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Will I change my driving habits if a neighbor buys an emissions-free car?

Unintended effects of environmental policies[1]

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Abstract

Several countries now promote purchase and use of emissions-free (green) cars through financial as well as non-financial incentives. We study how such incentives affect non-targeted consumers, that is, consumers who continue to drive a polluting (brown) car. The incentives have two effects. First, they make green cars more attractive, thereby reducing the number of brown cars on the road. Second, they influence the use of both types of cars. Using a simple model, we study the effects of policy instruments such as subsidizing green cars, taxing brown cars, and allowing green cars to drive in the bus lane. Car owners are influenced by price incentives, but also by external effects from traffic (such as queues) both in the regular lane and in the bus lane. In addition, we consider how change in the average driving habits in the local community affects the behavior of brown car drivers. We find that both subsidizing green cars and allowing green cars to drive in the bus lane can increase driving of brown cars, which is an unintended effect of the environmental policy.

Keywords: Emissions-free cars; environmental policies; external effects; habit formation; social norms

JEL classifications: D62, H23, Q54, R42, R48

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1. Introduction

Laws or policies are designed to influence behavior. Whereas laws may constrain the behavior of individuals or firms, policy instruments such as taxes or subsidies affect prices and therefore also agents' consumption and production decisions. Laws or policies may also change social norms or habits, thereby generating an effect that may persist even after the law or policy is revoked (Nyborg and Rege 2003). On the other hand, laws or policies that conflict with existing social norms may fail to modify behavior significantly (Acemoglu and Jackson 2017).

Laws or policy instruments are sometimes directed towards a specific group of agents. For example, lower-income families may be subsidized if their children attend a specific activity or educational program. Similarly, ethnic minority groups or a particular gender may be given priority for certain positions. In some cases, people are able to choose whether to be affected by such a policy or to choose which of two (or even several) policy instruments to face, by choosing which group to join. Consider economic policy instruments designed to induce consumers to choose an environmentally clean (green) good over a polluting (brown) good. For instance, consumers using the green good may receive a subsidy, while consumers who opt for the brown good may face a tax. While the response of consumers opting for the green good is well researched, we know far less about how brown consumers are influenced by polices directed towards green consumers.

According to the standard *homo oeconomicus* model, agents will generally not be affected by policies directed towards *other* agents. An exception is if market imperfections (such as negative or positive externalities) exist. For example, because technology spillovers may change the production possibilities of a company and therefore its production decisions, policies promoting technology innovation may affect other companies than those being targeted by the policy (e.g., competing companies in other countries). Furthermore, negative externalities such as climate change impacts, will affect people around the world. Thus, policies to mitigate greenhouse gas emissions may also influence other agents than those being targeted by the policies.

Another way in which a policy or law might influence the non-targeted group's behavior is by changing social norms, habits, or agents' sense of justice. If agents targeted by a policy

change their behavior, non-targeted agents may also change their habits or alter their views concerning what is the dominant social norm. The latter may be particularly likely if the targeted group has high social status. Moreover, if a policy is considered unfair (say, because it favors a particular group of people), it might affect the behavior of the non-targeted group. For example, the non-targeted group might vote for a different political party in the next election, or it could behave in a seemingly non-rational way to express dismay.

In this paper, we study effects of policies designed to stimulate the shift to a green economy. These effects may be both intended and unintended. They are unintended if they affect the behavior in a non-desired direction, for instance if the non-targeted group decides do behave less green. In particular, we focus on economic instruments and other regulations aimed at stimulating the transition to an emissions-free transport sector. Such instruments could offer benefits to consumers who buy and drive an emissions-free ("green") car. At the same time, they might punish drivers who stick to a petroleum-based ("brown") car.

The group of consumers not targeted by the instrument may be affected through externalities such as queues on the road. However, consumers with social preferences are likely to be affected differently by other agents' behavior than consumers who act in accordance with the standard *homo oeconomicus* model. In particular, consumers with social preferences may be influenced by people who drive a different car type (e.g., status effects) or by the average driving habits in their neighborhood. The question is, therefore, if the effectiveness of transport policies might suffer if they unintentionally also influence non-targeted consumers? The transport sector is responsible for a substantial share of global emissions;[5] hence, it is vital that policies to reduce emissions from this sector be effective. Globally, almost all energy used in the transport sector comes from petroleum-based fuels; however, the transport sector – particularly road transport – has started a transition to non-fossil energy (electricity, hydrogen, biofuels).

[5] In 2010, the transport sector was responsible for 14 % of global GHG emissions (IPCC 2014), while in Europe the transport sector contributed to 25.8% of total EU-28 greenhouse gas emissions in 2015, see https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-10.

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We present a simple model that includes two types of representative consumers, one driving a green car and one driving a brown car. The consumers are identical apart from the preferences for driving a green car. Policy instruments such as subsidies, taxes, and permission to drive in the bus lane affect this choice. Consumers gain utility from driving and disutility from queues on the road, which is a flow externality. We find that subsidizing green cars will increase driving with these cars and therefore increase queues on the road. Increased queues will reduce the use of brown cars. On the other hand, if green cars are permitted to drive in the bus lane in order to reduce queues and increase the share of green cars, driving with brown cars will also become more attractive. The reason is that buses will be negatively affected due to more traffic in the bus lane, and there will be a transition from public transport to cars. Finally, if brown consumers are motivated by other consumers' behavior (e.g., by the average level of driving in the neighborhood), more mileage driven by green consumers will incentivize brown consumers to drive more, thereby dampening the policy instruments' effect on queues. In some special cases, this may even increase driving with brown cars. Thus, policies to promote a transition to green cars may increase driving among those who decide to keep the brown cars.

The empirical parts of this paper focus on Norwegian policies aimed at stimulating consumers to purchase and drive electric vehicles (EVs). Norway is a leading country in the transition from petroleum-based to electric cars due to a significant subsidization program consisting of tax exemptions and local benefits, which reduce the cost of buying and an EV and makes it cheaper to drive it. At the same time, cars based on fossil fuels are being heavily taxed. In 2017, EVs constituted about 20% of the Norwegian car market. By the end of 2017, the aggregate share of EVs in the fleet remained as low as 5%;[6] however, it has been rapidly growing in the last few years (Autosys 2018). EVs are most common in and around cities, as the benefits are far more important there than in rural areas. Norway's ambitious policies to increase the share of EVs make it a good case for studying the induced effect (if any) of electric-car-enhancing policies on the behavior of fossil car drivers.

We use survey data to study the impacts of EV policies on driving with fossil fuel based cars. This is a survey that were sent to members of the Norwegian EV Association (NEVA), and

[6] Norway has the highest market share of electric cars in the world, while China has the largest market, see IEA (2017).

the Norwegian Automobile Association (NAF) in May 2018. Thus, those targeted for the survey were drivers of both EVs and petrol and diesel cars. The survey was broad in scope and contained some questions related to how EV policies influences driving habits of owners of petrol and diesel cars.
(*To be done…*)

Our work builds on the literature on externalities (see, e.g., Cornes and Sandler, 1996), but it also contributes to several different strands of literature on social preferences. The first strand focuses on unintended effects of policy instruments. As documented by behavioral economics, a tax (or a fee) may not produce the intended effect if it also affects non-monetary motivations. In particular, a monetary incentive may either crowd in or crowd out the motivation to carry out this task. Early contributions in this field include Frey and Oberholzer-Gee (1997), who found that an offer of monetary compensation decreased respondents' willingness to accept a hazardous waste treatment plant in their neighborhood. Similarly, Gneezy and Rustichini (2000) found that imposing a fine on parents arriving late to collect their children at day care *increased* the number of late-coming parents. Interestingly, this number remained high and stable even after the fine was cancelled. Furthermore, a tradeable permit system may reduce the incentive to behave "green" by crowding out moral motivation for doing so (see Kverndokk 2013). As Hansen (2009) points out, individual actions to reduce carbon footprint will have no impact in a tradable permit system: You simply free up emission permits for someone else, because the total emissions are fixed by the government. This feature might constrain the motivation to behave green.

When it comes to unintended effects of transportation policies, Davis (2008) found that policies to increase air quality in Mexico City in 1989 had no effect. Drivers were banned from driving one day a week based on the last number on their car's license plates. However, this regulation caused an increase in the size of the car fleet and a shift towards high-emission cars as drivers bought an additional car, typically an older and cheaper one, to be able to drive every day. Another example stems from France, where a combination of subsidies for low-emission cars and a purchase tax on high-emission cars (a feebate) was introduced in 2008 to reduce emissions. Unexpectedly, D'Haultfœuille et al. (2014) found that while this policy lead to a shift towards low-emission cars, the total number of cars also increased, leading to higher aggregate emissions.

A second strand consists of literature on habit formation, social norms and identity. While the absolute level of goods constitutes the main carrier of utility in neoclassical economics, behavioral economists have introduced external or internal reference levels in utility functions (e.g., Frank 1989; Rabin 1998). An example of external reference levels is status seeking, where individuals compare themselves to others. In contrast, examples of internal reference levels include habits, addiction, and adaptation, where the utility of consumption depends on past consumption levels (Becker 1992) or the utility of health depends on past health levels (Gjerde et al. 2005). Similarly, social norms may be seen as a reference point, a rule, or a standard that governs behavior (Bierstedt 1963), and an existing norm may be represented as a distribution of earlier behavior (Acemoglu and Jackson 2015). Acemoglu and Jackson (2017) represent external norms as the expected behavior in the population, where this expected behavior has important payoff consequences for the individual. In contrast, internal norms are based on moral reasons and may be related to the identity or self-image of the individual (see Akerlof and Kranton 2000; Brekke et al. 2003).

A third related strand of literature considers how laws and policies interact with social norms. Acemoglu and Jackson (2017) find that laws that conflict strongly with social norms will unlikely succeed in changing behavior. In contrast, a gradual tightening of laws may effectively influence both social norms and behavior. Nyborg and Rege (2003) find that a gradual tightening of laws changed social norms concerning smoking, because non-smokers' disapproval of smoking increased as they became less used to passive smoking. Finally, Sandel (2012) argues against tradeable emission permits on the grounds that they damage norms, encourage an instrumental attitude toward nature, and undermine the spirit of shared sacrifice.

Lastly, our work also relates to the literature on peer effects and bandwagon effects. Individual outcomes are found to correlate strongly with group average outcomes. There may exist a social spillover, which is often interpreted as a peer effect (see, e.g., Angrist 2014). A bandwagon effect may be said to exist whenever a consumer demands more (or less) of a good – at a given price – when other consumers demand more (less) of this good (Leibenstein 1950: 190). Surveys have revealed that consumers who buy an EV tend to drive more after the purchase than before (e.g., Rødseth 2009; Figenbaum and Kolbenstvedt 2016). A bandwagon effect would exist if this change in the behavior of EV owners causes owners of petroleum-based cars to drive more as well. Another type of bandwagon effect would exist if new

information on the performance of EVs increases their perceived benefits. For example, early adopters of EVs might help demonstrate the vehicles' usability and reliability, thereby reducing the perceived uncertainty and risk for subsequent adopters (Beisea and Rennings 2005: 8).

The rest of this paper is organized as follows. In section 2, we review existing literature on what factors motivate the decision to purchase an electric or hybrid vehicle, as well as how the purchase of an electric or hybrid vehicle influences the buyer's driving pattern. In section 3, we set up a simple model and derive hypotheses concerning how public-policy-induced changes in electric car users' driving pattern may change the driving pattern of petroleum-based car users. In section 4, we provide some empirical evidence. Finally, section 5 concludes.

2. Literature review

In this section, we review the existing literature on two related research questions concerning electric (and hybrid) vehicles. The first is what factors motivate the decision to purchase an electric vehicle (EV). The second is how the purchase of an EV influences the buyer's driving pattern.

2.1.Factors that influence the purchase decision

A substantial scholarly literature has addressed the first of these questions. The findings suggest that a multitude of factors may influence the decision to buy an EV.[7] These factors include purchase price and operating costs (including subsidies), fossil fuel taxes, non-tax incentives (such as free parking and permission to drive in the bus lane), mandatory compatibility in charging standards, density of charging stations, social norms, consumers' environmental values, and consumers' interest in new technology (see e.g., Mille et al. 2014; Kahn 2007; Ozaki and Sevastyanova 2009; Tran et al. 2012; Li 2016; Greaker and Kristoffersen 2017; Springel 2016).

For example, Tran et al. (2012) find that the purchase decision is influenced by the consumer's interest in new technology as well as by financial benefits, environmental values,

[7] Note that the effect of a particular factor may vary across different types of EV buyers. For example, Zhang et al. (2016) find that the effect on business consumers is smaller than the effect on personal consumers.

and policy-related benefits. Ozaki and Sevastyanova (2009) report that financial benefits constitute an important motivating factor for the purchase of a (hybrid) EV, while emphasizing that the nature of social norms and the consumer's willingness to comply with such norms are also influential. Li (2016) (see also Greaker and Kristoffersen 2017) show that mandating compatibility in charging standards is likely to expand the size of the market for EVs. Finally, Kahn (2007) finds that in California, environmentalists are more prone to purchase an EV than non-environmentalists are.

Based on an extensive literature review, Rezvani, Jansson and Bodin (2015) organize the factors influencing the purchase of an EV in five categories:

(1) "attitudinal factors" (e.g., advantageous ownership and operation costs)
(2) "environmental" factors (e.g., a desire to contribute to protecting the environment)
(3) factors related to "innovation adaption" (e.g., seeing EVs as the car of the future)
(4) "symbolic" factors (e.g., buying an EV to express one's identity)
(5) "emotional" factors (e.g., positive feelings associated with driving an EV).

While these and other studies have identified a large number of relevant explanatory factors, others have attempted to determine the relative importance of different factors. A particularly interesting finding for policy makers is that the type of incentive seems as important as the incentive size. For example, Gallagher and Muehlegger (2011) study the relative effectiveness at the US state level of political measures such as sales tax waivers, income tax credits, and non-tax incentives. They find that, conditional on value, sales tax waivers tend to produce more than ten times the increase in hybrid EV sales produced by income tax credits. Springel (2016) reports an additional result that support the same general point: NOK100 million spent on subsidies for charging stations produce more than twice the increase in EV sales produced by the same amount of price subsidies. This is also supported by Wang et al. (2017), who find that in China, "convenience policy measures" (such as sufficient charging infrastructure) are more important than financial incentives and relevant information (e.g., concerning vehicle reliability) for motivating consumers to buy an EV.

Egbue and Long (2012) find, based on a survey, that concern for sustainability and the environment influence the purchase decision; however, in terms of importance, such concern ranks below concern about financial costs and vehicle performance. Finally, Noppers et al.

(2014) use both a "direct" method (asking the respondents) and an "indirect" (regression-based) method to study the relative importance of symbolic, instrumental and environmental factors on the purchase decision. The direct method suggests that symbolic factors (e.g., a desire to signal that one is a green person) are less important than instrumental factors (e.g., the price and the number of seats) and environmental factors (e.g., EVs' effect on the environment, relative to that of other vehicle types). Interestingly, however, the indirect method indicates that instrumental factors are less important than symbolic and environmental factors.[8]

2.2. How purchase of an EV influences driving

The second research question – how purchase of an EV influences the buyer's driving pattern – has so far received less attention than the first has. Moreover, scholars focusing on this second question have almost exclusively focused on Norway, presumably because of Norway's role as a front-runner in stimulating purchase and use of EVs.

In an early study based on a survey of 600 EV owners and 600 randomly sampled license holders in the three biggest Norwegian cities, Rødseth (2009) finds that purchase of an EV caused the buyers to increase their car use.

A related result is reported by Figenbaum, Kolbenstvedt and Elvebakk (2014), who find that EV owners in Norway on average drive longer per day than owners of internal combustion engine vehicles (ICEVs) do. In their survey, the number of respondents who increased their driving distance after purchasing an EV outweighed the number who reduced their driving distance by a factor of about three.[9]

Finally, again using a survey, Figenbaum and Kolbenstvedt (2016) find that the average daily distance driven by owners of battery EVs (BEVs) is longer than the corresponding distance driven by owners of plug-in hybrid EVs (PHEVs) and by owners of ICEVs. The average distance driven (among those using their vehicle) was roughly 30% longer for BEV owners than for PHEV owners and ICEV owners.

[8] We interpret this finding to mean that the results are not particularly robust.
[9] However, a majority of the respondents reported that their average driving distance remained unchanged when switching from an ICEV to an EV.

Why do EV owners drive more? First, the operating costs per kilometer of driving an EV equal only a fraction of the operating costs of driving a fossil-fuel driven car (e.g., Millo et al. 2014). Second, many respondents report a switch from public transportation to their new car after purchasing an EV (Rødseth 2009). For example, in Norway BEVs constitute an attractive option for commuters, because they are eligible for free parking in many public parking spots, exempt from paying toll money, and permitted to drive in the bus lane (provided the driver is accompanied by at least one passenger). Finally, purchasing an EV seems to reduce the buyer's sense of moral obligation to limit car driving (Klöckner et al. 2013).

In summary, much scholarly work has considered consumers' motives for purchasing an EV. Moreover, some research has considered how purchase of an EV influences car use. In contrast, few (if any) studies have thus far considered how increased use of EVs might influence the use of fossil-fuel-driven vehicles. We aim to contribute towards closing this gap.

3. The model

Assume that there are two types of cars available in the society - *green* (*g*) and *brown* (*b*). The green type is largely emissions free, while the brown type creates air pollution through combustion of fossil fuel. This pollution entails both local environmental effects (e.g., particulates, sulfur, NOx) and global environmental effects (CO_2). Due to the air pollution, the government wants to reduce the emissions from transport by increasing the share of green cars.[10]

We first present and analyze a model based on standard *homo oeconomicus* assumptions. We then consider an extension that includes social preferences.

3.1 A homo oeconomicus model

3.1.1 A static model formulation

The number of consumers (car owners) is fixed and normalized to one for simplicity. Each consumer must choose between a green car and a brown car. This choice depends on the consumer's preferences, for instance concerning environmental protection and new

[10] In reality, green cars such as EVs also creates local pollution as, e.g., particulates, but to a lesser extent than brown cars (diesel and gasoline cars).

technology. Consumers also care about financial benefits and about other benefits that facilitate the use of a green car (see section 2.1). We assume that, for each consumer, a tipping point exists where the consumer will switch from a brown to a green car. Moreover, consumers are heterogeneous in the sense that the location of this tipping point varies across consumers. This variation can be thought of as a fixed addition to the utility function that does not influence the driving and consumption decisions.[11]

Given the choice of car, the utility function of a consumer driving car *i*, *i=g,b*, can be specified as

(1) $$u\left(x_i, G\right) + v(y_i) + w(c_i), \quad \mathrm{i} = g, \mathrm{b}$$

$$u'_x > 0,\ u''_{x,x} < 0,\ v'_y > 0, v''_{\mathrm{y,y}} < 0,\ w'_c > 0,\ w''_{\mathrm{c},c} < 0,$$

$$u'_G < 0, u''_{G,G} < 0, u''_{\mathrm{x},G} < 0,$$

where *x* is miles driven by car, *y* is miles travelled with public transport, *c* is consumption of other consumption goods, and *G* is a local public bad creating a negative flow externality. All consumers are assumed to be identical, except concerning their preferences for car type.

We further assume that the demand for transport is completely inelastic, so that the demand for public transportation is determined by the demand for driving a car. For simplicity, the total demand for transport is set equal to one, i.e., $0 \le x_i \le 1, i = g, b$:

(2) $$y_i = 1 - x_i, \quad i = g, b$$

[11] The utility function for a consumer *j* can be specified as $U_j = v\left(x_j, c_j, G\right) + K_j$, where $K_j = \begin{cases} 0 \ \ for\ a < a_j^* \\ \bar{K} > 0 \ \ for\ a \ge a_j^* \end{cases}$ and $a = a(\underline{m})$, where $\underline{m}$ is a vector of policy instruments, all of which influence a positively. The tipping point $a_j^* \in (0, \infty)$ depends on individual preferences on for instance environment and technology (see section 2.1 above). The higher the preference for the environment and for new technology, the lower is the value of a_j^*. When $a \ge a_j^*$, the consumer switches from a brown car to a green car, which gives a higher utility given by the constant term $\bar{K}$. $v\left(x_j, c_j, G\right)$ is specified in equation (1). In equation (1) we do not include the constant term as this does not matter for the driving decision. However, the choice of car is reflected in the specification of the share of consumers driving a green car, see equation (3) below.

The public bad can be queues on the road or accidents, which follow from the number of cars on the road. The higher the public bad, the lower is the marginal utility from driving. The *G*-function can therefore be specified as

(3) $$G = n(s,t)x_g + (1 - n(s,t))x_b ,$$

where $0 < n < 1$ is the share of consumers driving a green car. This share is increasing in policy instruments such as subsidies of green cars (*s*) and taxes of brown cars (*t*).

Assume that without public policies, the total cost per mile of driving a green car equals *r* and that the corresponding cost for driving a fossil-fuel-based car equals *p*. Thus, the unit cost of driving a green car after public policies are implemented equals $\mathrm{r}(1-s)$, where *s* is the subsidy rate,[12] while the corresponding unit cost of driving a brown car equals $p(1+t)$, where *t* is the tax rate, i.e., , $0 \le s < 1$ and $0 \le t < 1$. We further let *f* denote the unit price of public transport, while *q* denotes the price of consumption. Then, the budget constraints for consumers using green and brown cars, respectively, become:[13]

(4) $$\mathrm{r}(1-s)x_g + fy_g + qc_g = B$$

(5) $$p(1+t)x_b + fy_b + qc_b = B$$

Inserting from (2) gives:

(6) $$ax_g + f + qc_g = B$$

(7) $$dx_b + f + qc_b = B,$$

where $a = r(1-s) - f$ and $d = p(1+t) - f$.

[12] As the unit cost *r* includes all costs of driving a green car, including capital depreciation, *s* covers a wide set of policy instruments, such as tax exemptions on purchase, free parking, free use of toll roads, etc.
[13] Note that the cost of buying a car only enters the budget condition through the unit cost of driving.

Both green and brown car owners maximize their utility functions in equation (1), given their budget conditions in (6) and (7), taking the behaviour of other car owners and the flow externality in (3) as given. Thus, we can calculate the Nash equilibrium. See the Appendix for more details on the calculations.

3.1.2 The effect of policy instruments

We first study the effects on driving green and brown cars by increasing the subsidy, *s*. We find:[14]

$$\text{(8)} \qquad \frac{\partial x_g}{\partial s} = \frac{\frac{ar}{q} x_g w_{cc}'' - r w_c' - q u_{xG}'' \frac{\partial G}{\partial s}}{q\left(u_{xx}'' + v_{yy}''\right) + \frac{a^2}{q} w_{cc}''}$$

$$\text{(9)} \qquad \frac{\partial x_b}{\partial s} = \frac{-q u_{xG}'' \frac{\partial G}{\partial s}}{q\left(u_{xx}'' + v_{yy}''\right) + \frac{d^2}{q} w_{cc}''}$$

The effect on green car drivers will depend on the effect of the price change, but also the effect on the externality, *G*. If $a > 0$, we see that green car driving will increase due to the change in price, but modified as result of queues.

As seen, the effect on brown car drivers of an increase in *s* only depends on the effect on *G*. Thus, we need to study the effect on total traffic of an increase in the subsidy rate:

$$\text{(10)} \qquad \frac{\partial G}{\partial s} = n_s'\left(x_g - x_b\right) + n\frac{\partial x_g}{\partial s} + (1-n)\frac{\partial x_b}{\partial s}$$

The effect on total traffic depends on three factors. The first term on the right-hand side is the effect of more consumers switching to a green car. If the unit cost of driving a green car is lower than that of driving a brown car, that is, $r(1-s) < p(1+t)$, then $x_g > x_b$,[15] and this term is positive (which is in line with the empirical literature in section 2.2). The second term

[14] See the Appendix for details.

[15] This follows from the optimization problems above as the only difference between the optimization problems for green and brown drivers are the prices of driving.

reflects the effect on green car driving. From (8) we see that the effect on x_g of an increase in s is positive (for $a > 0$), but moderated by the change in G. Finally, we see from (9) that the effect on x_b goes in the opposite direction of the effect on G. Thus, we find that $\frac{\partial G}{\partial s} > 0$ and $\frac{\partial x_b}{\partial s} < 0$.[16][17]

The intuition is the following. A subsidy on green cars makes green cars more attractive, and therefore increases the share of green cars on the road. In addition, green car owners drive more, because of a reduction of the unit cost of driving. Green car owners' use of public transport go down, meaning more traffic on the road. This change has a negative effect on brown car owners, who reduce their driving and increases their use of public transport. This gives Proposition 1:

Proposition 1: *An increase in the subsidy rate reduces driving by brown cars due to a negative externality following from more cars on the road.*

Next, we study the effect of a higher tax rate, t, on green car driving and brown car driving, respectively:

$$\text{(11)} \qquad \frac{\partial x_g}{\partial t} = \frac{-qu''_{xG}\frac{\partial G}{\partial t}}{q\left(u''_{xx} + v''_{yy}\right) + \frac{a^2}{q}w''_{cc}}$$

$$\text{(12)} \qquad \frac{\partial x_b}{\partial t} = \frac{-\frac{dp}{q}x_b w''_{cc} + pw'_c - qu''_{xG}\frac{\partial G}{\partial t}}{q\left(u''_{xx} + v''_{yy}\right) + \frac{d^2}{q}w''_{cc}}$$

[16] $\frac{\partial G}{\partial s} < 0$ gives a contradiction as this would make both x_g and x_b increase.

[17] The effect of less traffic on CO_2 emissions is not clear, because it depends on how fast the traffic flows without queues. The lowest emissions follow from a speed of about 60-70 kilometers an hour (km/h), and there are large emissions for speeds more than 100 km/h. Moreover, a queue that involves multiple starts and stops generates more emissions. For a study on emission factors related to car driving, see Fontaras et al. (2014). See also www.hbefa.net.

We see that the effect on green car driving only goes through the change in traffic on the road. Brown car driving will go down (for $d > 0$), but is moderated by the change in traffic.

The effect on traffic of taxation can be found from (3):

$$\text{(13)} \qquad \frac{\partial G}{\partial t} = n_t^{'}\left(x_g - x_b\right) + n\frac{\partial x_g}{\partial t} + (1-n)\frac{\partial x_b}{\partial t}$$

The first term on the right-hand side is the effect of a larger share of green cars on the road. Again, this effect is positive if the unit cost of driving a brown car exceeds the unit cost of driving a green car. The third term is negative, as driving with brown cars go down. Finally, the effect on green car owners (the second term) goes in the opposite direction of the effect on G, see (11). However, the effect on G is indeterminate, as the other two effects go in opposite directions. Thus, while an increase in taxation of brown cars reduces driving with brown cars and increases the demand for public transport by brown car owners, the effect on green car driving is indeterminate because the effect on total traffic is also indeterminate. Thus, the effect on total traffic is not necessarily symmetric for an increase in brown car taxation and green car subsidization. This gives Proposition 2:

Proposition 2: *A tax on brown cars will reduce driving with brown cars. The effect on total traffic and green car driving will be indeterminate.*

We now introduce a new policy instrument that can reduce the externality from traffic on the road, and at the same time can have a positive effect on increasing the share of green cars, namely allowing green car driving in the bus lane.[18]

Define α as the share of green cars that drive in the bus lane. Allowing driving in the bus lane means that green cars are less exposed to traffic, and this is therefore a non-financial benefit that increases the attractiveness of driving a green car (see section 2.1). We assume that this benefit adds to the other benefits of green car driving and has a positive effect on the transition to green cars. On the other hand, it increases traffic in the bus lane and may have a negative externality on public transport.

[18] This policy instrument was introduced in Norway in 2003 and it still applies even though there is now a restriction on the number of passengers in the car (see section 4.1).

The utility function for consumer *i* can now be written as:

(14) $$u\left(x_i, G\right) + v(y_i, \mathrm{F}) + w(c_i), \quad \mathrm{i} = g, \mathrm{b},$$

where *F* is the queue in the bus lane. In addition to the properties given in equation (1), we also assume that $v''_{yF} < 0, v'_F = 0$.

From the optimization problem of consumers (see the Appendix), we find that an increase in the number of green cars driving in the bus lane, α, gives:[19]

(15) $$\frac{\partial x_g}{\partial \alpha} = \frac{q\left(-u''_{xG}\frac{\partial G}{\partial \alpha} + qv''_{yF}\frac{\partial F}{\partial \alpha}\right)}{q\left(u''_{xx} + v''_{yy}\right) + \frac{a^2}{q}w''_{cc}},$$

(16) $$\frac{\partial x_b}{\partial \alpha} = \frac{q\left(-u''_{xG}\frac{\partial G}{\partial \alpha} + qv''_{yF}\frac{\partial F}{\partial \alpha}\right)}{q\left(u''_{xx} + v''_{yy}\right) + \frac{a^2}{q}w''_{cc}}.$$

As an increase in α does not have any impact on prices, the effects on driving with green and brown cars, respectively, are *symmetric* and depend only on the queues in the two lanes. Thus, the effects follow from how much traffic increases in the regular lane as well as in the bus lane. Note that while an increase in *G* reduces driving, an increase in *F* increases driving through lower demand for public transport.

Setting $F = n(\mathrm{s}, \mathrm{t}, \alpha)\alpha x_G$, we find:[20]

[19] This can be thought of as allowing driving in the bus lane, building more bus lanes so that more green cars can take advantage of them, or for instance reducing the number of passengers required for green cars to be allowed to drive in the bus lane.

[20] Note that if traffic in the bus lane is defined as $n\alpha x_g$, we assume that public transport is unaffected by the change in driving patterns, i.e., public transport enters as a constant which does not have any impact on the optimization and is, therefore, set equal to zero. This implies that a change in driving only affects the number of passengers on a bus and not the frequency of buses.

(17) $$\frac{\partial F}{\partial \alpha} = n^{'}\alpha x_g + n x_g + n\alpha \frac{\partial x_g}{\partial \alpha},$$

which is positive provided that the increase in α does not induce a large enough fall in green car driving, i.e., $\left| n\alpha \frac{\partial x_g}{\partial \alpha} \right| < n^{'}\alpha x_g + n x_g$.

Furthermore, total traffic in the regular lane equals:

(18) $$G = n\left(s,t,\alpha\right) x_g (1-\alpha) + (1-n\left(s,t,\alpha\right)) x_b .$$

The effect of an increase in α is:

(19) $$\frac{\partial G}{\partial \alpha} = n_{\alpha}^{'}\left(x_g(1-\alpha) - x_b\right) + n(1-\alpha)\frac{\partial x_g}{\partial \alpha} - n x_g + (1-n)\frac{\partial x_b}{\partial \alpha} .$$

The effects on G depends on several factors. First, as this is a benefit exclusively for green car owners, some consumers will switch to green cars ($n_{\alpha}^{'} > 0$). If α is substantial, so that $x_g(1-\alpha) - x_b < 0$, this switch will reduce traffic, i.e., G. Furthermore, this policy instrument has an impact on driving with green cars. If this effect is positive ($\frac{\partial x_g}{\partial \alpha} > 0$), it goes in the direction of more traffic. The third effect is the impact of moving green cars from the regular lane to the bus lane, thereby reducing traffic in the regular lane, while the final effect on traffic depends on how brown car owners are affected. Thus, the overall effect on traffic of allowing green cars to drive in the bus lane is indeterminate; in particular, it depends on how brown car owners react.

As the effect on G is indeterminate, we cannot determine the effects on driving with green and brown cars. However, if α is sufficiently large, permitting green cars to drive in the bus lane will likely increase green car driving, because such permission may reduce travelling time significantly. This can be the case when commuting into large cities. The effects on the two types of cars are symmetric: hence, we will then also get an increase in driving with brown cars. This effect is driven by reduced traffic in the regular lane (G goes down) and by reduced

demand for public transport due to more queues in the bus lane (*F* increases). We summarize these effects in Proposition 3.

Proposition 3: *While allowing driving in the bus lane accelerates the transition from brown to green cars, the effect on driving with the two types of cars is symmetric and indeterminate. One possible outcome is that both green and brown car owners will drive more.*

Finally, the effect of this policy instrument on CO_2 emissions is also indeterminate. A transition to more green cars has a negative impact on emissions, but emissions may still increase if brown cars end up driving (sufficiently) more.

3.2 The effect of changing driving habits

As mentioned in the introduction, consumers may be influenced by the behavior of other consumers. In section 2.2, we provided evidence that purchase of an EV tends to cause the buyer to drive more. This evidence is consistent with the model above if the unit price of driving a brown car exceeds the unit price of driving a green car (which is typically the case). Increased driving by EV owners may influence the behavior of brown car owners in other ways than the ones studied above. For instance, habits concerning driving may change, and social norms for accepted driving may also change.

As mentioned in the introduction, increased driving by EV owners might tempt petroleum-based car owners to drive more as well (a bandwagon effect). An observation by one of the authors of this paper may serve as an example. His son and all the boys in his class went to a summer course close to the city center, where it was hard to find parking spots and the public transport options were good. Nevertheless, EV owners began organizing driving groups where parents took turns in driving the boys to and from the course site. Many of the other parents (brown car owners) then followed by organizing driving groups as well.

Increased driving with green cars could also reduce the motivation of brown car owners to behave environmentally friendly. In Norwegian media, there is an ongoing debate about the effect on greenhouse gas emissions and other pollutants from EVs. Such debate might lead people to doubt that driving an EV really is more environmentally friendly than driving a petroleum-based car, thereby reducing their motivation to use public transport or other alternatives on shorter journeys.

Below we study how changes in the use of green car can change the habits of brown car drivers, due to bandwagon effects, social norms or to changes in motivation. We first start by extending the static model above before turning to a dynamic model.

3.2.1 A static model of social preferences

We know from the literature on peer effects that individual outcomes are highly correlated with group average outcomes, see the Introduction (section 1). Thus, if average driving in a neighborhood increases as a result of increased green car driving, brown car driving may also increase. We therefore now assume that the group average driving, that is, the average driving in the local community, influences brown car driving. We do not model the same effect on green car driving, as green car drivers are (at least at the present stage) the consumers who choose to deviate from the average local driving habits when switching to an EV.

Note that, as the number of consumers in the model is normalized to one, average driving when access to the bus lane is not permitted equals G as defined in equation (3). Based on this, we can specify the utility function of brown car owners as

$$(20) \qquad u\left(x_b, G\right) + v(y_b) + w(c_b) - \frac{\beta}{2}\left(x_b - G\right)^2,$$

while the utility function of green car owners is as given in equation (1). $\beta \geq 0$ determines how much weight the consumer attaches to the behavior of other consumers.

The effects on brown car use of an increase in the policy instruments s and t, respectively, now equals:

$$(21) \qquad \frac{\partial x_b}{\partial s} = \frac{-q\left(u''_{xG} + \beta\right)\frac{\partial G}{\partial s}}{q\left(u''_{xx} + v''_{yy}\right) + \frac{d^2}{q} w''_{cc} - \beta q}$$

$$(22) \qquad \frac{\partial x_b}{\partial t} = \frac{-\frac{dp}{q} x_b w''_{cc} + p w'_c - q\left(u''_{xG} + \beta\right)\frac{\partial G}{\partial t}}{q\left(u''_{xx} + v''_{yy}\right) + \frac{d^2}{q} w''_{cc} - \beta q}$$

The effect of each policy instrument depends on how much weight the consumer attaches to the change in the average driving habits. For $\beta > 0$, we see that the effect of habits reduce the effects of the policy instruments. For $u''_{xG} + \beta < 0$, the direction of the change remains unchanged, although the size of the effect is smaller. However, for $u''_{xG} + \beta \geq 0$, the effect of a higher subsidy will produce no reduction in brown car driving or even cause an increase. When it comes to the effect of taxation, the likely result is still a reduction in brown car driving; only for very high values of β could such driving increase.

The effect on the use of green cars still follows from (8) and (11); however, the size will change due to changes in *G*.

We can also find the effects of allowing green cars to drive in the bus lane. In this case, the utility function of a brown car driver will be:

$$(23) \qquad u\left(x_b, G\right) + v(y_b, F) + w(c_b) - \frac{\beta}{2}\left(x_b - H\right)^2.$$

Note that in this case, average driving will differ from *G*, as *G* follows from (18). Thus average driving will be:

$$(24) \qquad H = n\left(s,t,\alpha\right)x_g + (1 - n\left(s,t,\alpha\right))x_b.$$

The effect on the use of brown cars from increasing α will, therefore, be:[21]

$$(25) \qquad \frac{\partial x_b}{\partial \alpha} = \frac{q\left(-u''_{xG}\dfrac{\partial G}{\partial \alpha} + v''_{yF}\dfrac{\partial F}{\partial \alpha} - \beta\dfrac{\partial H}{\partial \alpha}\right)}{q\left(u''_{xx} + v''_{yy}\right) + \dfrac{d^2}{q}w''_{cc} - \beta q}.$$

[21] Again, the effect on green car driving is given by (15). Thus, the effects will not be symmetric anymore.

As before, including social preferences in the utility function of brown car owners generates the opposite effect of the other externalities, and may change the result from less to more driving with brown cars.

This gives Proposition 4:

Proposition 4: *If consumers are influenced by the average driving habits in the local community, the effects of policy instruments will be reduced and may even go in the opposite direction. In particular, brown car driving could increase.*

3.2.2 A dynamic model of social preferences

Habits can change slowly as they may be a function of earlier behavior. Assume that the brown car owner is influenced by the average driving in the community over a certain number of years (*h*) where the influence is higher for more recent events. Thus, a habit function can be specified as:

(26) $$I_t = \sum_{t-h}^{t} \mu_i G_i \ ,$$

where $\sum_i \mu_i = 1, \quad \mu_t \geq \mu_{t-1}$. This means that $G_t \geq I_t$.

As before, the drivers assume that their impact on *G* is negligible, thus they take *G* as given. However, introducing a policy instrument today will have impacts in *h* time periods ahead. Thus, it will influence behavior in all these time periods both for green and brown car owners.

For simplicity, we only study the impacts of increasing the subsidy on green car driving, *s*. We assume that there is an increase in subsidies at time *t*, and that the subsidy level is constant at this level in all future periods. All other prices are assumed constant.

As a special case, we first assume that $\mu_t = 1$, thus only average driving in the present period matters. In this case, there is a sequence of static optimization problems, and the results be as in equation (21) above, as the green and brown consumers immediately adjusts to a driving pattern they will keep in the periods to come.

In the general case, there is a partial adjustment to a new driving level. As the brown car driver takes *G* as given, she will just update her habits in the next period. All prices are constant, and the *I* will therefore, converge to *G* in the long run.

4. Empirical results

The model gives predictions on how the different policy instruments affects the use of polluting cars due to changes in prices, externalities and habits. As several policy instruments are introduced at the same time, it may be hard to predict which mechanisms will be the most important. Thus, we will use survey data to study the impacts on the use of polluting cars.

We first start with a description of the policies to promote EVs in Norway, before turning to the empirical results of the different methods.

4.1 Norwegian policies to promote electric cars

The development of the Norwegian Battery Electric Vehicle (BEV) policy has been the result of opportunities generated from niche market activities and actors, a weak national automotive regime, a powerful governance level, and international developments spanning 27 years (Figenbaum 2017).

The Norwegian policy framework for EVs dates back to 1990 when the first EV imported to Norway was granted an exemption from the import tax (Figenbaum 2017). That exemption has remained in force ever since, and in the 1990s it enabled the initial experimentation with EVs in cities and also an attempt to industrialize BEVs. The exemption was insufficient to stimulate sales and industrialization efforts. New incentives came with free driving on toll roads from 1997, free parking from 1998, and the value added tax (VAT) exemption from 2001 (Ibid). The latter must be seen in view of Ford Motor Company taking over the Norwegian BEV producer Think in 1999, creating the prospect of a national BEV industry. Fords main motivation was to produce BEVs for the Californian Zero Emission Vehicle (ZEV) mandate. Following the 2002 changes to the ZEV mandate, Ford decided that Think BEVs were no longer needed, and sold Think, which later went bankrupt. BEV industrialization hibernated internationally after 2003, and no BEVs were produced in Norway anymore. The Norwegian Public road authorities in Norway allowed BEVs to use the

bus lane from 2003 in Oslo and elsewhere from 2005. The other incentives were kept in place. Import of second hand BEVs kept the BEV option alive, and by 2008 more than 2000 BEVs were in use.

A focus on BEV adoption to meet climate policy targets led to a renewal of BEV policies with the introduction in 2009 of reduced rates for BEVs on ferries. The effects of the 2008/2009 financial crisis were counteracted with loans for the manufacture of BEVs to Nissan for the Leaf (in the UK), and a program to install the first public charging stations in Norway.

A giant window of opportunity appeared and Mitsubishi imported a BEV model to Norway from 2011, followed by sister models from Citroën and Peugeot and the Leaf from Nissan. With all the incentives still in place, several thousand experienced BEV owners, attractive local incentives and nationwide dealers, an instant success was achieved (Figenbaum 2017). The market expanded further with new models from Tesla, VW and BMW in 2013-14, and Kia and Hyundai 2015-16, and substantial price reductions as well as the installation of fast chargers along major roads. BEVs were, thanks to the tax exemptions, highly competitive in all market segments by 2015. Local incentives, i.e. the exemption from toll roads, reduced ferry rates, free parking and access to the bus lane, having an average value of 1500 Euro/BEV/year (Figenbaum and Kolbenstvedt 2016) boosted the market further. Other conditions favoring BEV adoption include cheap and clean electricity and access to home parking for the majority of households (Figenbaum and Kolbenstvedt 2015). BEVs are now an integral part of Norwegian Climate Policy (Figenbaum 2017).

4.2 Survey on transportation habits

4.2.1 About the survey

A survey of BEV and ICEV owners will be carried out in May 2018. This survey will be sent out among members of the Norwegian EV Association (NEVA), and the Norwegian Automobile Association (NAF). When buying a BEV at a dealer in Norway, the buyer gets one year of membership in NEVA for free. NEVA members are thus a representative sample of BEV owners. NAF is an interest organization for vehicle owners in general, thus representing a sample of vehicle owners in the Norwegian vehicle fleet. The survey will be broad in scope and will contain some questions related to how BEV ownership influences vehicle km driven.

Earlier surveys (Figenbaum et al 2014, Figenbaum and Kolbenstvedt 2016) have shown that BEV owners constitute a distinct group, being younger than average vehicle buyers, being full time workers belonging to households with children owning more than one vehicle, and having larger than average transportation needs. The 2016 survey showed that BEVs were bought as an additional vehicle (22%) more often than ICEVs were (12%). Buying an additional vehicle was, however, often the result of relocation of home or work place, change in the family situation, or frustration with the quality or availability of public transport. The majority (72%) of the respondents who replaced an ICEV with a BEV said total driving in the household remained unchanged (Figenbaum and Kolbenstvedt 2016), 20% of households drive more, 8% less than before, but the magnitude of the change is not known.

The responses from ICEV owners to the questions about BEVs reveal differences in opinions compared to BEV owners. Existing surveys, however, provide no data that could be used to identify external effects and a potential bandwagon effect of increased vehicle based travel among ICEV owners as a result of an increase in BEV ownership. This bandwagon effect could be difficult to identify with a general user survey, but the 2018 survey will be designed to provide more insights into these issues.

4.2.2 Results from the survey

To be done

5. Conclusions

Because transport accounts for a large part of greenhouse gas emissions, more than 25% in the EU, a reduction in emissions from transport is necessary to meet the targets of the Paris agreement. In addition, transport and particularly car use also create local pollution with adverse impacts on health. As one way to reduce the emission from transportation, governments in several countries have begun promoting purchase and use of emissions-free cars, such as EVs through financial as well as non-financial incentives.

In this paper, we study how such incentives affect non-targeted consumers, that is, consumers who choose to drive a polluting (brown) car. The incentives have two effects. First, they make non-polluting (green) cars more attractive, thereby reducing the number of brown cars on the road. Second, they change the use of both types of cars. Even if a policy instrument is

successful in causing a transition to green cars, total emissions could still increase if it results in more use of the remaining brown cars.

We present a simple model to study how different policy instruments such as subsidizing green cars, taxing brown cars, and allowing green cars to drive in the bus lane, affect driving with both types of cars. Car owners are influenced by price incentives, but also by external effects, such as accidents and queues outside and inside the bus lane. The latter may generate a substitution from public transport to car driving.

All policy instruments studied here are assumed to produce a transition from brown to green cars, based on the literature survey in section 2. Unsurprisingly, a subsidy on green cars will increase driving with such cars as the unit price of driving falls. This subsidy reduces driving with brown cars due to the negative externality from more cars on the road. Furthermore, a tax on brown cars reduces driving with brown cars. This reduction also makes green cars more attractive and increases the number of green cars. However, the effect on green car driving depends on change in traffic, and is indeterminate if green cars drive more than brown cars due to lower costs of driving. In this case, more green cars will increase traffic, while less driving with brown cars goes in the other direction.

We have also studied the implications of permitting green car driving in the bus lane. While such permission spurs the transition to green cars, the effect on driving is symmetric for both types of cars and depends on the impact on the traffic both in the regular lane and in the bus lane. The effect on traffic in the regular lane is indeterminate, as it depends mainly on the share of green cars that drive in the bus lane. If all green cars or a majority of these cars are allowed in bus lane, it is likely that traffic in the regular lane goes down. In addition, more traffic in the bus lane slows down buses and causes a transition from public transport to cars. Thus, a likely outcome is that driving with both types of cars increase.

Finally, we studied how change in average driving habits in the local community affects brown car driving through other channels. More driving with green cars may change the social norms of what is acceptable driving. It could also reduce the motivation of brown car drivers to behave environmentally friendly if they are annoyed by the policy to offer benefits to green car drivers. We model these possibilities by assuming that average driving has a positive impact on how much brown car owners choose to drive. Change in average driving

depends on the increase in the share of green cars (as green cars on average drive more due to lower costs) and on how much green car driving and brown car driving change due to use of the policy instruments. We show that if brown car driving is influenced by the group average driving, then the effects of policy instruments get weaker and may even change direction, so that brown car driving increases.

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Appendix

1. <u>The optimization problem for a *green* car driver</u>

The Lagrangian for a consumer driving a *green* car is:

(27) $$L_g = u\left(x_g, G\right) + v(1-x_g) + w(c_g) + \lambda_g \left(B - \left[r(1-s) - f\right]x_g - f - qc_g\right) ,$$

where λ_g is the Lagrange multiplier and $y_g = 1 - x_g$.

This gives the following first-order conditions, where the behavior of other drivers as well as G are taken as given:

(28) $$u_x^{'} - v_y^{'} = \lambda_g \left[r(1-\mathrm{s}) - \mathrm{f}\right]$$

(29) $$w_c^{'} = \lambda_g q$$

This gives

(30) $$\frac{u_x^{'} - v_y^{'}}{w_c^{'}} = \frac{a}{q} ,$$

where

(31) $$a = r(1-s) - f \ .$$

Equation (30) and the budget condition (6) determine x_g and c_g.

To find the effect of *an increase in s*, we get from (30) and (6):

(32) $$\frac{\partial x_g}{\partial s}\left(u_{xx}^{''} + v_{yy}^{''}\right)q = w_{cc}^{''} a \frac{\partial c_g}{\partial s} - w_c^{'} r - u_{xG}^{''} q \frac{\partial G}{\partial s}$$

(33) $$\frac{\partial c_g}{\partial s} = \frac{r}{q} x_g - \frac{a}{q}\frac{\partial x_g}{\partial s}$$

Inserting (33) into (32) gives:

$$(34) \qquad \frac{\partial x_g}{\partial s} = \frac{\frac{ar}{q} x_g w''_{cc} - r w'_c - q u''_{xG} \frac{\partial G}{\partial s}}{q\left(u''_{xx} + v''_{yy}\right) + \frac{a^2}{q} w''_{cc}} \ .$$

To see the effect of *an increase in t*, we find from (30) and (6):

$$(35) \qquad \frac{\partial x_g}{\partial t}\left(u''_{xx} + v''_{yy}\right) q = w''_{cc} a \frac{\partial c_g}{\partial t} - u''_{xG} q \frac{\partial G}{\partial t}$$

$$(36) \qquad \frac{\partial c_g}{\partial t} = -\frac{a}{q}\frac{\partial x_g}{\partial t}$$

Inserting (36) into (35) gives:

$$(37) \qquad \frac{\partial x_g}{\partial t} = \frac{-q u''_{xG} \frac{\partial G}{\partial t}}{q\left(u''_{xx} + v''_{yy}\right) + \frac{a^2}{q} w''_{cc}}$$

2. <u>The optimization problem for a *brown* car driver</u>

The Lagrangian for a consumer driving a *brown* car is:

$$(38) \qquad L_b = u\left(x_b, G\right) + v(1 - x_b) + w(c_b) + \lambda_b \left(B - \left[p(1+t) - f\right] x_b - f - q c_b\right)$$

where λ_b is the Lagrange multiplier and $y_b = 1 - x_b$.

The behavior of other drivers as well as *G* are taken as given. This gives the following first-order conditions:

$$(39) \qquad u'_x - v'_y = \lambda_b \left[p(1+t) - \mathrm{f}\right]$$

(40) $w_c^{'} = \lambda_b q$

This gives

(41) $$\frac{u_x^{'} - v_y^{'}}{w_c^{'}} = \frac{d}{q} \ ,$$

where

(42) $$d = p(1+t) - f \ .$$

Equation (41) and the budget condition (7) determine x_b and c_b.

To find the effect of *an increase in s*, we get from (41) and (7):

(43) $$\frac{\partial x_b}{\partial s}\left(u_{xx}^{''} + v_{yy}^{''}\right)q = w_{cc}^{''} d \frac{\partial c_b}{\partial s} - u_{xG}^{''} q \frac{\partial G}{\partial s}$$

(44) $$\frac{\partial c_b}{\partial s} = -\frac{d}{q}\frac{\partial x_b}{\partial s}$$

Inserting (44) in (43) gives:

(45) $$\frac{\partial x_b}{\partial s} = \frac{-q u_{xG}^{''} \dfrac{\partial G}{\partial s}}{q\left(u_{xx}^{''} + v_{yy}^{''}\right) + \dfrac{d^2}{q} w_{cc}^{''}}$$

To see the effect of *an increase in t*, we find from (41) and (7):

(46) $$\frac{\partial x_b}{\partial t}\left(u_{xx}^{''} + v_{yy}^{''}\right)q = w_{cc}^{''} d \frac{\partial c_b}{\partial t} + w_c^{'} p - u_{xG}^{''} q \frac{\partial G}{\partial t}$$

(47) $$\frac{\partial c_b}{\partial t} = -\frac{p}{q} x_b - \frac{d}{q}\frac{\partial x_b}{\partial t}$$

Inserting (33) into (32) gives:

(48) $$\frac{\partial x_b}{\partial t} = \frac{-\frac{dp}{q} x_b w_{cc}'' + p w_c' - q u_{xG}'' \frac{\partial G}{\partial t}}{q\left(u_{xx}'' + v_{yy}''\right) + \frac{d^2}{q} w_{cc}''} \ .$$

3. <u>Introducing driving in bus lanes</u>

The Lagrangian for a consumer driving a *green* car is now:

(49) $$L_g = u\left(x_g, G\right) + v(1 - x_g, \mathrm{n}\alpha x_g) + w(c_g) + \lambda_g \left(B - \left[r(1-s) - f\right] x_g - f - q c_g\right) \ ,$$

where λ_g is the Lagrange multiplier, $y_g = 1 - x_g$, $a = r(1-s) - f$, $F = n\alpha x_G$ and

(50) $$G = n\left(s,t,\alpha\right) x_g (1-\alpha) + (1 - n\left(s,t,\alpha\right)) x_b$$

As long as the behavior of other car drivers and the externalities, *G* and *F*, are taken as given, the first-order conditions are the same as given by (28) and (29). Differentiating (30) and taking into account the effects on *G* and *F* give:

(51) $$\frac{\partial x_g}{\partial \alpha}\left(u_{xx}'' + v_{yy}''\right) q = w_{cc}'' a \frac{\partial c_g}{\partial \alpha} - u_{xG}'' q \frac{\partial G}{\partial \alpha} + v_{yF}'' q \frac{\partial F}{\partial \alpha}$$

(52) $$\frac{\partial c_g}{\partial \alpha} = -\frac{a}{q} \frac{\partial x_g}{\partial \alpha}$$

Inserting (52) in (51) gives:

(53) $$\frac{\partial x_g}{\partial \alpha} = \frac{q\left(-u_{xG}'' \frac{\partial G}{\partial \alpha} + q v_{yF}'' \frac{\partial F}{\partial \alpha}\right)}{q\left(u_{xx}'' + v_{yy}''\right) + \frac{a^2}{q} w_{cc}''} \ .$$

In a similar way, we find the effects on brown car driving:

(54) $$\frac{\partial x_b}{\partial \alpha} = \frac{q\left(-u''_{xG}\frac{\partial G}{\partial \alpha} + qv''_{yF}\frac{\partial F}{\partial \alpha}\right)}{q\left(u''_{xx} + v''_{yy}\right) + \frac{d^2}{q}w''_{cc}} .$$

We also get

(55) $$\frac{\partial F}{\partial \alpha} = n'\alpha x_g + nx_g + n\alpha\frac{\partial x_g}{\partial \alpha}$$

(56) $$\frac{\partial G}{\partial \alpha} = n'_\alpha\left(x_g(1-\alpha) - x_b\right) + n(1-\alpha)\frac{\partial x_g}{\partial \alpha} - nx_g + (1-n)\frac{\partial x_b}{\partial \alpha}$$

4. <u>Introducing social preferences for brown car drivers</u>

The Lagrangian for a consumer driving a *brown* car is now:

(57) $$L_b = u\left(x_b, G\right) + v(y_b) + w(c_b) - \frac{\beta}{2}\left(x_b - G\right) + \lambda_b\left(B - \left[p(1+t) - f\right]x_b - f - qc_b\right)$$

where G follows from (3).

Setting $d = p(1+t) - f$ and $y_b = 1 - x_b$, the first order condition for a consumer who takes *G* as given is:

(58) $$\frac{u'_x - v'_y - \beta(x_b - G)}{w'_c} = \frac{d}{q} .$$

Differentiating this with respect to *s* gives:

(59) $$\frac{\partial x_b}{\partial s}\left(u''_{xx} + v''_{yy} - \beta\right)q = w''_{cc}d\frac{\partial c_b}{\partial s} - q\left(u''_{xG} + \beta\right)\frac{\partial G}{\partial s}$$

From the budget condition we have:

(60) $$\frac{\partial c_b}{\partial s} = -\frac{d}{q}\frac{\partial x_b}{\partial s}$$

Inserting (60) into (59) gives:

(61) $$\frac{\partial x_b}{\partial s} = \frac{-q\left(u''_{xG} + \beta\right)\frac{\partial G}{\partial s}}{q\left(u''_{xx} + v''_{yy}\right) + \frac{d^2}{q}w''_{cc} - \beta q}$$

Differentiating (58) with respect to *t* gives:

(62) $$\frac{\partial x_b}{\partial t}\left(u''_{xx} + v''_{yy} - \beta\right)q = w''_{cc}d\frac{\partial c_b}{\partial t} + w'_c p - q\left(u''_{xG} + \beta\right)\frac{\partial G}{\partial t}$$

From the budget condition we have:

(63) $$\frac{\partial c_b}{\partial t} = -\frac{p}{q}x_b - \frac{d}{q}\frac{\partial x_b}{\partial t}$$

Inserting (63) into (62) gives:

(64) $$\frac{\partial x_b}{\partial t} = \frac{-\frac{dp}{q}x_b w''_{cc} + pw'_c - q\left(u''_{xG} + \beta\right)\frac{\partial G}{\partial t}}{q\left(u''_{xx} + v''_{yy}\right) + \frac{d^2}{q}w''_{cc} - \beta q}$$

When introducing driving in bus lanes for green cars, the Lagrangian for a consumer driving a *brown* car will be:

(65) $$L_b = u\left(x_b, G\right) + v(y_b, F) + w(c_b) - \frac{\beta}{2}\left(x_b - H\right) + \lambda_b\left(B - \left[p(1+t) - f\right]x_b - f - qc_b\right),$$

where *G* follows from (18) and *H* is defined as:

(66) $$H = n(s,t,\alpha)\,x_g + (1 - n(s,t,\alpha))x_b\,.$$

The first-order condition for a consumer who takes *G*, *F*, and *H* as given is:

(67) $$\frac{u_x^{'} - v_y^{'} - \beta(x_b - G)}{w_c^{'}} = \frac{d}{q}\ .$$

Differentiating this with respect to α gives:

(68) $$\frac{\partial x_b}{\partial \alpha}\left(u_{xx}^{''} + v_{yy}^{''} - \beta\right)q = w_{cc}^{''} d\,\frac{\partial c_b}{\partial \alpha} - q u_{xG}^{''}\,\frac{\partial G}{\partial \alpha} + q v_{yF}^{''}\,\frac{\partial F}{\partial \alpha} - q\beta\,\frac{\partial H}{\partial \alpha}$$

From the budget condition, we have:

(69) $$\frac{\partial c_b}{\partial \alpha} = -\frac{d}{q}\frac{\partial x_b}{\partial \alpha}$$

Inserting (69) into (68) gives:

(70) $$\frac{\partial x_b}{\partial \alpha} = \frac{q\left(-u_{xG}^{''}\,\frac{\partial G}{\partial \alpha} + v_{yF}^{''}\,\frac{\partial F}{\partial \alpha} - \beta\,\frac{\partial H}{\partial \alpha}\right)}{q\left(u_{xx}^{''} + v_{yy}^{''}\right) + \frac{d^2}{q}\,w_{cc}^{''} - \beta q}\ .$$