estimate for the UK is 150 cents per gallon, with range 69–326 cents per gallon.

Carbon emissions per gallon are subsequently converted into per mile units by dividing by baseline fuel efficiency as presented in Table 1. Throughout, we abstract from any effects of fuel taxation on the cost of carbon.

3.1.3 | External cost of air pollution (distance pollution), $Z^{P^{in}_{M}}$

Local air pollution is caused by car tyre and break wear emissions of $PM_{2.5}$ and PM_{10}, which are approximately proportional to miles travelled, and by gases from incomplete fuel combustion processes. For the USA, estimates of the cost of air pollution per mile range from high value \$0.089 (OECD 2015) to extremely low value \$0.007 (Muller *et al.* 2011), with several values in between, for example, \$0.03 in Mashayekh *et al.* (2011), and \$0.06 in Parry *et al.* (2014). To reflect this uncertainty, we adopt values \$0.012, \$0.054 and \$0.107 as the low, central and high estimates for the USA, respectively.

For the UK, national project evaluations use a value \$0.036 per mile (Hitchcock *et al.* 2014). OECD (2015) reports a high value \$0.08 per mile travelled, while the average for a passenger car in the EU is estimated at \$0.009 per mile for gasoline and \$0.033 per mile for diesel cars. Reflecting the 55–45% split between gasoline and diesel cars in the UK, and updated costs of air pollution (Birchby *et al.* 2019), we adopt values \$0.012, \$0.043 and \$0.096 as the low, central and high estimates.

3.1.4 | External cost of congestion, Z^C

Congestion is defined as the travel delay due to crowding of roads. For the USA, we adopt the values of Inrix (2019a), which provides a central value \$0.119 per mile, and range \$0.036–0.167 per mile. In the UK, we follow Inrix (2019b) and set the per-mile congestion costs at \$0.06, with lower and upper bounds \$0.001 and \$0.087, respectively.

3.1.5 | External cost of accidents, $Z^{A_{\overline{M}^{in}}}$ and $Z^{A_{\overline{M}^{ac}}}$

There are two components to accident costs: the internalized cost of knowing and accounting for the risk of getting into a crash (see Useche *et al.* (2019) and Cornago *et al.* (2023) for empirical support); and the external cost of the increased risk of causing an accident imposed on others by travelling.[15] Hence using the full cost of accidents per mile driven would overestimate the size of the accident externality. Instead, we adopt the approach by Lemp and Kockelman (2008), who estimate the external costs of transport in the USA and assume that 50% of accident costs are external.[16]

Using accident data and cost estimates from the report by Blincoe *et al.* (2015), we find that accident costs attributable to inactive modes of transport, $Z^{A_{\overline{M}^{in}}}$, amount to \$0.076 per mile, with range \$0.024–0.215 per mile for the USA. Accident costs attributable to active modes of transport, $Z^{A_{\overline{M}^{ac}}}$, amount to \$0.063 per mile, with range \$0.018–0.179 per mile. The relatively high accident cost attributed to active transport modes is due to the proportionately higher death rate per mile travelled for active modes.

In the UK, $Z^{A_{\overline{M}^{in}}}$ amounts to \$0.019 per mile, with range \$0.012–0.027 per mile. Accident costs attributable to active modes of transport, $Z^{A_{\overline{M}^{ac}}}$, amount to \$0.019 per mile as well, with range \$0.014–0.027 per mile (DfT 2018a).

3.1.6 | Cost of inactivity, Z^Q

The health benefits of exercise are well known to be the most substantial health-related impact of active travel, dwarfing air pollution or accident effects. For example, De Hartog *et al.* (2010) estimate, for the Netherlands, that people shifting from car to bicycle for short trips lose 7 days of life due to traffic accidents, and 21 days of life due to air pollution, but gain 8 months of life due to physical activity. This relationship is confirmed for Global North countries, where road safety is much better compared to many Global South cities (Woodcock *et al.* 2017; Garcia *et al.* 2021). Our analysis requires translating such benefits into monetary values for the USA and the UK.

First, health benefits comprise all mortality- and morbidity-reducing effects. Second, there may be productivity benefits, due to a reduction in absenteeism (taking sick leave), and presenteeism (being at work but having lower productivity due to illness). Third, better health reduces (public) health system costs. Depending on the characteristics of the health system (and the extent to which the individual bears the cost of absenteeism), the costs can be labelled as private or external. In the remainder of the analysis, we focus on the value of unrealized private health benefits only, as they are much larger than the direct productivity gains to the economy.

In order to calculate the marginal value of the private health benefits from physical activity for the UK and the USA, we used the Health Economic Assessment Tool (HEAT) developed by the World Health Organization (Kahlmeier *et al.* 2017). HEAT calculates the value of the changes in mortality arising from a specified change in walking and cycling for travel purposes.[17]

Further details regarding the HEAT model, inputs and corresponding data sources can be found in Section B.4 of the Online Appendix.

We convert the HEAT output to an estimate of the health benefit per mile of active travel. We obtained a central Z^Q value $8.25 per mile for the USA, with range $4.81–11.93 per mile. For the UK, this value is $2.91 per mile, with range $1.74–8.15 per mile. The UK–USA discrepancy has two sources: higher value of statistical life estimates for the USA, and higher US baseline mortality rates for younger members of the population.

3.1.7 | Rate of health internalization, ω

The extent to which individuals internalize the health benefits of exercise and active travel is captured by the parameter ω. Estimating internalities is inherently empirically complex, and as a consequence there are relatively few well-identified empirical estimates regarding the size of the internality. Examples of studies that are informative about the size of the internality are Haase *et al.* (2004), Coups *et al.* (2008) and Bennett *et al.* (2009), who find that individuals underestimate the probability of disease associated with physical inactivity.

To obtain a proxy for ω, we consider three types of studies: first, stated preference surveys of cyclists/pedestrians and drivers on their reasoning for choosing that particular mode of transport (see Table 2); second, surveys asking the general population about their knowledge of the health benefits of physical activity (see Table 3); and third, results from experiments and policies aimed at incentivizing health behaviour (see Table 4). While they find substantial variation in the extent to which individuals do, or do not, internalize health benefits of physical activities, these studies provide overwhelming evidence that this internalization is incomplete, that is, $\omega < 1$. In Section B.5 of the Online Appendix, we summarize the details of the studies listed in Tables 2–4. Based on this exercise, we choose a central value 0.5 and range 0.3–0.7 for ω, to be transparent about the broad range of estimates and their high uncertainty.

3.1.8 | Crowding out of other exercise, ς

The empirical literature shows little to no effect of fuel taxes on other forms of exercise O. Specifically, the review by Wanner *et al.* (2012) finds no systematic evidence in favour of crowding in or out, and more recent studies generally suggest that exercise through active travel is additive, rather than crowding out other forms of exercise (Dons *et al.* 2018; Foley *et al.* 2015; Laeremans *et al.* 2017; Martin *et al.* 2015; Panik *et al.* 2019). Based on this, we set $\varsigma = 0$, implying that active travel is the only channel through which fuel taxation affects health. While the evidence in Martin *et al.* (2015) could also justify low positive values of ς, the sensitivity analysis for the rate

TABLE 2 Studies of Stated Reasons for Walking and Cycling Regularly

ω	Question	Source
0.52	Factors affecting cycling	Börjesson and Eliasson (2012)
0.82	Factors affecting cycling to work	Fernández-Heredia *et al.* (2014)
0.42–0.94	Factors affecting cycling to work	De Souza *et al.* (2014)
0.68	Factors affecting cycling	De Geus *et al.* (2008)
0.38	Factors affecting cycling	Useche *et al.* (2019)

TABLE 3   Studies of Health Awareness Used for the Calculation of the Rate of Health Internalization

ω	Question	Source
0.4–0.6	Link with heart disease	Haase *et al.* (2004)
0.6	Link with cancer	Oh *et al.* (2010)
0.15	Link with cancer	Coups *et al.* (2008)
0.3	Link with cancer	Keighley *et al.* (2004)
0.5	Link with diabetes	San Diego and Merz (2020)
0.2–0.8	Probabilities of developing diseases	Fredriksson *et al.* (2018)
0.5	Knowledge of weekly guidelines	Morrow Jr *et al.* (2004)
0.33	Knowledge of weekly guidelines	Bennett *et al.* (2009)
0.01	Knowledge of weekly guidelines	Kay *et al.* (2014)
0.44	How much movement is needed	Fredriksson *et al.* (2018)
0.22	Knowledge of weekly guidelines	Piercy *et al.* (2020)
0.5	Knowledge of own activity levels	Ronda *et al.* (2001)
0.4–0.6	Knowledge of own activity levels	Godino *et al.* (2014)

TABLE 4   Studies of Behaviour Bias Used for the Calculation of the Rate of Health Internalization

ω	Question	Source
–	Overprojection of gym attendance	DellaVigna and Malmendier (2006)
–	Overprojection of gym attendance	Acland and Levy (2015)
0.57–0.7	Response to incentive & commitment	Charness and Gneezy (2009)
0.65	Response to incentive & commitment	Royer *et al.* (2015)
1	Response to commitment	Carrera *et al.* (2018)

of health internalization ω also applies for varying ς. The reason is that an increase in ς has an effect on the optimal tax equivalent to an increase in ω (see equation (14)).

3.2 | Social cost comparison to Parry and Small (2005)

Figure 2 specifies the parametrization of social costs in Parry and Small (2005) in US cents per mile travelled and updated to 2022 prices. A comparison of Figures 1 and 2 reveals that in particular, the social cost of carbon, and therefore the fuel pollution component of the fuel tax, has increased in value. While it was a minor component of the optimal fuel tax in Parry and Small (2005), it contributes significantly to the tax in our parametrization. In addition, while Parry and Small (2005) estimated UK congestion costs at twice the value of the US congestion cost, our parametrization based on Inrix (2019a,b) reverses these values. Going beyond Parry and Small (2005), we show that the social cost of inactivity is at least an order of magnitude larger than all the passenger transport externalities (see Table 1 and Figure 1).
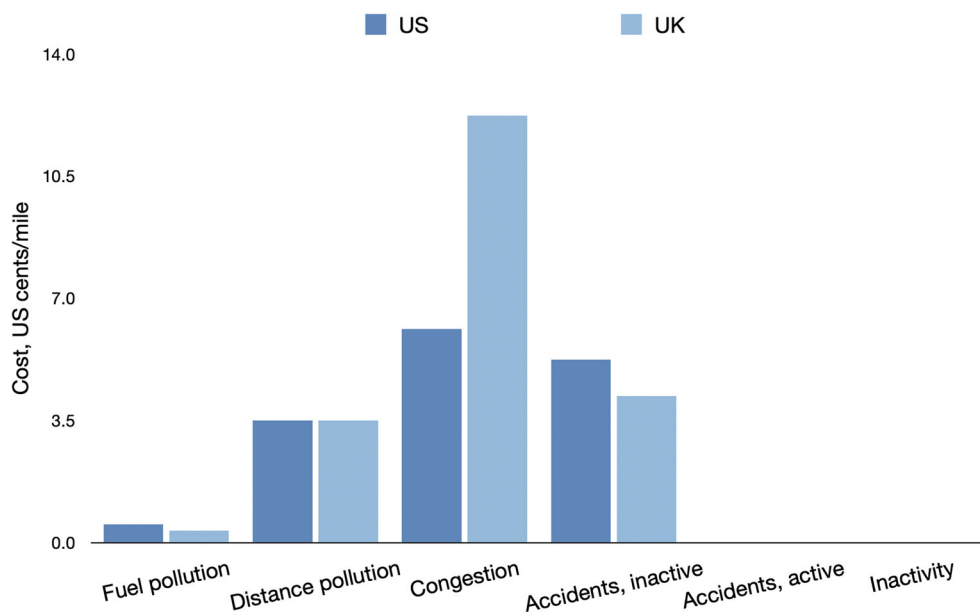
FIGURE 2 Social costs of personal car travel in US cents per mile in 2022 prices; Parry and Small (2005) calculations.

3.3 | Implications for first-best policy

Table 1 and Figure 1 permit a quantitative conclusion about first-best policy. In a first-best world, there exist appropriate policy instruments to address all market failures, as well as non-distortive (e.g. lump-sum) taxes to generate government revenues. One can verify that under these assumptions, the optimal carbon (fuel) tax is equal to the cost of fuel pollution $Z^{P_{\overline{F}}}$. Similarly, the socially optimal level of the price instruments for all other externalities (and internality, by analogy, that is paying individuals for active travel and other exercise) are at their respective Pigouvian levels. For the internality, this Pigouvian level is equal to the social cost of inactivity, multiplied by the uninternalized share $(1 - \omega)$. On a per-mile basis, this means that a first-best subsidy paid to individuals for incentivizing active travel modes would be at a much higher level than any of the tax levels for the externalities, or indeed, the sum of all other externality taxes.[18]

4 | QUANTITATIVE RESULTS

4.1 | Second-best optimal fuel tax rates

We use equations (13)–(15) and the parameter estimates provided in Table 1 to calculate the optimal fuel tax.[19] An increase in fuel taxation will reduce fuel use and inactive miles travelled, which will in turn affect the optimal tax through equation (14). To account for those effects, we follow Parry and Small (2005), and endogenize F, M^{in} and M^{ac} in our numerical solution (see Section B.6 of the Online Appendix).

We find an optimal fuel tax $6.31 per gallon of fuel in the UK, which is significantly higher than the current fuel tax.[20] In the USA, the optimal fuel tax amounts to $12.92 per gallon of fuel, which is more than twenty times the current (population-weighted) average fuel tax across the fifty states. Table 5 lists the optimal tax levels and their decomposition. This decomposition shows that costs associated with physical inactivity, congestion and fuel pollution

T A B L E 5   Central Calculations of the Optimal Fuel Tax Rate

Cost, USD cents per gallon	USA	UK
Fuel efficiency, M^{in}/F	28.4	29.3
Adjusted Pigouvian tax:		
Pollution, fuel-related, $Z^{P_{\overline{F}}}$	160	150
Pollution, distance-related, $Z^{P_{\overline{M}^{in}}} \beta^{M^{in}} M^{in}/F$	107	92
Congestion, $Z^{C} \beta^{M^{in}} M^{in}/F$	235	128
Accidents, inactive, $Z^{A_{\overline{M}^{in}}} \beta^{M^{in}} M^{in}/F$	150	41
Accidents, active, $Z^{A_{\overline{M}^{ac}}} \beta^{M^{ac}} M^{ac}/F$	−5	−2
Physical inactivity, $(1-\omega)Z^{Q} \beta^{M^{ac}} M^{ac}/F$	305	159
Adjustment to MEC for excess burden	−89	−51
Ramsey tax	430	108
Congestion feedback	−1	4
Optimal fuel tax rate with physical activity, t_1^{f*}	1292	631
Optimal fuel tax rate without physical activity	899	456
Naive fuel tax rate	758	492
Parry and Small optimal tax rate	177	235
Actual (2023) tax rate	50	382

Notes: Based on equations (13) and (14), the optimal rate is the adjusted Pigouvian tax, adjustments for the excess burden, the Ramsey tax, and the congestion feedback, combined. The naive rate is given by MEC_F (excluding the health internality) from equation (14) with $M^{in}/F = M^{in,0}/F^0$, $\beta^{M^{in}} = 1$ and $\beta^{M^{ac}} = -1$.

are the main contributors to the adjusted Pigouvian tax, albeit it is somewhat reduced due to the compensation for the marginal excess burden of labour taxation. Ramsey taxes are substantial, especially in the USA; the congestion feedback does not influence the optimal fuel tax rate significantly.

Including physical activity increases the UK fuel tax by 38%, and the US fuel tax by 44%. Although this increase is significantly smaller than the pure per-mile social cost of physical inactivity, the inactivity component is still the largest contributor to the MEC part of the tax. Even without including physical activity, we obtain an optimal fuel tax that is two to five times the tax computed by Parry and Small (2005) (adjusted to 2022 values), which is due to much higher current values on social cost of carbon predominantly.

Consistent with both Parry and Small (2005) and Santos (2017), we find that for the USA, the second-largest externality component of the second-best optimal fuel tax is congestion. For the UK, the contribution of fuel pollution (CO_2) exceeds the contribution of congestion. This is despite the fact that London, whose congestion impacts are 28 times higher than the EU average (Cookson 2016), greatly influences the congestion costs for the UK.

Fuel pollution is a substantial contributor to optimal fuel taxes as the social cost of carbon has increased significantly over the last two decades, reflecting increasing estimated climate damages (see the second subsubsection of the first subsection of Section 3). Contrary to Parry and Small (2005), air pollution costs for both countries contribute less to the fuel tax than carbon emissions. This is due primarily to increasingly stringent fuel air pollutant emissions standards.

In the USA, traffic accidents are associated with a far higher per-mile cost, even though the rates of traffic injuries are very similar in both countries. This is explained by a higher nominal value that is attached to human life in the USA,[21] and leads to a fuel tax component due to the inactive travel accident externality of inactive travel that is considerably higher in the USA than in the UK.

In addition to the second-best optimal tax, we compute the 'naive' tax rate, which is based on three assumptions. First, in absolute terms, all β terms are equal to 1; that is, both active and inactive miles travelled are equally responsive to fuel taxation as fuel use. Second, the feedback of tax-induced changes in fuel use and miles travelled to the tax rate is ignored. Third, interactions of the fuel tax with the labour tax, as well as the Ramsey component, are abstracted from. Instead, the only relevant components to the tax are the external effects of car use. The naive rate thus mimics common practice in transport and cost–benefit analysis evaluations.[22] In our central calculations, $\beta^{M^{in}} = 0.69$ (USA) or $\beta^{M^{in}} = 0.73$ (UK), and $\beta^{M^{ac}} = -0.51$ (USA) or $\beta^{M^{ac}} = -0.39$ (UK). Values $\beta^{M^{in}} < 1$ are due to a low fuel price elasticity of inactive travel, $\eta^{M^{in}F}$. This reflects the very inelastic demand for VMT, meaning that most reduction in fuel use comes from increases in fuel economy of driving and the vehicle fleet, not reductions in distances covered in cars. Thus mileage-related externalities (air pollution, congestion and accidents) are all inflated in the naive fuel tax calculation.

Treating fuel efficiency, fuel consumption and distance travelled as endogenous, rather than exogenous, in the second-best optimal fuel tax calculation causes fuel consumption to fall by 42.5% and 15.6% in the USA and UK, respectively. Inactive travel M^{in} falls slightly less, by 32% in the USA, and this is more than compensated for by an increase of 33% in active travel. In the UK, inactive travel also falls by less than fuel consumption, by 11.6%. However, as active travel increases by only 6.7%, total travel in the UK falls. The change is more drastic in the USA because of the low fuel efficiency of motor vehicles, and higher contingent valuation of people's time and lives, resulting in a bigger Pigouvian tax. In the UK, the current tax level is much closer to the optimal level. The fuel efficiency of motor vehicles in the UK therefore does not change much in response to moving to the optimal level, and the endogenous solution does not change the optimum level significantly.

4.2 | Welfare effects

The welfare gain of implementing the second-best optimal fuel tax is presented in Table 6. We use the current tax rate as a benchmark, and consider a fuel tax that does, and does not, take into account active travel benefits. All gains are expressed as a share of current fuel expenditure. The analytical derivation of the welfare benefit is discussed in Section B.7 of the Online Appendix. The welfare gain of implementing the second-best optimal tax that accounts for the health internality is 115% for the USA, but only 4% for the UK. Contrary to the UK, in the USA, any increase in the fuel tax yields significant welfare improvements. This difference is primarily due to the very low current US fuel tax, while the UK fuel tax is already closer to the optimal rate.

Additionally, we present the changes in active and inactive miles travelled following the change in the fuel tax. In the UK, the small change in the fuel tax results in relatively small changes in distance travelled. In the USA, however, the fuel price changes are large, and induce a substantial shift from inactive to active miles.[23]

Finally, we compute the effect of the tax increase on mortality through increased active travel using the HEAT tool, described in the subsubsection 'Cost of inactivity, Z^Q' of the first subsection of Section 3, and Section B.4 of the Online Appendix. Increases in active travel save lives only by improving health from increasing exercise (see also Section B.8 of the Online Appendix).[24] Due to a larger tax increase and larger population size, lives saved are greatest in

T A B L E 6 Welfare Effects of Fuel Taxation

Fuel tax type	Rate (cents per gallon)	Welfare change	M^{in} change	M^{ac} change	Annual lives	Lives per $ per 100,000 population
USA						
t^{f*}	1292	114.68%	−31.95%	32.96%	6262 saved	0.24
t^{f}, excl. health	899	63.98%	−26.91%	26.11%	4960 saved	0.28
UK						
t^{f*}	631	3.93%	−11.61%	6.74%	280 saved	0.25
t^{f}, excl. health	456	0.40%	−4.12%	2.25%	93 saved	0.28

Notes: Welfare effects calculated relative to the current fuel tax rate, expressed as a percentage of current fuel expenditure (approximately $1800 in the USA, and $1500 per person per year in the UK, according to household expenditure surveys (US Bureau of Labor Statistics 2019; Office for National Statistics 2019). The current US fuel tax rate is $0.50 per gallon, and the current UK fuel tax rate is $3.82 per gallon. The last column reports the number of lives saved due to increased active travel per a one dollar change in the tax, per 100,000 population.

the USA: setting the fuel tax at its optimal level saves 6262 lives each year. The difference of 0.24 versus 0.25 lives saved per unit tax change, per a unit of 100,000 population in the USA and UK, respectively, is negligible, largely due to the cross-elasticity of active travel. The gain is achieved by increasing active travel by 0.03 and 0.11 miles per day for the UK and the USA, respectively.

4.3 | Sensitivity analysis

In Figure 3, we illustrate the sensitivity of the second-best optimal fuel tax with respect to the elasticities and rate of health internalization, keeping all other parameters at their central values (denoted X in the graphs). Figure B.2 in the Online Appendix presents additional results where we vary the cost parameters Z. Importantly, as the potential rate crowding out $(1 - \varsigma)$ is directly multiplicative with the rate of internalization $(1 - \omega)$ in our model (see equation (14)), we do not carry out sensitivity analysis around the degree of crowding out. If a value of crowding out greater than zero should be tested (see the final subsubsection of the first subsection of Section 3), this is equivalent to greater internalization. Further details and figures can be found in Section B.9 of the Online Appendix.

For both the UK and the USA, the fuel tax is most sensitive to η^{FF}, the fuel price elasticity. This elasticity affects the optimal fuel tax directly through $\beta^{M^{in}}$ and $\beta^{M^{ac}}$ in the MEC component (see equation (14)), and indirectly by governing the response of fuel use F to the introduction of the fuel tax. Jointly, this results in a positive relationship between the fuel price elasticity and the optimal fuel tax, as shown in Figure 3. Using the upper or lower bound of the fuel price elasticity, as opposed to the central value, can either increase or decrease the fuel tax by as much as 75%. Varying the cross-elasticity of active travel $\eta^{M^{ac}F}$ has a similar, though smaller, effect. Conversely, the net effect of the elasticity of inactive travel (VMT) with respect to the fuel prices, $\eta^{M^{in}F}$, on the fuel tax is negative. Using the upper bound instead of the central value for $\eta^{M^{in}F}$ reduces the fuel tax by up to 70%; using the lower bound instead has a noticeably smaller effect. The income elasticity of inactive travel affects the fuel tax, especially for the USA. This effect materializes via the Ramsey tax component, which is comparatively large for the USA to begin with (see Table 5). The fuel tax is relatively insensitive to the rate of health internalization.
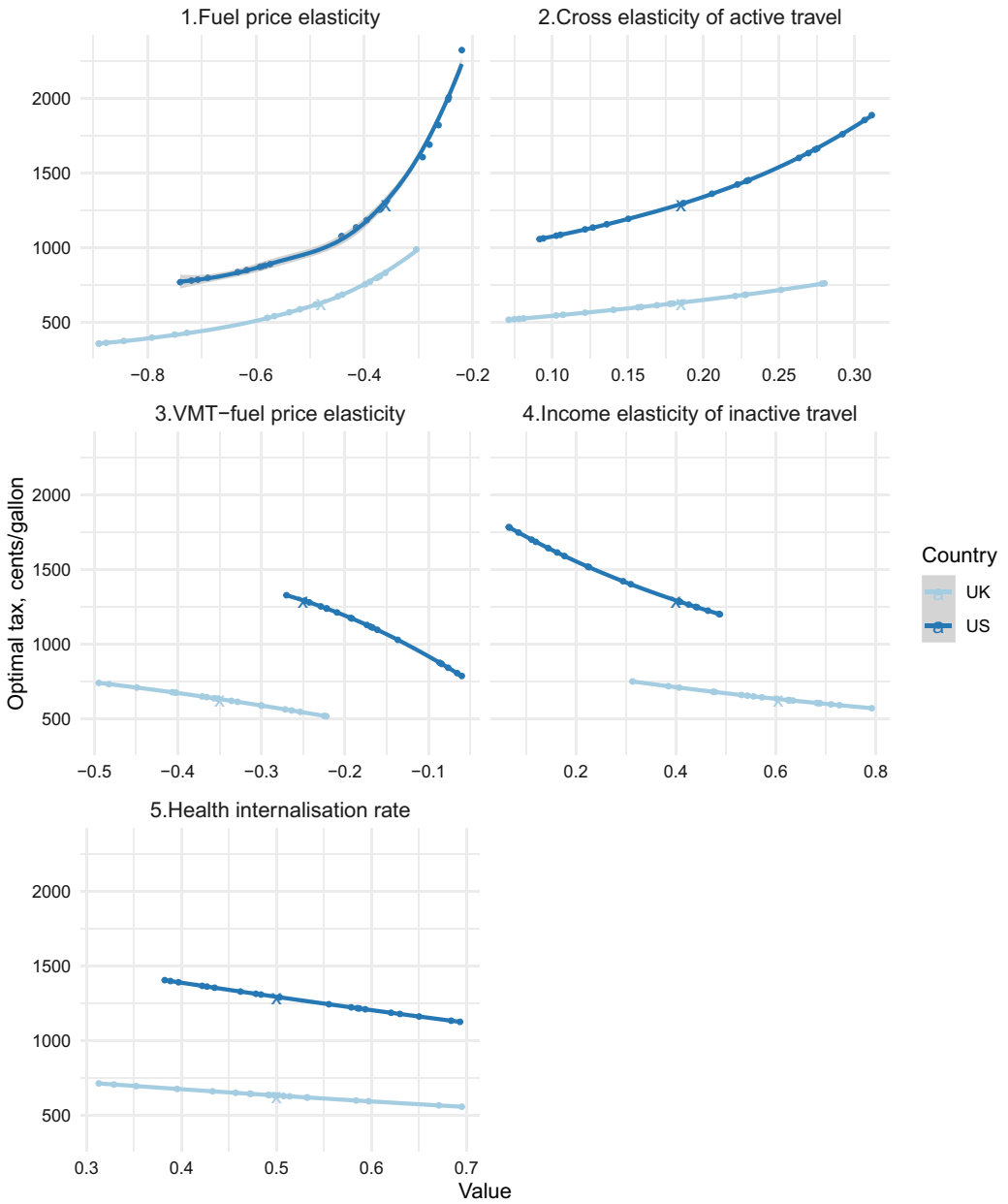
FIGURE 3 Sensitivity of the fuel tax to relevant elasticities and the rate of health internalization.

The fuel tax in both the USA and the UK increases approximately linearly with all social cost parameters and the cost of inactivity (i.e. $Z^{P_{\overline{F}}}$, $Z^{A_{\overline{M}}^{in}}$, $Z^{A_{\overline{M}}^{ac}}$, $Z^{P_{\overline{M}}^{in}}$, Z^{C} and Z^{Q}), reacting most strongly to $Z^{P_{\overline{F}}}$, fuel pollution, that is, the social cost of carbon. For more details, see Section B.9 of the Online Appendix.

Figure 4 presents the results of a Latin hypercube parameter sensitivity analysis using the *pse* package in R (Chalom and de Prado 2015). We varied parameters for external costs and the elasticities using 20 values drawn at random from a uniform distribution, and allowed fuel use and mileage to be generated endogenously. The function was run 200 times, with 50 bootstrap
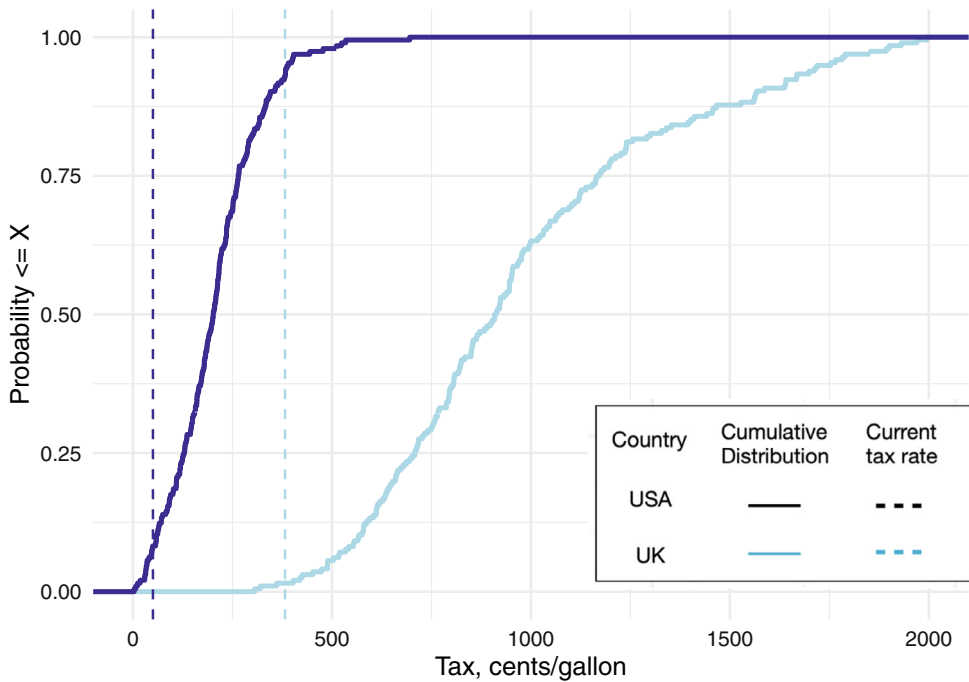
FIGURE 4 Cumulative distribution function of optimal fuel tax values for both the USA and the UK.

replicates. For the USA, the optimal fuel tax is less than 0.01% likely to be below the current 50 cents per gallon. For the UK, the optimal fuel tax is below the current fuel tax of 382 cents per gallon with a 2% probability.

5 | DISCUSSION

This paper shows that it may be costly to societies not to reap the health benefits from choosing travel modes that lead to more physical activity. Including these benefits in an analysis of optimal fuel taxation demonstrates that the optimal fuel tax increases significantly, although to a lesser extent than one might expect based on assessments of the benefits of active travel measured in public health. Here, we discuss how our findings align with current thought on optimal transport policy, and subsequently discuss limitations of our approach.

Experts on urban transport policy have long argued for a mix of 'push' and 'pull' factors to reduce efficiently societal costs from car use (Pucher and Buehler 2007; Creutzig and He 2009). 'Push measures' discourage car use and include fuel or road pricing and parking fees; 'pull measures' encourage uptake of other forms of transport by making them more attractive. Our study considers explicitly only a fuel tax, but a number of conclusions about other policy instruments may be drawn.

First, both active and inactive miles travelled are relatively inelastic to the fuel tax. This not only affects the second-best optimal level, but also implies that a fuel tax on its own is not an ideal instrument for reducing mileage-related externalities.[25] Parry and Small (2005) suggest that using a VMT tax for all externalities other than carbon emissions would be preferable. Indeed, there is renewed academic interest in alternative road pricing mechanisms, such as congestion or GPS-based charging, cordon pricing, optimal toll pricing or real-time road pricing (see Guo *et al.* 2017; Cramton *et al.* 2018; Bjertnæs 2019; Arlinghaus *et al.* 2023). However,

ideal externality-correcting mechanisms have not been implemented widely, and most plans to introduce congestion charging are advancing slowly. The benefit of the fuel tax over a congestion charge is that a fuel tax can, at least indirectly, address all large externalities caused by driving concurrently, and be used to generate a broader revenue base for the government (Rietveld and van Woudenberg 2005). It also encourages improvements in the fuel economy of the fleet by encouraging the purchase of more efficient new cars, and in some cases, more fuel-efficient driving patterns (Dhondt *et al.* 2013; Bjertnæs 2019).

Second, our study has further implications for policies encouraging active transport. Akin to congestion charges, a straightforward public finance approach could involve a direct subsidy for active modes of travel (Wardman *et al.* 2007; Employee Benefits Scheme 2020) or indirect subsidies in the form of suitable cycling and washing facilities for employees that would improve the comfort of cycling relative to driving (Useche *et al.* 2019).

Appropriate active travel infrastructure may, however, be a more important 'pull' measure to make walking and cycling attractive. Car-free city centres, bicycle lane networks and improvements in public transport provision will increase the mode share of active travel (Pucher and Buehler 2007; Buehler and Pucher 2012; Gössling 2013; Kraus and Koch 2021). For example, in a study of 167 European cities, Mueller *et al.* (2018) find that increasing bicycle lane infrastructure in urban areas up to 315 km per 100,000 inhabitants increases the mode share of cycling up to 24.7%. Further, the lack of appropriate street lighting, and badly maintained roads and cycle lanes, have all been identified as factors impeding active commuting (Yang *et al.* 2017; Federal Highway Administration 2019). Investing in cycling infrastructure has not been considered a significant investment strategy until recently, and infrastructure cost assessments have not been including it in their analyses (van Essen *et al.* 2011). Due to the large differences in the effectiveness of cycling infrastructure investments, or alternatively soft, information-based measures, it is difficult to estimate their effectiveness relative to a fuel tax change.

Our optimal tax result signals that the extent to which an increase in fuel taxes is welfare enhancing is constrained by the presence of viable low-carbon alternatives (high β terms). This result was also demonstrated by Martens (2016), and (in part) justifies the grievances of the Gilets Jaunes in France and similar movements. Conversely, this implies that improvements in infrastructure designed for active travel and public transport as discussed above could further support increased fuel taxation.[26] While greater willingness of citizens to switch to active travel in particular would manifest itself in a higher responsiveness of active travel to fuel taxation, $\eta^{M^{ac}F}$, it would likely also result in higher active miles travelled M^{ac}, lower fuel use F, and higher (absolute) elasticities $\eta^{M^{in}F}$. From equations (13)–(15), all of these effects would justify higher fuel taxes.

A full characterization of the 'pull effect', would include the public good characteristics of infrastructure—everyone benefits from safer and more comfortable cycling infrastructure—which will lead individuals to derive more utility from active travel and therefore 'pull' them into these modes. This channel is not considered in our model and yet could lead to either higher *or lower* second-best optimal fuel taxes (Siegmeier 2016), once infrastructure changes are seen as an additional policy instrument rather than an exogenous change in elasticities (similar to Bovenberg and van der Ploeg 1994). In other words, as improved public transport infrastructure moves active travel decisions closer to optimal decisions, it may reduce the need for and value of higher fuel taxes as captured through Z^Q. We believe that this is a crucial area for further work.

We note a number of limitations to our study: health manifests itself only as an internality within the utility function, though there is evidence that health–labour feedback loops might exist, specifically between physical activity and productivity (Proper *et al.* 2006), and presenteeism (Pereira *et al.* 2015). We abstract from these effects in our analysis; if anything, including such effects would strengthen the case for including health benefits from active travel in transport policy assessments. Also, our model is not designed for an accurate assessment of the potential

of subsidizing non-travel-related physical exercise, in part because it is not straightforward to include a time cost of such 'other exercise.

Furthermore, our estimate of the degree of internalization is arguably crude: that levels of inactivity vary between countries merits further empirical studies of the rate of internalization and its determinants. It is, for instance, conceivable that the rate of internalization may be affected by (tax) policy, transport infrastructure and geography. There also exists evidence that in particular, interventions that support planning and commitment for exercise are effective in increasing exercise levels (Charness and Gneezy 2009; Royer *et al.* 2015). While such interventions would arguably reduce the internality, as long as they do not lead to full internalization, a rationale for including health benefits in the optimal fuel tax computation remains. This said, we would like to stress that the model framework is ignorant about the determinants of the rate of internalization. Insofar as this is influenced by alternative interventions such as informational campaigns or access to commitment devices, the optimal fuel tax is affected. This could include health policy interventions to generally increase levels of exercise (say, mandated tracking of total exercise through step counters and appropriate fiscal incentives by health insurance companies). As such, our analysis does not rule out the relevance of alternative policy interventions; rather, it highlights the implications of any remaining internalities for optimal fuel taxation.

Further, we do not consider distributional concerns of the policy instruments, especially related to income, location or race (see Bento *et al.* 2009; Tessum *et al.* 2019; Creutzig *et al.* 2020). In the context of fuel taxation with health internalities, at least five types of distributional effects are at play: first, the fact that relative spending on transport fuels differs with income (Grainger and Kolstad 2010; Sterner 2012); second, the empirical observation that fuel price elasticities depend on household income levels and that this relationship also depends on the country analysed (Wang and Chen 2014; Mattioli *et al.* 2018); third, the decreasing incidence of obesity, sedentariness and related diseases such as diabetes and cardiovascular diseases with increasing income (Ameye and Swinnen 2019; Eurostat 2022; Levine 2011); fourth, the fact that transport and commuting times might also vary by income (Dargay and Van Ommeren 2005; Plaut 2006); fifth, heterogeneity in extent of internalization across income levels (Allcott *et al.* (2019a), for instance, find greater behavioural bias for low-income households).

In sum, the distributional effects of an increased fuel tax (at least in terms of utility and health outcomes) can go both ways, and the resulting overall effect is not clear *ex ante*. As the relative spending on transport fuels differs with income, some households will be hit harder by the tax. This will not be mitigated by their demand reactions, as lower-income households in the UK and the USA appear to have smaller elasticities, which might exacerbate the regressive effect of a price increase in terms of disposable income. In addition, households with longer commuting times would be affected disproportionately by the tax. On the contrary, when looking at health and utility outcomes, both in the UK and the USA, lower income quintiles show a higher prevalence of obesity and related diseases such as diabetes, so could benefit more from the reduction in negative health outcomes. As the main focus of our paper is on how the inclusion of a health internality changes the optimal fuel tax, and because heterogeneity in a model of optimal fuel taxation without health internalities has already been explored in Bento *et al.* (2009), modelling heterogeneity explicitly goes beyond the scope of this paper. However, future research should examine the trade-off between harming poorer households by fuel taxes and related instruments, and high health benefits from generating more physical activity, as pioneered by Allcott *et al.* (2019a).

Further, we do not model explicitly pre-existing regulation such as fuel efficiency standards, which are an important element in current transport regulation (Greene 2011). Assuming separable utility in leisure and the social costs contributes to analytical tractability and allows for direct comparison to Parry and Small (2005), yet is also restrictive and therefore a significant limitation. Finally, we combine public transport with walking and cycling as an active mode of

transport, and so omit recent trends in urban travel such as ride-hailing and sharing apps such as Uber, or the increasing popularity of e-scooters.

6 | CONCLUSION

This paper shows that optimal fuel tax rates increase significantly if the health benefits from increased active travel, such as reduced rates of diabetes, cardiovascular diseases, dementia and depression are not fully internalized by citizens. Building on the established framework developed by Parry and Small (2005), we present an assessment of optimal fuel taxation when an internality through physical inactivity is also considered in the tax design.

We confirm the main conclusion of a large body of research in public health that, per mile travelled, the social costs of inactivity dominate the social costs from transport externalities by an order of magnitude. We examine how this fact changes the appropriate second-best optimal fuel tax, which targets active travel health benefits only indirectly. We conclude that the second-best optimal fuel tax increases from $4.56 to $6.31 per gallon in the UK, and from $8.99 to $12.92 per gallon in the USA. Due to the inelastic demand for vehicle miles travelled and low cross-elasticity of active travel, the tax rate increases by less than the value of the per-mile internality.

In contrast to Parry and Small (2005), we find that the fuel tax rate in the UK is too low when the health benefits from active travel are accounted for. We confirm that even without these benefits, in the USA, fuel is significantly undertaxed: it significantly exceeds the current average fuel tax rate across the 50 states, as well as the previous estimate by Parry and Small (2005). Over the past two decades, the economic costs of damage to human health (air pollution and accident externalities) have risen significantly; more time is being spent in congestion on US roads, and the value of time has also risen faster than inflation. Further, the social cost of carbon estimates that we derived from the literature ($73–343 per tCO_2) are now several times higher than the values Parry and Small used in 2005 ($11.9 per tCO_2, $0.5–47.3 per tCO_2 in 2022 prices). Whereas pollution linked to carbon emissions once contributed the least to their Pigouvian tax component, it is the largest component after congestion and inactivity according to our estimates.

The main contribution of our analysis is that the significant health benefits from active travel imply that fuel taxes should be increased—in absence of introducing more targeted policies. Fuel taxes are an established instrument for addressing all social costs of transport, but beyond our specific formal analysis demonstrating the importance of health benefits for overall transport policy, we remain neutral about how much of the desirable changes in mobility patterns should come from fuel price increases (and how much from specifically targeted, local policies) in actual policymaking. Rather, we see this as central for future research. The modest relevance of a fuel tax on an individual's decision to walk or cycle indicates that the fuel tax may not be the most appropriate policy instrument to encourage active travel.

The last point is reinforced by noting that optimal US fuel tax can be deemed politically unrealistic, especially due to concerns of car-dependency of low-income households. Targeted measures to increase the relative price of car travel, such as congestion charges, and measures aimed at reducing barriers to other modes of transport, such as building better active travel infrastructure, will permit societies to reap the high health benefits. Congestion charging would be effective in both the UK and the USA for this purpose (Cramton *et al.* 2018). The USA specifically would benefit from more public transit infrastructure that would result in more active trips as people reach the transit stops by foot or bicycle. The UK, characterized by denser cities, would especially benefit from improved urban infrastructure for walking and cycling. Nonetheless, without an associated change in the price signal in the form of a fuel tax rise or congestion charge,

infrastructure investment is unlikely to lead to sufficient changes in travel decisions on its own (Pucher *et al.* 2010; Buehler *et al.* 2017). Different policies at multiple levels are needed to realize meaningful change in passenger transport.

ENDNOTES

[1] 'Current' values are correct as at January 2023.

[2] Sensitivity analysis shows that the second-best optimal tax varies significantly within the range of realistic parameter values, from $6 per gallon to $23 per gallon for the USA, and from $4.75 per gallon to $11.25 per gallon for the UK.

[3] Chetty (2015), Bhargava and Loewenstein (2015), Allcott and Sunstein (2015), and Allcott *et al.* (2019b) all provide more extensive discussions of why regulating internalities is desirable, arguing that the complexity of choices that people face, and large internal costs in, for example, health and energy efficiency, warrant the greater use of behavioural economics in regulation.

[4] Accounting for the physical health benefits from active travel increases further the gap between actual and optimal fuel taxes. It may be argued that, especially in the US case, realizing such an increase is politically unrealistic in the foreseeable future. Still, our result indicates that current fuel tax rates are further below their desirable levels than previously thought, which implies that fuel tax increases have greater benefits.

[5] Equation (1) models the utility from health and leisure as separable. As a consequence, any improvement in health will leave the labour–leisure trade-off unaffected.

[6] Even though large passenger volumes can congest public transport, this does not typically increase travel time. Bicycle paths do not generally get congested to the extent that travel time increases. Still, congestion on roads may increase travel time of buses, for example. In Section C.1 of the Online Appendix, we present an extension accounting for such effects.

[7] Substantial emissions of particulate matter from transport are due to tyre, brake and road abrasion, rather than fuel consumption. Fuel emissions contribute mostly to noxious gas emissions such as NO_x and ozone.

[8] Note that any adverse effect of pollution on health is already subsumed in $\varphi(P)$.

[9] Additionally, publicly financed healthcare systems and moral hazard in health insurance imply that individuals may not bear the full cost of unhealthy decisions.

[10] We take p^o as exogenous, and thus abstract from any effects of fuel taxes on cost incurred for other exercise. Section C.2 of the Online Appendix discusses an extension where other exercise requires travel (e.g. to reach a gym).

[11] The term Γ^{in} in Z^C captures the notion that congestion is costly for two reasons: it creates a direct disutility (see equation (1)) and reduces time available to allocate to labour (see equation (10)).

[12] The β terms are equal to the response of miles travelled to fuel taxes relative to the response in fuel taxes. As such, they capture the relative effectiveness of fuel taxes in inducing changes in miles travelled, both active and inactive.

[13] The lower fuel price elasticity of miles travelled as compared to the fuel price elasticity of fuel use is explained by the fact that the most significant response of an increase in fuel price is typically not reduction in the distance travelled by people, but rather upgrading to a higher-fuel-economy car (Coglianese *et al.* 2017).

[14] As fuel mix is almost exclusively gasoline in the USA but approximately half and half gasoline and diesel in the UK, the marginal cost of climate damages per gallon of fuel is not the same in both countries.

[15] We abstract from behavioural approaches to how exactly accident risk is valued under uncertainty, including implications of overconfidence and focusing on outcomes rather than probabilities, as our analysis does not model risk explicitly (Svenson 1981; de Blaeij and van Vuuren 2003; Mattauch *et al.* 2016).

[16] To determine the external cost of accidents associated with inactive travel, we consider all costs associated with car-on-car and car-on-pedestrian accidents, as well as 50% of the car-on-cyclist accident costs. Similarly for active travel, we include pedestrian-only and cyclist-on-pedestrian accident costs, and the remaining half of the car-on-cyclist accident costs.

[17] HEAT is designed as a practitioner-oriented tool for health impact assessments. More complex assessments could quantify the effect of exercise on morbidity as well as mortality. Our results are therefore likely to be conservative estimates of the health benefits of physical activity.

[18] For comparison to second best see Section 3, and for the policy implications of that comparison see Section 5.

[19] We used R for all computations. Code available at https://github.com/ssulikova1/optimalfueltax.

[20] The total tax on UK fuel includes VAT (116 cents per gallon) and fuel duty (265 cents per gallon). In the USA, value-added and other indirect taxes are not levied on fuel.

[21] To be clear, it is a standard feature that national income affects the value of statistical life, as this represents an opportunity cost of saving lives. The analysis abstracts from a dimension of redistribution across countries. See the second subsection of Section 4 for a presentation of effects in terms of lives saved instead.

[22] In applied transportation research, the differences between the responsiveness of fuel consumption to fuel prices, and miles travelled to fuel prices, are often disregarded, and assumed to be unitary. Multiplying externalities only by fuel efficiency, and not by the responsiveness of VMT to fuel price, is considered the naive approach in the literature, and can sometimes lead to a doubling of the optimal fuel tax estimation (Newbery *et al.* 1995).

[23] However, as we used constant fuel price elasticities to calculate these changes, these results should be interpreted with caution. It is unlikely that a 20-fold increase in the fuel tax in the USA would induce the same rate of response as a 20% increase in the tax.

[24] HEAT computes only the lives saved due to an increase in active travel. Higher fuel taxation also reduces inactive miles travelled, which reduces air pollution and vehicle traffic fatalities. As we do not capture these effects, the values reported in Table 6 can be considered a lower bound for the lives saved due to the tax increase.

[25] Standalone marginal increases in fuel taxes are unlikely to spur significant behaviour change in drivers, because the response to a fuel tax is to alter fuel consumption, but not to reduce the amount or distances travelled by car—the demand for VMT is more inelastic than the demand for fuel (Gillingham and Munk-Nielsen 2019).

[26] Future research could investigate how cost–benefit analysis of a public transport infrastructure project changes once health benefits are taken into account. Such an analysis should note that the health benefits are distributed unevenly across the population.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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