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To cite this article: Manuel Frondel *et al* 2021 *Environ. Res. Lett.* **16** 034041

ENVIRONMENTAL RESEARCH
LETTERS

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OPEN ACCESS

RECEIVED
9 November 2020

REVISED
23 December 2020

ACCEPTED FOR PUBLICATION
20 January 2021

PUBLISHED
1 March 2021

LETTER

Reducing vehicle cold start emissions through carbon pricing: evidence from Germany

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Keywords: German Mobility Panel, fuel prices, car use

Abstract

A large proportion of local pollutants originating from the road transport sector is generated during the so-called cold-start phase of driving, that is, the first few minutes of driving after a car has stood inactive for several hours. Drawing on data from the German Mobility Panel (MOP), this paper analyzes the factors that affect the frequency of cold starts, approximated here by the number of car tours that a household takes over the course of a week. Based on fixed-effects panel estimations, we find a negative and statistically significant effect of fuel prices on the number of tours and, hence, cold starts. Using our estimates to explore the spatial implications arising from fuel price increases stipulated under Germany's Climate Programme 2030, we find substantial impacts on the number of avoided tours even for modest fuel price increases of 20 cents per liter, particularly in urban areas. This outcome lends support to using carbon pricing as a means to improve both global climate and local air quality, pointing to a co-benefit of climate policy.

1. Introduction

Local air pollutants, such as nitrogen oxides (NO_x), and other nonmethane organic gases (NMOG), mainly originate from the road transport sector and pose a major health hazard, accounting for over 70 000 premature deaths in Germany annually (EEA 2019, p 68). A large proportion of these pollutants is generated during the so-called cold-start phase, that is, the first few minutes of driving after a car has stood inactive for several hours. According to estimates by Drozd *et al* (2016), a warmed-up vehicle may drive a distance of up to 200 miles to equal the NMOG emissions from a single cold start.

Consequently, the frequency with which motorists initiate a cold start has important implications for air quality and human health, particularly in urban areas. This is all the more relevant given that some 50% of car trips in the EU are shorter than 5 km (Hooftman *et al* 2018). The urgency of this issue has been raised in the Real Driving Emissions regulations of the European Commission (EC 2017), which notes that cold starts contribute significantly to air pollution in cities and should therefore be regulated appropriately. The study of Pozzer *et al* (2020) on deaths from COVID-19 highlights the stakes. These authors find that particulate air pollution, which is disproportionately released during cold starts (Weber *et al* 2019), is a significant contributor to COVID-19 related mortality.

Drawing on data from the German Mobility Panel (MOP 2020), this paper analyzes the factors that affect the frequency of cold starts, approximated here by the number of car tours that a household takes over the course of a week. We are particularly interested in estimating the effect of fuel prices on the number of tours, but we also probe whether the magnitude of this effect varies by geography and other socioeconomic characteristics of households. Based on fixed-effects panel estimations, we find a negative and statistically significant effect of fuel prices on the number of tours and, hence, cold starts.

One implication of these results is that fuel taxes will have heterogenous distributional consequences across geography owing to the fact that car transport has higher external costs in urban settings, where the density of cars is high (Creutzig *et al* 2020). To explore these implications, we use our estimates to

gauge the spatial pattern of avoided tours resulting from a 20-cent increase in fuel prices, as will be induced by the carbon pricing scheme stipulated under Germany's Climate Programme 2030. This exercise reveals beneficial impacts particularly for urban residents, pointing to a co-benefit of climate policy that warrants recognition in assessments of carbon pricing.

The subsequent section anchors this research in the existing literature. Section 3 describes the data base and the methodological approach. Section 4 presents our empirical results, while section 5 employs the estimates to explore the implications for air quality. The last section summarizes and concludes.

2. Related literature

This research builds on two strands of literature, one investigating the behavioral response of motorists to changes in fuel prices and the other analyzing the technical relationship between vehicle emissions and the driving phase. The first strand focuses primarily on the estimation of the fuel price elasticity, a measure of the percentage change in distance driven given a percentage change in the fuel price. The magnitude of such estimates varies widely across studies, ranging from below 0.1 to upwards of 0.3 in North American-based studies (Hughes *et al* 2008, Liu 2014, Linn 2016, Goetzke and Vance 2020) to between 0.3 and 0.6 in studies from Europe (De Borger *et al* 2016, Frondel and Vance 2018, Gillingham and Munk-Nielsen 2019). Being derived from a continuous measure of mobility demand, the fuel price elasticity can be used to quantify the effect of price-based instruments like fuel taxes in reducing global pollutants, such as carbon dioxide (CO_2). It is less suited, however, to quantifying the associated effect on local pollutants because of their disproportionate generation during the cold start phase.

The second strand of literature, drawn from engineering studies, takes up the question of the excess vehicle emissions from cold starts. While global pollutants from vehicles have dropped in recent years, in part owing to regulatory limits on CO_2 (Frondel *et al* 2011), cold starts continue to be an important source of local pollutants, including particulate matter (PM), uncombusted hydrocarbons (HC), carbon monoxide (CO), and NO_x (Reiter and Kockelman 2016). Quantification of these emissions is complicated by the diverse array of factors that determine them, including fuel type (Dardiotis *et al* 2013), ambient temperature (Weilenmann *et al* 2009), the drive cycle (Bishop *et al* 2016), and engine stop time (Favez *et al* 2009). Moreover, there is no universally recognized time frame to designate the cold start phase. For example, Drozd *et al* (2016) note that cold start emissions occur almost entirely in the first 30 to 60 s for newer vehicles, while Yusuf and Inambao (2019) define the cold-start phase as the first 237 s.

These complexities notwithstanding, several studies have documented that the average emissions from the cold start phase are substantially higher than those of the hot phase. Table 1, adapted from the study of Faria *et al* (2018), provides an illustration based on real driving conditions in Lisbon. Across pollutant species, the emissions of the cold phase far exceed those of the hot phase for both diesel and petrol cars, often by more than 100%, confirming similar conclusions reached by other studies (Weilenmann *et al* 2009, Bielaczyc *et al* 2011, Suarez-Bertoa *et al* 2017). Suarez-Bertoa *et al* (2017), for example, focus on NH_3, a precursor of $PM_{2.5}$, finding that gasoline cold start emissions are up to two orders of magnitude higher than during the entire road trip.

Local pollutants are thus predominantly determined by the frequency of starting a cold vehicle, rather than the distance driven. As a consequence, policy measures such as fuel taxes—even when successful in reducing total mileage—may have only a muted effect in improving local air quality. Whether this holds true ultimately depends on the relationship between the fuel price level and the frequency of car use, a question taken up in the empirical analysis below.

3. Data and methods

Data for the econometric analysis is drawn from the German Mobility Panel (MOP 2020), an ongoing publicly available travel survey commissioned and financed by the German Federal Ministry of Transport and Digital Infrastructure since 1994. To explore the implications of the model results for air quality, we draw on a second data source from RWI-GEO-GRID 2014, which contains counts of the number of diesel and petrol cars on a 1×1 km grid covering Germany.

3.1. German mobility panel

The MOP is structured as a panel survey with a rotating sample. Participating households are surveyed for three consecutive years. Each year, a share of the households is replaced by a new cohort, with the cycle continually repeating itself in overlapping waves. The data analyzed here spans 15 years, from 2004 until the survey from 2018 (our coverage begins in 2004 because this was the year a question on household income was introduced).

Households are surveyed on two occasions each year, in the fall and in the following spring, with the latter referred to as the 'tank survey'. The fall survey covers a complete week from Monday to Sunday and collects general household-level information, such as income and neighborhood attributes, as well as person-related characteristics, including gender, age, and employment status. In addition, all household members over 10 years of age fill out a detailed

Table 1. Average emissions of CO, HC, and NO_x in cold start and hot phases.

	CO ($g\,km^{-1}$)		HC ($g\,km^{-1}$)		NO_x ($g\,km^{-1}$)	
	Diesel	Petrol	Diesel	Petrol	Diesel	Petrol
Hot phase	0.19	0.29	0.07	0.01	0.38	0.05
Cold start phase	0.75	2.93	0.13	0.28	0.80	0.24

Source: Faria *et al* (2018), p 553.

travel log capturing relevant aspects of travel behavior for each day of the week, including distances traveled for each trip, the modes used, and the trip durations.

The dependent variable is calculated from these logs by summing the total number of car tours taken by the household over the seven-day week. A tour is defined as a trip or sequence of trips that begins and ends at home. We do not sum individual trip segments because we assume that the decision to use the car is made on a single occasion upon departing home, irrespective of whether one or several trips are subsequently undertaken. The dependent variable is thereby a conservative measure of cold starts given that tours may include stops during which the car is at rest for a long period before being restarted (e.g. at work), but one that aligns with our aim of quantifying the influence of the fuel price on the frequency of car use.

Our key explanatory variable is the fuel price, which is collected during the MOP's tank survey, when respondents maintain a log of each visit to the gas station over a 6 week period. During this time, they record the price paid for fuel and the odometer reading for each car in the household. The survey also records sundry automobile attributes such as the car's fuel type. We use this data to calculate the average price paid for petrol and/or diesel fuel for each household. About 10% of the sample households own a mix of petrol and diesel cars, so that prices for both are recorded. Using a household identifier, we merge these prices with the tour counts recorded in the fall survey. To account for the changes in the price level between the spring and preceding fall, we apply a weight constructed from a time-series of monthly fuel prices published by the fuel company Aral (Aral 2020). The price series is additionally deflated using a consumer price index for Germany obtained from Destatis (2020).

In addition to the fuel price, we avail a suite of control variables to include in the model specification, presented in table 2. Three dummy variables indicate the composition of the household's car stock, where we distinguish by only petrol, only diesel, or a mix of fuel types. To capture the age of the car, a dummy is included indicating whether the newest car owned by the household is less than two years old. We also include several socioeconomic variables capturing the household's income level, the number of children, the number of employed, and a dummy indicating residence in a nonurban area. The specification is completed with two controls for weather conditions during the week of the survey: the average temperature and the total rainfall.

The data was pruned along two dimensions. First, we limit the sample to car owners, which comprise about 83% of German households. We also eliminate 71 households—about 1.7% of the sample—who reported having an alternative fuel vehicle (e.g. electric, hybrid, LPG). The resulting sample comprises 4048 households, 1755 of which are observed over two years of the survey and 2293 over 3 years, with 10 389 observations in total.

3.2. Econometric model

Exploiting the longitudinal structure of the data, we employ fixed-effects panel estimation methods to estimate the impact of the fuel price on the number of tours using the following econometric specification:

$$\#\text{tours}_{it} = \beta + \beta_p p_{it} + \boldsymbol{\beta}_x^T \mathbf{x}_{it} + \theta_i + \tau_t + \nu_{it}, \quad (1)$$

where p_{it} denotes the per-liter price paid for either petrol or diesel fuel by household i in period t and β_p measures the fuel price response. For households that own a mix of diesel and petrol cars, we assign the diesel price to this variable, noting that results change negligibly if the petrol price is assigned. Vector $\mathbf{x}$ contains time-varying control variables and vector $\boldsymbol{\beta}_x$ captures the parameters to be estimated. In addition, we control for household-fixed-effects θ_i and a set of year-fixed-effects τ_t. ν_{it} denotes the idiosyncratic error term that captures unobserved shocks.

Whether we can ascribe a causal interpretation to the fuel price estimate rests crucially on the conditional independence assumption (CIA), which requires that all variables that influence fuel prices and may be related to the number of car tours are observable. While bias from omitted variables can never be completely ruled out, several features of the analytical set-up provide support for the CIA. One is the panel's relatively short time dimension of three years, which leaves little room for the omission of time-varying determinants that are not already captured by both the household- and year fixed effects. Coupled with the controls for time-varying socioeconomic and demographic characteristics, biases that

Table 2. Variable definitions and descriptive statistics for the estimation sample.

Variable name	Variable definition	Mean	Std. Dev.
# tours	Number of tours of a household per week	9.7	5.9
p	Real fuel price in Euros per liter	1.35	0.19
Diesel car stock	Dummy 1: If household owns only diesel cars	0.20	—
Mixed car stock	Dummy 1: If household owns both diesel and petrol cars	0.12	—
Petrol car stock	Dummy 1: If household owns only petrol cars	0.68	—
New car	Dummy 1: If household's newest car <2 years old	0.22	—
High income	Dummy 1: If household is considered as wealthy	0.26	—
Medium income	Dummy 1: If household has a medium income	0.52	—
Low income	Dummy 1: If household is considered as poor	0.21	—
# kids < 18	Number of kids younger than 18 in the household	0.33	0.67
# employed	Number of employed household members	1.00	0.85
Non-urban	Dummy 1: If household resides in a suburb or a rural area	0.61	—
Temperature	Average temperature in degrees centigrade per week	11.2	3.9
Rainfall	Total rainfall per week in milliliter	36.3	50.5

Note: Number of observations employed for estimations: 10 389.

could otherwise emerge from the correlation of unobserved household characteristics with fuel prices appear to be unlikely.

4. Empirical results

Table 3 presents the estimates from three models, distinguished by the inclusion of interaction terms to test for differential effects of the fuel price according to the household's stock of cars, income level, and location. The results of the base model, which excludes interaction terms, indicate a negative and statistically significant association of the fuel price with the number of car tours. In quantitative terms, each Euro increase in the fuel price is associated with 1.56 fewer tours per week. The corresponding elasticity, evaluated at the mean values of tour counts and the fuel price, suggests that a 10% increase in fuel prices results in a roughly 2.2% decrease in tours. This result is in line with other research on German household mobility, which finds that the driving distance response to a 10% increase in fuel prices is somewhat higher, ranging from 3% to 6% (Frondel and Vance 2009, Frondel and Vance 2010, Keller and Vance 2013). Collectively, this evidence suggests that taxing car fuels by carbon pricing is a promising instrument for reducing both local and global pollutants.

Of the car stock attributes, only the dummy variable *newcar* is statistically significant. The coefficient estimate indicates that households owning a car less than two years of age undertake 0.3 more tours per week. This finding buttresses the analysis of Drozd *et al* (2016), who, considering newer vehicles, conclude that future NMOG emissions will become more spatially and temporally correlated with cold starts, so that emissions are 'increasingly located where people live [...] and work' (p 13 597).

The socioeconomic controls for wealthy households, those living in non- or suburban areas, and the number of employed household members are likewise statistically significant, all with positive coefficients. The largest effect is seen for households residing in suburban or rural areas, which engage in 1.23 more tours per week than their urban counterparts. Weather conditions also matter. A 10 °C increase in temperature is associated with a decrease in the number of car tours per week of about 0.4. Considering that the survey was undertaken in the fall, when the mean temperature was 11°, this finding is consistent with the idea that warmer weather conditions decrease car use. Along similar lines, increases in rainfall is positively associated with the number of car tours.

The middle columns of table 3 present the results of a specification that expands the base model by including interactions of the fuel price with the two dummy variables indicating whether the household owns only diesel vehicles or a mix of diesel and petrol vehicles. Households with only petrol vehicles are the base case. The pattern of estimates from this specification is similar to the base model, both with respect to the statistical significance and magnitude of the estimates. Neither of the interactions are statistically significant, suggesting that the composition of the car stock does not mediate the effect of the fuel price.

Table 3. Fixed-effects estimation results on number of tours of a household per week.

	Base model		Models with interactions			
	Coeff.	Std. Err.	Coeff.	Std. Err.	Coeff.	Std. Err.
p	-1.556^{**}	(0.538)	-1.477^{*}	(0.579)	-2.108^{**}	(0.718)
Mixed car stock	0.467	(0.334)	0.888	(1.296)	1.255	(1.335)
Diesel car stock	−0.339	(0.332)	−0.297	(0.990)	−0.175	(0.998)
$p \times$ mixed car stock	—	—	−0.335	(0.987)	−0.594	(1.014)
$p \times$ diesel car stock	—	—	–0.024	(0.713)	−0.102	(0.721)
New car	0.300^{*}	(0.123)	0.300^{*}	(0.123)	0.336	(0.829)
$p \times$ new car	—	—	—	—	−0.022	(0.606)
High income	0.466^{*}	(0.217)	0.466^{*}	(0.217)	−1.351	(1.021)
Low income	−0.146	(0.177)	−0.145	(0.177)	−1.053	(0.931)
$p \times$ high income	—	—	—	—	1.346	(0.730)
$p \times$ low income	—	—	—	—	0.652	(0.641)
Non-urban	1.229^{**}	(0.453)	1.224^{**}	(0.452)	0.682	(1.038)
$p \times$ non-urban	—	—	—	—	0.398	(0.635)
# employed	0.557^{**}	(0.162)	0.555^{**}	(0.162)	0.554^{**}	(0.162)
# kids < 18	0.149	(0.215)	0.150	(0.215)	0.138	(0.215)
Temperature	-0.042^{**}	(0.011)	-0.042^{**}	(0.011)	-0.042^{**}	(0.011)
Rainfall	0.010^{**}	(0.001)	0.010^{**}	(0.001)	0.010^{**}	(0.001)
Constant	10.094^{**}	(0.832)	9.991^{**}	(0.892)	10.845^{**}	(1.086)
Year dummies:	Yes		Yes		Yes	
Number of observations:	10 398		10 398		10 398	

Notes: Standard errors clustered at the household level are in parentheses. ** and * denote statistical significance at the 1% and 5% level, respectively.

The final specification reported in the last two columns of table 3 includes additional interaction terms of the fuel price with dummy variables indicating a new car, the income categories, and residence in a non- or suburban area. The magnitude of the fuel price coefficient increases substantially, suggesting a 2.11 decrease in tours per week given a 1 Euro increase in the fuel price for medium-income households. Owing to the inclusion of the interactions, this estimate measures the price response among middle-class households that reside in urban areas, use petrol fuel, and do not own a new car. Altogether, none of the interaction terms is statistically significant, leading to the conclusion that there is moderate heterogeneity with respect to the fuel price response.

Probing a bit deeper, we see, for example, that low-income households are somewhat less responsive to the fuel price, but the effect size of $-1.46(= -2.108 + 0.652)$ remains statistically significant. Among wealthy households, the fuel price response is even lower at $-0.763(= -2.108 + 1.346)$ and, in this case, is not statistically different from zero. We would therefore conclude that the incidence of a fuel tax would fall primarily on wealthier households, comprising about 26% of the sample—see the mean of the high-income dummy variable in table 2. Other effects, not captured by this analysis, would include those arising from greater reliance on public transit among low- and middle-income households, which would likely entail higher travel time.

A similar pattern of a moderately weaker response to fuel prices is seen for non-urban households. However, the difference is small and is not statistically significant. This absence of heterogeneity likely reflects the high quality of Germany's nationwide public transit infrastructure, which affords even rural households the ability to substitute car trips in the face of high fuel prices.

5. Spatially differentiated impacts of higher fuel prices

At the close of 2019, Germany introduced its Climate Action Programme 2030, a series of measures targeted at the reduction of greenhouse gas emissions. A centerpiece of the programme is the introduction of a price on carbon dioxide (CO_2), starting at €25 per tonne in 2021 and increasing incrementally to €55 by 2025, after which a trading regime for CO_2 certificates commences. This carbon pricing scheme will have a bearing on the prices for transport fuels. For instance, given a CO_2 price of €55 per tonne, prices

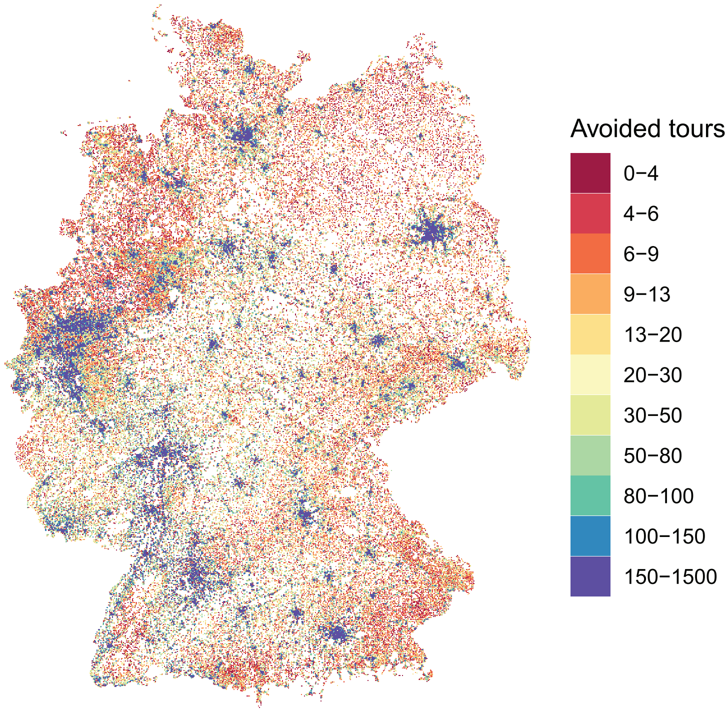

Figure 1. Number of avoided tours.

for petrol and diesel will increase by approximately 15.5 and 17.3 cents per liter by 2025, respectively[5].

To approximate the impacts of carbon pricing on cold start emissions, we assume a 20-cent increase in the fuel prices per liter, being slightly higher than the fuel price increases due to a carbon price of €55. Referring to the estimate of −1.556 from the base model presented in table 3, this fuel price increase would correspond to 0.311 fewer car tours of a household per week. As households own 1.47 cars on average, this implies a reduction of 0.212 tours per car per week. Drawing on RWI-GEO-GRID data and multiplying the estimated reduction in tours per car with the number of cars in each square kilometer grid cell, we obtain the total number of avoided tours per week in a grid cell due to a 20-cent increase in fuel prices.

Figure 1 illustrates the results of this exercise. Not surprisingly, the number of avoided tours is particularly high in those areas where the number of cars is large, notably in urban areas. In the city of Berlin, for instance, where according to the RWI-GEO-GRID data there are 796 538 petrol and 220 710 diesel cars, a 20-cent increase in fuel prices leads to a reduction of about 215 000 tours per week and, thus, at least as many cold starts.

Given the absence of a differential effect of fuel price increases across petrol and diesel cars evidenced from the econometric modeling, the associated percentage change in cold start emissions for all pollutant species is calculated by dividing the change in cold starts per car (0.212) by the average number of cold starts per car, which amounts to 10/1.47 = 6.8, where 10 equals the average number of tours per household (table 2). Thus, a 20-cent increase in the fuel price is associated with a reduction of 3.1% in cold start emissions.

Calculation of the resulting health impacts from this change would require the application of a chemistry-transport model to estimate spatially resolved population exposure (Chossière *et al* 2017), which extends beyond the scope of the present study. Nevertheless, related research suggests that the health consequences from both morbidity and mortality are likely to be high. Focusing on just nitrogen oxides, a meta study by Stieb *et al* (2012) detects a negative association between NO_2 exposure and the birth weight of new born babies. In a similar vein, WHO (2013) establishes that the risk of suffering from bronchitic symptoms is elevated among children aged 5–14 years as a response to higher NO_2 exposure. In addition, Mehta *et al* (2012) detect a notable positive effect on the number of doctor visits among adults with respiratory preconditions, such as bronchitis, following a higher exposure to NO_2. Addressing mortality, Chossière *et al* (2017) analyze the excess NO_x emissions resulting from the Volkswagen diesel scandal, calculating a cost of 1.9 billion EUR in life years lost.

Taken together, this evidence suggests the potential of higher fuel prices to improve health conditions

[5] Using the emissions factors of 2.37 and 2.65 kg CO_2 per liter petrol and diesel, respectively (see FEA 2019), and taking the value-added tax of 19% into account, prices for petrol and diesel will increase by 15.5 and 17.3 cents per liter when the CO_2 price reaches €55 per tonne.

of the exposed population. Such effects will be particularly pronounced in dense urban settings, where pollution costs are found to be twice as high as in rural settings (van Essen *et al* 2019). Higher fuel taxes in urban areas may therefore be called for, not only recognizing the greater scope for mode switching in cities, but also the larger health benefits.

Nevertheless, long-run effects should also be recognized: relatively lower fuel prices in rural areas can be expected to increase automobile dependency, which is in turn a main driver of urban sprawl (Glaeser and Kahn 2004). In this regard, it could be worthwhile to complement carbon pricing by implementing or re-calibrating other policy measures. These could include cordon pricing of cities to further reduce urban emissions (Börjesson and Kristoffersson 2015), the avoidance of fiscal instruments such as subsidies and tax write-offs that encourage new housing in low-density areas (Nuissl and Rink 2005), or measures—such as were codified in recent reforms of Germany's zoning laws (BauNVO 2017)—that promote high urban densities and mixed land uses combining social, cultural, and residential purposes.

6. Summary and conclusions

Drawing on data from the German Mobility Panel (MOP), this paper has explored the relationship between fuel prices and the number of cold vehicle starts, which disproportionately affect the emissions of local air pollutants. Higher fuel prices will result from the new carbon pricing regime, which was established as of 2021 under Germany's Climate Protection Programme. Against this background, we have econometrically identified the impact of fuel prices and other variables on the number of tours taken with a car, which is used here as a proxy for cold starts. Coupling the price coefficient estimate with georeferenced data on car density, we have calculated the number of avoided car tours, presuming a 20-cents increase in the fuel price. This increase can be expected for 2025, when the price of carbon dioxide (CO_2) will amount to €55 per tonne.

Among our key findings are: (a) There is a statistically significant negative relationship between fuel prices and the number of car tours, with an elasticity of roughly −0.22. (b) The magnitude of this estimate is largely invariant to the socioeconomic characteristics of households like car stock, income and residential location. (c) A 20-cent increase in the fuel price would result in a roughly 3.1% reduction in emissions from cold starts. Given the higher density of cars in cities, the associated improvements in air quality would be particularly pronounced in cities.

To conclude, these findings buttress the case made by Creutzig *et al* (2020) for a geographically differentiated approach to fuel taxation, one that reflects the higher external costs of transport in dense urban settings.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

The authors gratefully acknowledge the following sources of financial support: Manuel Frondel and Stephan Sommer by the Collaborative Research Center 'Statistical Modeling of Nonlinear Dynamic Processes' (SFB 823) of the German Research Foundation (DFG), within Project A3, 'Dynamic Technology Modeling' and by the Federal Ministry of Education and Research (BMBF) under grant 03SFK5C0 (Kopernikus Project ARIADNE) and grant 01LA1823A (Project Eval-Map II) within the funding measure 'Economics of Climate Change'; Clemens Marggraf by the European Commission under grant 812730 (Project SmartBEEjs), and Colin Vance by BMBF under grant 01LA1809C (Project DIPOL). We thank two anonymous reviewers for providing excellent commentary.

References

Aral 2020 Durchschnittpreise auf Monatsbasis (available at: www.aral.de/de/global/retail/kraftstoffe-und-preise/kraftstoffpreise/kraftstoffpreis-archiv.html)

BauNVO 2017 Verordnung über die bauliche Nutzung der Grundstücke (available at: www.gesetze-im-internet.de/baunvo/BauNVO.pdf)

Bielaczyc P, Szczotka A and Woodburn J 2011 The effect of a low ambient temperature on the cold-start emissions and fuel consumption of passenger cars *Proc. Inst. Mech. Eng.* D **225** 1253–64

Bishop J D, Stettler M E, Molden N and Boies A M 2016 Engine maps of fuel use and emissions from transient driving cycles *Appl. Energy* **183** 202–17

Börjesson M and Kristoffersson I 2015 The Gothenburg congestion charge effects, design and politics *Transp. Res.* A **75** 134–46

Chossière G P, Malina R, Ashok A, Dedoussi I C, Eastham S D, Speth R L and Barrett S R 2017 Public health impacts of excess NO_x emissions from Volkswagen diesel passenger vehicles in Germany *Environ. Res. Lett.* **12** 034014

Creutzig F, Javaid A, Koch N, Knopf B, Mattioli G and Edenhofer O 2020 Adjust urban and rural road pricing for fair mobility *Nat. Clim. Change* **10** 591–4

Dardiotis C, Martini G, Marotta A and Manfredi U 2013 Low-temperature cold-start gaseous emissions of late technology passenger cars *Appl. Energy* **111** 468–78

De Borger B, Mulalic I and Rouwendal J 2016 Substitution between cars within the household *Transp. Res.* A **85** 135–56

Destatis 2020 Verbraucherpreisindex (available at: www.destatis.de/DE/Themen/Wirtschaft/Preise/Verbraucherpreisindex/_inhalt.html)

Drozd G T *et al* 2016 Time resolved measurements of speciated tailpipe emissions from motor vehicles: trends with emission control technology, cold start effects and speciation *Environ. Sci. Technol.* **50** 13592–9

EC 2017 Commission Regulation (EU) 2017/1154 (available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017R1154&from=EN)

EEA 2019 Air quality in Europe–2019 report (https://doi.org/10.2800/02825)

Faria M V, Varella R A, Duarte G O, Farias T L and Baptista P C 2018 Engine cold start analysis using naturalistic driving data: city level impacts on local pollutants emissions and energy consumption *Sci. Total Environ.* **630** 544–59

Favez J-Y, Weilenmann M and Stilli J 2009 Cold start extra emissions as a function of engine stop time: evolution over the last 10 years *Atmos. Environ.* **43** 996–1007

FEA 2019 Kohlendioxid-Emissionsfaktoren für die deutsche Berichterstattung atmosphärischer Emissionen 1990–2017 20.2.2019. Federal Environmental Agency (available at: www.umweltbundesamt.de/publikationen/co2-emissionsfaktoren-fuer-fossile-brennstoffe)

Frondel M, Schmidt C M and Vance C 2011 A regression on climate policy: the European Comission's legislation to reduce CO_2 emissions from automobiles *Transp. Res.* A **45** 1043–51

Frondel M and Vance C 2009 Do high oil prices matter? Evidence on the mobility behavior of German households *Environ. Resour. Econ.* **43** 81–94

Frondel M and Vance C 2010 Driving for fun? Comparing the effect of fuel prices on weekday and weekend fuel consumption *Energy Econ.* **32** 102–9

Frondel M and Vance C 2018 Driver's response to fuel taxes and efficiency standards: evidence from Germany *Transportation* **45** 989–1001

Gillingham K and Munk-Nielsen A 2019 A tale of two tails: commuting and the fuel price response in driving *J. Urban Econ.* **109** 27–40

Glaeser E L and Kahn M E 2004 Sprawl and urban growth *Handbook of Regional and Urban Economics* vol 4 (Amsterdam: Elsevier) pp 2481–527

Goetzke F and Vance C 2020 An increasing gasoline price elasticity in the United States? *Energy Econ.* 104982

Hooftman N, Messagie M, Van Mierlo J and Coosemans T 2018 A review of the European passenger car regulations–real driving emissions vs local air quality *Renew. Sustain. Energy Rev.* **86** 1–21

Hughes J, Knittel C R and Sperling D 2008 Evidence of a shift in the short-run price elasticity of gasoline demand *Energy J.* **29** 113–34

Keller R and Vance C 2013 Landscape pattern and car use: linking household data with satellite imagery *J. Transp. Geogr.* **33** 250–7

Linn J 2016 The rebound effect for passenger vehicles *Energy J.* **37** 257–88

Liu W 2014 Modeling gasoline demand in the United States: a flexible semiparametric approach *Energy Econ.* **45** 244–53

Mehta A J *et al* 2012 Acute respiratory health effects of urban air pollutants in adults with different patterns of underlying respiratory disease *Swiss Medical Wkly.* **142** 1–17

MOP 2020 *German Mobility Panel* (Karlsruhe: Karlsruhe Institute of Technology) (available at: mobilitaetspanel.ifv.kit.edumobilitaetspanel.ifv.kit.edu)

Nuissl H and Rink D 2005 The 'production' of urban sprawl in eastern Germany as a phenomenon of post-socialist transformation *Cities* **22** 123–34

Pozzer A, Dominici F, Haines A, Witt C, Münzel T and Lelieveld J 2020 Regional and global contributions of air pollution to risk of death from COVID-19 *Cardiovascular Res.* **116** 2247–53

Reiter M S and Kockelman K M 2016 The problem of cold starts: a closer look at mobile source emissions levels *Transp. Res.* D **43** 123–32

Stieb D M, Chen L, Eshoul M and Judek S 2012 Ambient air pollution, birth weight and preterm birth: a systematic review and meta-analysis *Environ. Res.* **117** 100–11

Suarez-Bertoa R, Mendoza-Villafuerte P, Riccobono F, Vojtisek M, Pechout M, Perujo A and Astorga C 2017 On-road measurement of NH_3 emissions from gasoline and diesel passenger cars during real world driving conditions *Atmos. Environ.* **166** 488–97

van Essen H *et al* 2019 Handbook on the External Costs of Transport, Version 2019 – 1.1 Technical report (https://doi.org/10.2832/51388)

Weber C, Sundvor I and Figenbaum E 2019 Comparison of regulated emission factors of Euro 6 LDV in nordic temperatures and cold start conditions: diesel-and gasoline direct-injection *Atmos. Environ.* **206** 208–17

Weilenmann M, Favez J-Y and Alvarez R 2009 Cold-start emissions of modern passenger cars at different low ambient temperatures and their evolution over vehicle legislation categories *Atmos. Environ.* **43** 2419–29

WHO 2013 Health risks of air pollution in Europe–HRAPIE project (Copenhagen: World Health Organization)

Yusuf A A and Inambao F L 2019 Effect of cold start emissions from gasoline-fueled engines of light-duty vehicles at low and high ambient temperatures: recent trends *Case Stud. Thermal Eng.* **14** 100417