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Money for nothing? Revisiting scrappage subsidy programmes

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Abstract

We study the effects of eligibility requirements for participation in scrappage subsidy programmes on consumer behaviour and environmental outcomes. We develop a theoretical framework illustrating how requirements on retired and replacement products affect consumer behaviour. We then empirically analyse the effects of a Dutch car scrappage subsidy programme on discarding and replacement decisions using quasi-experimental econometric methods. Differences in the effects of the programme by fuel type illustrate how the stringency of eligibility requirements determines outcomes. We find that the programme led to a strong increase in scrappage, especially for gasoline vehicles. About 40% of the extra scrappage is caused by individuals accelerating the sale of their old car. The programme also induced the purchase of newer, lighter and less polluting vehicles. We estimate that 3-7% of participants owning an old gasoline vehicle bought a younger vehicle than originally intended to meet the eligibility requirements of the programme.

Keywords: Scrappage, subsidy, free-rider, emissions, triple differences, regression discontinuity.

JEL codes: H23, H31, Q53, Q58.

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1. Introduction

Achieving environmental and climate goals requires households and firms to replace polluting and energy inefficient technologies with cleaner and more efficient ones. Governments employ a wide array of instruments to stimulate such replacements, including energy efficiency and emissions standards, taxes on emissions, cap-and-trade systems and technology adoption or replacement subsidies (see e.g. Stechemesser et al., 2024).

Technology replacement subsidies are a popular policy instrument in this context (Linn, 2020; Morrison et al., 2024). Such subsidies can be offered to households for a wide range of durable goods, but one of their most familiar applications is scrappage subsidy programmes for light-duty vehicles. Vehicle scrappage programmes have commonly been implemented in response to mounting concerns over the environmental effects of road transport, as well as to economic downturns hitting the car industry. For example, these were the main drivers of a wave of national programmes implemented during the 2008-2009 Great Recession, such as the 'Cash for Clunkers' programme in the US, and contemporaneous policies in Japan and many European countries (Grigolon et al., 2016; IHS Global Insight, 2010a; Li et al., 2013).

The goal of the scrappage subsidy programme and the information available to the government determine the eligibility criteria set for participation. Past vehicle scrappage programmes aimed to promote the purchase of the latest technologies and to offer short-term stimulus to the car market in difficult economic times, so they included criteria restricting the set of eligible replacement vehicles to (almost) *new* ones (IEA, 2020; IHS Global Insight, 2010b; Wappelhorst, 2020). However, environmental outcomes do not only depend on the replacement vehicle, but also – often crucially – on the retired one (Davis and Kahn, 2010). Furthermore, dirty technologies are often in the hands of lower-income households who are unable to afford purchasing a new vehicle (Jacobsen et al., 2023). Strict age requirements on replacement vehicles may therefore not only leave an important share of dirty technologies in operation, but also exclude lower-income households from scrappage programmes. Such an outcome may be undesirable, especially considering the rising importance of fairness in environmental and climate policy (Ankney and Leard, 2024; Sallee, 2019), and that scrappage subsidies are a well-suited instrument to incentivise lower-income households to invest in technologies that save both emissions and money in the long term (Dimitropoulos and Vrijburg, 2024).

We are the first to study how the eligibility criteria of a scrappage programme for old vehicles affect car owners' selling, purchasing and scrappage behaviour. We first provide a theoretical framework analysing how the stringency of eligibility criteria for replacement cars determines programme participation and vehicle choice. Replacement cars do not need to be new – they can instead be relatively clean used cars. We subsequently confirm our theoretical insights and estimate the effects of real-world criteria's stringency on car scrappage and trade with an ex-post analysis of a programme implemented in the Netherlands.

We develop a stylized model of the car market in which heterogeneous individuals trade new and used vehicles. We model the empirical regularity that the quality of the discarded vehicle correlates with the quality of the replacement vehicle. Our model shows that stricter requirements on replacement cause some consumers to buy a different (cleaner) vehicle than originally intended, but also discourage others from participating in the programme. Furthermore, it illustrates that the well-known adverse-selection problem for scrappage subsidies erodes the environmental gains expected from stricter eligibility criteria for replacement vehicles. This is because amongst the group of individuals who are affected by the stricter requirement, it is those who own vehicles with the highest pollution potential who are the least likely to buy a cleaner vehicle due to the programme. The model also allows us to define various types of programme participants based on the type of behaviour change – or the absence thereof – induced by the programme's requirements.

We complement our theoretical framework with an ex-post analysis of the effects of a Dutch scrappage subsidy programme implemented in 2009-2010. Within this programme, the stringency of eligibility requirements on retired and replacement vehicles varied by fuel type. Most notably, the eligibility requirement on *replacement* gasoline vehicles in the Dutch scheme was relatively lax compared to the vast majority of other national scrappage programmes (see IHS Global Insight, 2010b): participants could opt for a second-hand vehicle up to 9 years old. On the other hand, replacement diesel vehicles had to be almost new.

We use quasi-experimental econometric methods and a unique combination of detailed microdata on new and second-hand car sales, scrappages and characteristics to estimate the effects of eligibility requirements' stringency on retirement, trade and emissions. To establish reliable counterfactuals of consumer behaviour in the absence of the programme, we exploit two requirements imposed by the policy on the retired vehicle: one on its minimum age, and another on the minimum duration of ownership by the same individual. Our analysis relies on both a triple-difference approach and a regression discontinuity design, in which randomisation over ownership duration has a central role. Using the triple-difference estimates, we then quantify the size of the various types of programme participants emerging from our theoretical framework.

Three key findings emerge from our analysis, all of which align with our theory. First, the programme induced a strong increase in scrappage, which for gasoline vehicles was on average equivalent to a doubling of the scrappage rate. Second, on average 40% of the estimated extra scrappage is caused by individuals accelerating the sale of their old car (participant type *early trader*). Third, the programme induced the purchase of newer, lighter, less polluting and more fuel-efficient vehicles than those that would have been bought in its absence. However, two different behavioural mechanisms underpin this last result: (i) participants bringing forward the purchase of an eligible vehicle that would have otherwise been made later (early traders); and ii) participants buying cleaner vehicles than those they would have bought without the programme due to the eligibility requirement on replacement vehicles (called *type adjusters* in our framework). We estimate that 3-7% of participants owning a gasoline vehicle are such type adjusters. For owners of (generally more valuable) diesel cars, we do not find empirical evidence of vehicle choice changes in response to the policy.

Our results overall suggest that laxer programme requirements on replacement gasoline cars led to high scrappage additionality and cleaner car purchases. By contrast, the strict requirements on replacement diesel vehicles mostly discouraged owners of polluting diesel cars from participating in the programme.

Considering only tailpipe emissions savings of CO_2 and air pollutants, we estimate the environmental and public health benefits of the policy to be about 30% of the average subsidy for retired gasoline cars – which account for about 90% of all retirements in the programme – and 48% for retired diesel ones. However, we caution that the magnitude of those estimates is sensitive to the assumptions used to compute them. Benefits from improved vehicle safety (see e.g. Laborda and Moral, 2019) and from redistributing resources to lower-income households would come on top of these environmental benefits of the policy.

We fill a gap in the empirical literature on car scrappage subsidies, whose focus has been on programme effects either exclusively on purchasing or on scrappage (discarding) behaviour. To the best of our knowledge, we are the first to provide ex-post estimates of the scrappage, replacement *and* purchase additionality of a scrappage programme. These estimates are used to distinguish between different behavioural responses to the policy, namely early scrappage, early trading and the purchase of a different vehicle than intended.

A first strand of this empirical literature focuses on purchase additionality and estimates the short- and longer-term effects of scrappage programmes on new vehicle sales, and on associated environmental and economic outcomes. This strand mainly studies scrappage programmes introduced to stimulate car trade during the Great Recession in the US and Europe, and finds that new vehicle sales substantially increased during their implementation. However, while the short-term increase in sales induced by the 2009 Cash-for-Clunkers programme in the US was completely offset by a decline in sales in the months following it (Hoekstra et al., 2017; Li et al., 2013; Mian and Sufi, 2012), no such counteracting trends in sales were identified after the implementation of contemporaneous scrappage programmes in Europe (Grigolon et al., 2016; Helm et al., 2023). This strand also shows that scrappage programmes caused substantial improvements in the fuel efficiency and the overall environmental performance of new vehicles sold (Grigolon et al., 2016; Li et al., 2013), although these improvements may have occurred at relatively high public costs (Li et al., 2013).

We contribute to this first strand of the literature by quantifying scrappage additionality and by providing insight into the relative size of the two behavioural channels leading to extra purchases discussed above: first, participants purchasing earlier the vehicle they were anyway planning to buy, and second, participants choosing a different car than initially planned. Furthermore, we estimate that the scrappage programme increased the trade of used gasoline vehicles by almost 4%, something that studies relying only on new car sales data cannot investigate.

Another strand of the empirical literature concentrates on scrappage additionality and the implications of scrappage programmes for fleet composition and emissions savings. In contrast to the literature focusing on effects on new vehicle purchases, these studies do not cover programmes implemented in response to the Great Recession. Sandler (2012) finds that California's Smog Check Program led to much smaller emissions savings from early scrappage in the period 1996-2010 than anticipated, as retired vehicles would be driven relatively few additional kilometres in its absence. In Spain, the second largest car manufacturing country in Europe, most participants in the eight waves of scrappage programmes implemented between 2012 and 2016 scrapped their vehicle early, causing substantial nitrogen oxide emissions savings (Laborda and Moral, 2019).

Our main contribution to this second strand of the literature is showing that some participants who were anyway planning to scrap their old vehicle at the time of the policy – free-riders from a discarding point of view – may still purchase a cleaner vehicle due to the subsidy.

The closest study to ours is probably that by Ankney and Leard (2024), who ex-ante examine the effects of linking an electric vehicle (EV) purchase subsidy in the US with a scrappage requirement on both purchase and scrappage additionality. By contrast, we provide an ex-post study of a scrappage programme implemented in Europe. Furthermore, the two studies differ in their focus. The primary focus of Ankney and Leard (2024) is on adding a *scrappage requirement* to a purchase subsidy targeting cutting-edge technology, whereas ours is on the effects of the stringency of the *purchase requirement* of a scrappage subsidy aiming to reduce air pollution. In addition, we contribute to the literature by distinguishing between purchase additionality due to early trading and due to buying a different vehicle than originally intended, while their study does not deal with intertemporal shifting of purchases.

The rest of the paper is structured as follows. Section 2 discusses the details of the Dutch scrappage subsidy programme and compares its objectives and design with those of similar policies implemented in other countries. Section 3 presents our stylized model of the car market and the resulting typology of participant types in scrappage subsidy schemes. The data used in our empirical analysis are presented in Section 4. Section 5 describes our empirical approach, and Section 6 discusses the results of our analysis of the effects of the Dutch programme. Section 7 uses our empirical estimates to quantify the size of the various participant types in this programme. Section 8 estimates the monetised environmental benefits of the programme, while Section 9 presents the conclusions of our study.

2. Institutional setting: The 2009 national scrappage subsidy programme

In the beginning of May 2009, the Dutch government announced a scrappage subsidy programme to reduce air pollution from motor vehicles and stimulate the domestic car market

Table 1: National scrappage and replacement subsidy, 2009-2010.

Category	Fuel	Built	Subsidy
Passenger car or Light commercial vehicle	Fuel types other than diesel	Before 1990	750 €
Passenger car or Light commercial vehicle	Fuel types other than diesel	1990 – 1995	1000 €
Passenger car or Light commercial vehicle <1800kg	Diesel	Before 2000	1000 €
Light commercial vehicle ≥1800kg	Diesel	Before 2000	1750 €

Source: MuConsult (2010).

which had been hit by the Great Recession (MuConsult, 2010). Participants in the programme were required to trade in their old vehicle for scrap and replace it with a vehicle meeting certain age or pollution control technology criteria. The policy was implemented from 29 May 2009 until 21 April 2010, when the budget of 85 million Euros was depleted. Slightly less than a quarter of the budget for the policy (20 million €) was financed by the organization that is responsible for the recycling of end-of-life vehicles in the Netherlands (ARN, 2009). Public funds were used to cover the rest of the budget. Table 1 presents the amount of subsidy offered per type of vehicle scrapped and replaced.[1]

Eligibility for participation in the scrappage subsidy programme was determined by criteria on the vintage and pollution control technology of the retired and the replacement vehicle, as well as on the length of ownership of the retired vehicle. The retired vehicle should have first been registered before 2000, if operating on a diesel engine, or before 1996, if powered by other fuel types. EURO III and EURO II vehicle emissions standards were introduced in these two years respectively, so the aim of the policy was to remove gasoline and other non-diesel vehicles up to EURO I and diesel vehicles up to EURO II from the fleet.[2] In addition, the replaced vehicle

[1] Concurrently with the national programme, the Dutch cities of Amsterdam and The Hague implemented their own scrappage programmes, which did not include a car replacement requirement. More details on these local programmes are provided in Appendix A. Our data do not contain information on the spatial distribution of vehicle registrations, so we are unable to analyse the effects of local policies. However, we conjecture that the total number of participants in the local schemes is only a small fraction of the participants in the national programme. The effects of these programmes on car scrappage and trade are thus expected to be substantially smaller than the effects of the national programme. Given the explicit discouragement of vehicle replacement in Amsterdam and survey results showing that 20% of participants in The Hague did not replace their vehicle, the main effect of local schemes was most likely the early scrappage of polluting vehicles.

[2] The policy relied on vintage as a proxy for the emission standard met by old vehicles, as information on the latter only started being systematically recorded as of 2010 (Ministry of Housing, Spatial Planning and Environmental

should have been registered under the name of the current owner before 1 March 2008 and have been approved for road use for a period of at least 3 months after the date on which the vehicle is traded in. The latter could be proved by the result of a periodic motor vehicle (APK in Dutch) test. This implies that not properly functioning vehicles – vehicles that would not receive an “APK” approval without substantial repairs – were excluded from the policy, in order to limit free-riding. Old vehicles in dealers’ stocks were also excluded from participation in the programme.

Replacement vehicles could be new or second-hand. Pollution control technology requirements were stricter for diesel replacement vehicles than for vehicles powered by other fuel types. Diesel replacement vehicles should come with a pre-installed particulate filter, reducing the particulate matter emissions of the vehicle to a maximum of 5 mg/km. This requirement implied that the diesel replacement vehicle should meet the particulate emissions limit set by the EURO V standard, which was introduced in 2009. While the first diesel vehicle models with such particulate filters were introduced to the market in 2003, few EURO IV and even fewer EURO III models satisfied this condition. In practice, a replacement diesel vehicle had to be almost new. The requirement on replacement cars powered by other fuel types was much laxer. They should be first registered from 2001 onwards, thus they could be 9 years old at the end of the programme.

3. How do scrappage subsidies’ eligibility conditions affect the car market?

We develop a stylized model of the used car market inspired by Hendel and Lizzeri (1999), Stolyarov (2002) and van den Bijgaart and Cerruti (2022) to identify the expected behaviour changes induced by the eligibility criteria of scrappage subsidy programmes.

These behaviour changes affect social welfare in various ways which we do not model explicitly. For example, social welfare depends on the environmental gain achieved by scrappage programmes and on the incidence of government policy across income groups. We assume that without the scrappage programme *some* cars are scrapped later than socially optimal. This

Management, 2009). The EURO standards regulate emissions of particulate matter, carbon monoxide, nitrogen oxides, total hydrocarbons and non-methane volatile organic compounds by road vehicles in Europe.

is for example caused by the existence of external costs from car use that increase with car age, such as air pollution emissions (see Jacobsen et al., 2023).[3]

The environmental gain achieved by the scrappage programme is maximized when the owners of vehicles with the highest future pollution potential participate in the programme. Ignoring general equilibrium effects and the role of the replacement vehicle, the environmental benefit (b) of a vehicle participating in the programme is equal to the product of the number of potential *future* kilometres (km) travelled in this vehicle and its emissions rate per kilometre (r): $b = km * r$. This environmental benefit is relatively low when a car generates few emissions per kilometre and/or would be scrapped soon also without the scrappage programme.

We assume that the government only directly observes vehicle age and therefore cannot directly regulate the vehicle characteristics that determine the future pollution potential of a vehicle (see also Jacobsen et al., 2023; Linn, 2020; Sandler, 2012). Consequently, part of the subsidy is spent on individuals who trade in a vehicle with a very low pollution potential for scrap. Such individuals are conventionally called free-riders. When public funds are scarce – i.e. the marginal cost of public funds is larger than one – freeriding reduces social welfare. We analyse how the eligibility criteria of scrappage programmes affect the degree of freeriding into the scheme.

3.1. A model of the used car market

We assume that in every period there exist vehicles of various quality degradation levels $d \in [0, w]$, with zero reflecting the quality degradation of new cars, and w denoting the highest degree of degradation, i.e. that of non-functional cars. These vehicles are demanded by individuals that have heterogeneous tastes θ for quality degradation, such that the surplus of using a car of degradation level *d* is given by:

$$U(d, \theta) = \theta[\mu - d] - p(d) + \beta E[p(d + z)], \qquad (1)$$

with $\mu > w$ reflecting the quality of a new car and $\theta > 0$. The first term on the right-hand side of Eq. (1) reflects the surplus from holding a car of degradation level d one period, and the last

[3] In addition, government policy solely targeted at new vehicles – such as air pollution standards and registration taxes – may further delay scrappage (the Gruenspecht effect), see Jacobsen et al. (2023). This is also relevant for the Netherlands due to the presence of a tax on the first registration of a vehicle and the Euro standards.

two terms reflect the effective price of holding it. This effective price is equal to the depreciation of the vehicle over the period, where $\beta \in (0,1)$ denotes the annual discount rate.

We study a small country whose car market is integrated into the EU-wide one such that the consumer price $p(d)$ for cars of quality degradation level d is exogenously determined. We assume that price is a negative exponential function of the degradation level, namely that $p'(d) < 0$ and $p''(d) > 0$, and that there exists a lower bound to this price function which is determined by a finite material value for a car $p(m)$ that an owner can always receive from a scrap dealer. This finite value entails that the depreciation from using a car of degradation level d = m, the highest degradation level for which $p(d) = p(m)$, or higher for another period is zero.

The heterogeneous set of cars that exists in every period follows from a process that is random from the government's point of view. Specifically, all *new* cars are of the same quality μ. Quality subsequently degrades after a period of use through a (bad) quality shock z, distributed with probability density function $f(z)$ with support $[0, z_{max}]$. For a car with quality degradation d in the beginning of a period, degradation will be $d + z$ at the end of the period. We assume z is observable by market participants such that it affects the price of the vehicle and does not cause adverse selection on the second-hand market. This process of quality degradation ensures that although car age (a) and average quality degradation (d) are positively correlated, cars of the same age may have a different level of quality degradation, and thus a different price.

In line with Linn (2020), z may follow from factors, such as intensity of use, that directly determine future pollution potential (b) due to fewer future kilometres, but can also follow from factors, such as visual non-essential damage to the exterior or interior of the car, that affect comfort or sentimental value and therefore indirectly reduce the future pollution potential by accelerating scrappage. As both the cumulative number of kilometres travelled and the probability of non-essential damage increase in vehicle age, the future pollution potential decreases in it (see also Jacobsen et al., 2023; Linn, 2020).

In the absence of transaction costs, the combination of a utility function that is linear in degradation level d and of a price that is a negative convex function of d implies a unique optimal private value of degradation d_θ at which the individual's *per period* utility is maximized.

The value d_θ is determined by $\theta = \beta E[p'(d_\theta + z)] - p'(d_\theta)$. In the absence of transaction costs, individuals will never prefer a car of degradation level $d > m$, because such a car is of worse quality and equally expensive to a car of degradation level m.

Trade takes place at the end of a use period. We assume there exist transaction costs c such that not all individuals trade and buy their preferred car (d_θ) every period. Transaction costs are revealed at the end of the period and are distributed over individuals with the cumulative distribution function $G(c)$ with finite support $c \in [0, c_{max}]$. We disregard the option of repair by implicitly assuming that it is cheaper to trade in the vehicle for a car of higher quality than to repair it to a degree that restores its quality level to that at the start of the period.[4]

3.2. A scrappage subsidy programme with conditions only on the vehicle sold

We start by analysing how a flat-rate subsidy $S(a_s)$, a fixed subsidy offered for the scrappage of a vehicle of age a_s or older, affects trade by individuals and therefore participation in the scheme (see also Linn, 2020). The programme relies on registered car age because older vehicles have higher air pollution emission rates (r) which, conditional on kilometres travelled, raise their future pollution potential (b) (Jacobsen et al., 2023).

After observing d at the end of the period, and after transaction costs (c) are revealed, individuals owning a car meeting the age criterion of the policy will decide to *hold on* to their vehicle, instead of selling it, when:

$$\theta[\mu - d] + \beta\{E[p(d+z)] + P(\theta)\} > \max\{p(d), S(a_s)\} - c + V(\theta). \quad (2)$$

The left-hand side of Eq. (2) equals the expected surplus from using a car one extra period plus a payoff $P(\theta)$ afterwards. The right-hand side equals the financial reward of selling the car net of *revealed* transaction costs, plus the expected lifetime surplus – denoted by $V(\theta)$ – from buying and using the preferred car next period. If the car is sold at the end of next period, $P(\theta) = V(\theta) - E(c)$, i.e. the payoff equals the lifetime surplus from buying a car of the preferred quality net of expected transaction costs. However, the individual may hold on to the

[4] Our approach is therefore similar to Hendel and Lizzeri (1999), Stolyarov (2002) and van den Bijgaart and Cerruti (2022), who also model the option of either selling or trading without the option of repairing the existing car.

existing car for multiple periods, depending on the series of quality draws received, until it reaches the maximum degradation level the individual is willing to accept, defined as $d_\theta + x_\theta$.[5]

In the absence of $S(a_s)$, Eq. 2 defines the transaction costs $c_v(\theta, d)$ at which an individual with preference θ, who owns a car of degradation level d is indifferent between trading or holding this vehicle another period. The introduction of $S(a_s)$ increases the surplus from trading for individuals who own a car of age $a \geq a_s$ and of a degradation level for which $S(a_s) > p(d)$, henceforth the *potential set of participants*. The marginal transaction costs at which potential participants are indifferent between holding and trading are $c_v^s(\theta, d, a) > c_v(\theta, d)$. Eq. (2) allows us to categorize the participants in subsidy scheme $S(a_s)$ based on the realization of transaction costs:

I. *Counterfactual traders* would have also traded their car in the absence of the subsidy scheme. These individuals own an eligible car of degradation level d, for which $p(m) < p(d) < S(a_s)$ at the end of the period, and have transaction costs $c \leq c_v(\theta, d)$. They participate in the subsidy scheme causing *additional scrappages*, but not extra trade.
II. *Early traders* would have traded later without the subsidy. These individuals own an eligible car of degradation level d, for which $p(d_\theta + x_\theta) < p(d) < S(a_s)$ at the end of the period, and have transaction costs $c_v(\theta, d) < c \leq c_v^s(\theta, d, a)$. Due to these individuals, the subsidy scheme causes *both additional trade and additional scrappages*.
III. *Free-riders* would have also traded and offered the vehicle for scrap without the subsidy scheme. These individuals own an eligible car of degradation level d, for which $p(d) \leq p(m)$ at the end of the period, and have low transaction costs $c \leq c_v(\theta, d)$.

Adverse selection due to the government's inability to observe vehicle degradation limits the environmental and cost-effectiveness of the programme (Sandler, 2012). Conditional on the age of the vehicle, the scrappage programme attracts participants with relatively high values of vehicle degradation and low transaction costs. As degradation lowers the pollution potential,

[5] The *expected lifetime surplus* from vehicle use for an individual of type θ, $V(\theta)$, differs from the expression in Eq. (1), because it includes the discounted flow of expected *surpluses* from subsequent periods in which cars of various quality degradation levels are used ($d_\theta, \ldots, d_\theta + x_\theta$, where $d_\theta + x_\theta$ is the highest level of degradation an individual of type θ may hold when the highest possible transaction costs c_{max} are revealed), and a discounted stream of expected transaction costs. Specifically, the maximum degradation level that type θ will hold and use for another period ($d_\theta + x_\theta$), is defined at the point where Eq. (2) holds with equality for the maximum level of transaction costs c_{max}. Although individuals can always offer a vehicle for scrap at price $p(m)$, transaction costs may induce individuals with low values of θ to hold and use cars of a degradation level above m, i.e. this implies that $m < d_\theta + x_\theta \leq w$.

part of the subsidy is spent on individuals who trade in vehicles with a low future pollution potential. Introducing restrictions on the quality of the replacement vehicle can help increase the environmental and cost-effectiveness of the scrappage programme, as we will show in the following subsection.

3.3. A scrappage subsidy programme that restricts selling and buying

We now extend the analysis by adding an extra eligibility criterion to the subsidy scheme. Specifically, we study a flat-rate subsidy $S(a_s, a_b)$, where a_b denotes the *maximum* age of the *replacement* vehicle that the individual is allowed to buy.

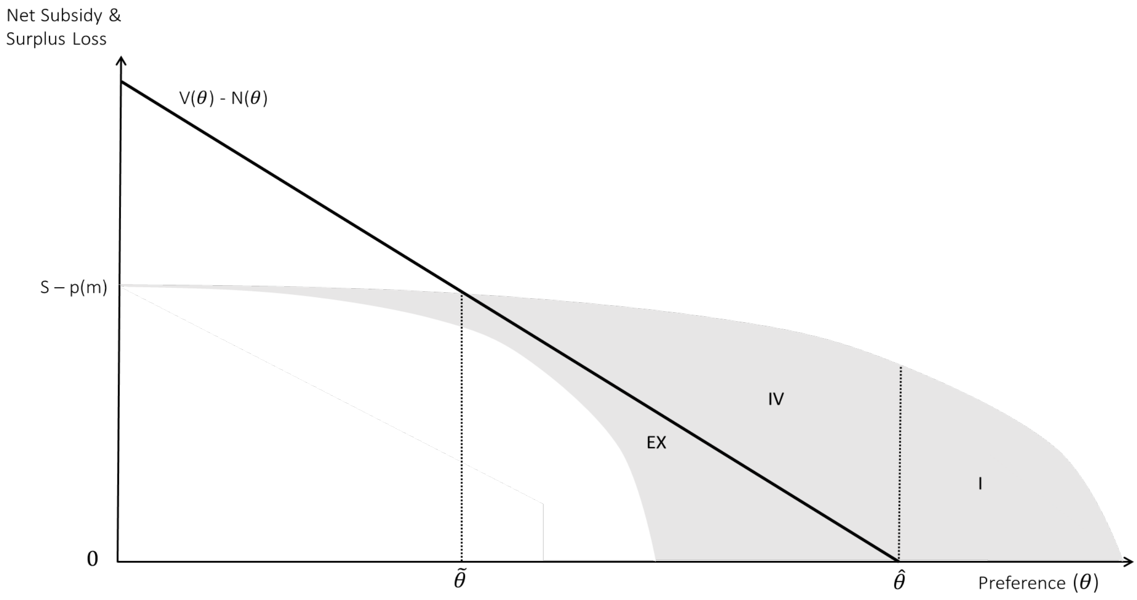
The criterion on the *replacement* vehicle complements criteria on the *replaced* vehicle in determining not only the *type of vehicles*, but also effectively the *type of owners* participating in a scrappage programme. The positive correlation between age and degradation level in our model implies that the maximum permitted age of the replacement vehicle, a_b, translates into a maximum allowed degradation level: $\hat{d} = a_b * z_{max}$. Individuals can be ranked according to their preferred car by parameter θ. The marginal individual not affected by the age requirement on the replacement vehicle is characterised by $\hat{\theta}$, such that $d_{\hat{\theta}} = \hat{d}$. Individuals with a value of $\theta \geq \hat{\theta}$ remain unaffected by this requirement. Individuals with preferences $\hat{\theta} > \theta$ either need to buy a car of higher quality than preferred to participate in the scheme, or are excluded from it.

Whether an individual with preferences $\theta < \hat{\theta}$ is willing to buy a car of higher quality depends both on the distance between the preferred and the marginally eligible vehicle, and on the vehicle currently owned. First, consider a *counterfactual trader* with transaction costs $c \leq c_v(\theta, d, a)$. As individuals can always opt out of the scheme and trade on the second-hand market, counterfactual traders *will only participate* when the net subsidy compensates the surplus loss, $V(\theta) - N(\theta)$, caused by the requirement on the replacement car:

$$S(a_s, a_b) - p(d) > V(\theta) - N(\theta). \qquad (3)$$

The surplus loss is defined as the difference between the lifetime surplus from holding the preferred car, $V(\theta)$, and the lifetime surplus $N(\theta) < V(\theta)$ from holding a (replacement) car that meets the requirement of the programme. While the net subsidy on the left-hand side of Eq. (3) is fully determined by the old vehicle owned, the surplus loss on the right-hand side depends on individual preferences for the replacement vehicle.

Figure 1: Identifying vehicle type adjusters



Note: The grey area illustrates the net subsidy faced by potential participants with $c \leq c_v(\theta, d)$. For every θ, the lower bound of the net subsidy is determined by individuals who own their preferred car (d_θ) at the start of the period, and whose car does not degrade during the period ($z = 0$). The upper bound of the net subsidy is determined by individuals who decided to hold on to a car of the lowest acceptable degradation level ($d_\theta + x_\theta$) at the start of the period, and whose car incurred the maximum possible degradation during the period ($z = z_{\max}$). The negative exponential price function $p(d)$, with a minimum determined by $d = m$, implies that the net subsidy reaches a maximum and the lower and upper bound converge to a constant for low values of θ, for which $d_\theta = m$. The solid line illustrates the surplus loss due to the eligibility requirement on the replacement vehicle. The figure shows an intermediate case where the subsidy is high enough to ensure that at least some individuals participate ($S > p\left(d_{\hat{\theta}} + x_{\hat{\theta}}\right)$), but is not high enough to persuade all individuals with $\theta \leq \hat{\theta}$ to participate ($S < V(0) - N(0) + p(m)$). We only show positive values for the net subsidy, because individuals for whom the net subsidy is negative will not be interested in the scheme.

The different terms of Eq. (3) as a function of θ are illustrated in Figure 1. The value of the net subsidy for all potential participants is represented by the grey area, while the surplus loss as the solid line (linear for ease of exposition). The net subsidy exceeds the surplus loss for individuals above the solid line and, hence, these individuals participate in the scheme.

The net subsidy is presented by an area, because it is determined by the degradation level of the old vehicle. On average, individuals with a lower θ own cars with a lower value, and thus benefit from a higher net subsidy. However, individuals with a given preference θ own cars of various degradation levels, so the net subsidy varies accordingly. The surplus loss declines in θ, because individuals with a higher aversion for degradation value the required minimum quality of the replacement car more relative to the higher price of such a car.[6]

Individuals with $\theta \geq \hat{\theta}$ participate in the scheme and are defined as counterfactual traders in Section 3.2 (indicated by I in Figure 1). Individuals with $\theta < \hat{\theta}$ who own a relatively valuable car are shown below the solid line and are effectively excluded from the policy (individuals indicated by EX). This includes individuals with $\theta < \tilde{\theta}$, for which the surplus loss always exceeds the net subsidy received, regardless of the car owned. Participation in the extended scheme $S(a_s, a_b)$ is therefore strictly smaller than under $S(a_s)$. Individuals with $\theta < \hat{\theta}$ who own less valuable cars are shown above the solid line, and participate in the scheme by buying a car of higher quality than preferred. This yields the final participant type:

IV. *Pure type adjusters* participate in the scrappage subsidy scheme by buying a car of higher quality than preferred. This causes additional trading of cars of low degradation. They are individuals with preferences $\tilde{\theta} < \theta < \hat{\theta}$ who own an eligible car of degradation level d for which Eq. (3) holds, and have transaction costs $c < c_v(\theta, d)$.

In general, the restriction on the replacement vehicle raises environmental effectiveness by excluding individuals with low values of θ. This is because these individuals own *on average* cars of a high degradation level and, hence, relatively low pollution potential. However, similarly to the scheme without a buying condition, self-selection implies that within this group of individuals with $\tilde{\theta} < \theta < \hat{\theta}$, the individuals most likely to participate in the scheme (type IV) are those who own the most degraded vehicles (with the lowest pollution potential). This limits the potential gain in environmental effectiveness.

The discussion thus far focused on counterfactual traders (with $c \leq c_v(\theta, d)$). However, also potential *early traders*, with $c > c_v(\theta, d)$, are similarly affected by incentives offered by the extended subsidy scheme. The difference is that early traders who would prefer to buy an ineligible car without the scheme will only participate in it if the surplus from participation compensates *both* the relatively high transaction costs and the surplus loss caused by the requirement on the replacement car. If it does, not only do early traders sell their vehicle earlier

[6] The value of the surplus loss $V(\theta) - N(\theta)$ is determined by: i) a surplus gain due to the participant buying (and using) a vehicle of a lower degradation level ($\hat{d}$) than the preferred vehicle (d_θ), and; ii) a surplus loss due to the participant having to pay a higher price for a better quality car $p(\hat{d}) - p(d_\theta) > 0$.

but also buy a different vehicle than preferred.[7] As the requirement on the replacement vehicle reduces the surplus from participation also for early traders, we conclude that the number of early traders due to the extended scheme $S(a_s, a_b)$ is strictly smaller than under $S(a_s)$.

4. Data

We now proceed to the description of the data used in our empirical analysis of the effects of the Dutch scrappage subsidy scheme. We make use of four sets of administrative microdata in this analysis, linked and merged through vehicles' unique license plate numbers. The first three are obtained from the Netherlands Vehicle Authority (RDW), while the fourth one from the Netherlands Enterprise Agency (RVO). The first dataset contains the complete registry of cars in the Netherlands from 2007 until July 2016. We observe registrations per individual identifier (id) and vehicle license plate number.[8] The second dataset contains information on an extensive set of characteristics for each car in the registry, including brand and model name, fuel type, date of first registration, vehicle weight, engine characteristics, and (type-approval) CO_2 and air emissions. The third dataset contains information on all vehicle retirements from the fleet. For each retirement, it presents the date it occurred and the reason for which the car was retired from the fleet, such as for scrappage or export. The fourth dataset provides a complete list of the cars participating in the scrappage programme. Each scrapped vehicle is matched with the vehicle replacing it and with the amount of subsidy received by its owner.

By merging the microdata mentioned above, we construct a dataset that consists of unique car-owner combinations. This dataset contains the following information per combination: the start and end dates of ownership, the car's characteristics, and whether the car has subsequently been scrapped in, or exported from, the Netherlands.

The replacement vehicle can be determined with some uncertainty. We only observe the number of days between subsequent deregistrations and new registrations made by an

[7] Compared to Section 3.2, the requirement on the replacement vehicle reduces the surplus from participation, and therefore reduces the transaction costs at which the marginal individual is indifferent between holding and trading to $c_v^b(\theta, d, a) < c_v^s(\theta, d, a)$. In the limit, individuals with the lowest preference for degradation in this set $(\theta \rightarrow \tilde{\theta})$, who are almost indifferent between participating and adjusting their buying decision or not participating at all, will also not trade earlier under subsidy scheme $S(a_s, a_b)$.

[8] We focus on registrations by individuals as we want to study their replacement decisions. We cannot reliably identify vehicle replacements by firms, as they frequently make multiple registrations simultaneously.

Table 2: Aggregate descriptive statistics on transfer, scrappage, export and replacement

	Total		Gasoline					Diesel				
	Vehicles #	Scrap. #	Share %	End. %	Scrap %	Exp. %	Repl. %	Share %	End. %	Scrap %	Exp. %	Repl. %
2008	4,996,347	157,993	82%	25%	3%	2%	14%	18%	28%	2%	8%	15%
2009	5,129,261	235,158	82%	25%	5%	2%	14%	18%	28%	3%	7%	15%
2010	5,231,490	175,706	82%	25%	4%	2%	15%	18%	29%	2%	8%	15%
2011	5,284,163	179,447	81%	25%	4%	3%	14%	19%	28%	2%	8%	15%
2012	5,320,986	174,942	81%	24%	4%	2%	13%	19%	27%	2%	8%	14%

Note: The years mentioned in the left column start on May 29th of the respective year. The headings of the columns have the following definitions: *Share:* the share of a fuel type in the vehicle fleet; *End.:* vehicle ownership terminations; *Scrap.:* scrappage, *Exp.:* export; *Repl.:* replacements. Ownership terminations, scrappages, exports and replacements are all defined relative to the total number of cars at the start of the period. Although replacement is conditional on ownership termination, the percentage reflects replacements relative to the total number of cars.

individual, as well as the characteristics of registered and deregistered vehicles. In about 50% of the cases, one car is deregistered and another car is simultaneously registered by the same individual, strongly suggesting a replacement. But in some cases, deregistration and registration are separated by two months or more, such that it is unclear whether this is a replacement decision – in an economic sense – or two separate decisions, one on sale and another on purchase. When multiple cars are purchased around the time of a vehicle's deregistration, we use information on weight to determine which of the purchased vehicles has most likely replaced the old vehicle.

Based on these observations, we coded a car being a replacement vehicle when: (i) the registration of this car by an individual occurs within 30 days before or after the deregistration of another car by the same individual; (ii) the car is closest in weight to the replaced car, in case multiple potential replacement cars fall in the time window of 61 days (for example, when an individual trades in a family car and buys back one family car and one additional car); and (iii) the duration of ownership of the new vehicle is at least 30 days, to rule out small-scale car traders. The first condition highlights that replacement should be made by the same person. When someone sells their car, and another person – maybe from the same household - buys a car that serves as a replacement, this cannot be traced by our dataset.[9]

[9] We internally validated our replacement algorithm by applying it to the vehicles participating in the policy, as identified in our fourth dataset. In 83% of the cases, our replacement algorithm was successful in pinpointing the car that was actually registered as the replacement car in the subsidy programme. In the rest of the cases, we

Based on the start and end date of registrations, we can follow car-owner combinations over time and compute the fraction of vehicle ownership transfers, scrappages, and replacements for every year of our analysis. A *policy year* is defined from May 29th until May 28th in the subsequent calendar year, in line with the fact that the policy took effect on 29 May 2009. Table 2 presents summary statistics per year and fuel type for vehicles aged 6 years or older at the time of the introduction of the policy. According to our calculations, on average 56% of the observed ownership terminations (End.) are followed by a replacement (Repl.) by the same individual within 60 days, some 750,000 replacements a year.

5. Empirical approach

We estimate the effects of the scrappage programme on scrappage, trade in used vehicles, and sales of eligible vehicles using two empirical strategies. First, a regression discontinuity design that allows us to estimate the 'local' effects of the policy around eligibility requirement thresholds. Second, a triple-difference approach which enables estimating the more global effects of the policy. The latter is used to identify the direct causal effects of the policy that follow from the model discussed in Section 3, and informs the policy evaluation in Sections 7 and 8.

5.1. Regression Discontinuity Design

We start by focusing on the marginal (local) effect of the policy. To this end, we use a cross-section of cars just before the policy was enacted and exploit the discontinuities in the eligibility requirements on the minimum age of the old vehicle and on the minimum period it should have been held by an individual at the time the programme was launched. Our regression discontinuity design yields a consistent estimate of the intention to treat because the policy excludes anticipation effects (see Section 2), and there are no other national policies with the same thresholds implemented on 29 May 2009.[10]

We construct a snapshot of cars on 29 May 2009 and define an indicator y_i for *each* car-owner combination i in our cross-section that shows whether a given event occurred in a subsequent period. The events we study are ownership terminations (deregistrations) and scrappages of

were not able to identify the right replacement vehicle either because it was registered under another individual, or because the replacement occurred too late to fall within our economic definition of replacement, or because the replacement vehicle was registered under the same individual for a period shorter than 30 days.

[10] A stricter local scrappage subsidy scheme was implemented in the city of Amsterdam on the same date (see Appendix A.2), but the subsample we use does not include vehicles eligible for that scheme.

old vehicles, purchases (registrations) of replacement vehicles, and purchases of replacement vehicles of a *qualifying type*, i.e. vehicles under the age limit set by the policy.[11]

Furthermore, we construct variables that measure the distance to the eligibility threshold of interest, $x_{g,i}$, with *g* capturing either the age threshold (*a*) or the ownership duration threshold (*o*), both measured in days. Finally, we construct indicator variable $e_{g,i}$ that determines whether car-owner combination *i* was eligible for the policy. The regression discontinuity estimate now separates the continuous effect of distance to eligibility from the effect of the discrete jump in eligibility due to the policy (α):

$$y_i = \beta_{a<e}\, x_{a,i} + \gamma_{a>e}\, x_{a,i} + \beta_{o<e}\, x_{o,i} + \gamma_{o>e}\, x_{o,i} + \alpha\, e_{a,i}\, e_{o,i} + \varepsilon_i \tag{4}$$

where ε_i denotes the residual.

We reduce the cross-section of car-owner combinations considered to cars that: (i) have been in the possession of the current owner for 394 to 514 days (eligible if possessed for at least 454 days); and (ii) are 12-15 years old and drive on gasoline (eligible if at least 14 years old) or 8-11 years old and drive on diesel (eligible if at least 10 years old).

Following Hoekstra et al. (2017), we vary the period of interest. We estimate the effect in the first year after which the policy is active, but also in the longer run (until May 28th, 2013). The latter estimate provides insight into the extent of intertemporal shifting due to the programme. If the policy causes only limited intertemporal shifting of car scrappage and replacement, there will be no noticeable difference between the treatment and control group in the longer run.

5.2. Triple-difference estimator

We rely on a triple-difference approach to estimate an average intention-to-treat effect of the scrappage subsidy on the ownership termination (deregistration), scrappage and replacement of old vehicles, and the purchase of eligible replacement vehicles. Again, we exploit the eligibility requirements of the programme that allow us to construct control groups of vehicle-owner combinations that were ineligible to participate in it and thereby were not affected by

[11] No age criterion applies to diesel replacement cars, but instead a requirement for a pre-installed particulate filter and a maximum limit for PM emissions per km. As we lack complete information on these vehicle characteristics, we use the age of the diesel vehicle, which serves as a relatively good proxy for the existence of a pre-installed particulate filter.

the policy.[12] The identifying assumption underlying the triple-difference estimator in this context is a parallel trend in the differential between the two age groups and the two ownership duration groups (Olden and Møen, 2022).

For the triple-difference estimator we do not use individual cars or individual owners as our unit of observation, but we construct baskets of similar car-owner combinations and follow these baskets over time (Policy years). A basket is characterised by car age,[13] fuel type, and the duration of current ownership. From this definition, it follows that cars that belong to a particular basket are either eligible to participate in the policy or not. The basket is eligible when vehicles are old enough and have been with the same owner for a long enough period. We only follow cars aged between 6 and 25 years old, and we define 23 ownership duration groups.

We follow baskets for five *policy* years, from 29 May 2008 until 28 May 2013. This definition implies that the policy is effective in the second year of our panel, from 29 May 2009 until 28 May 2010. We thus observe one year before the policy and three years after.

For each basket and fuel type, we define outcome variables $y_{ao,t}$ that are equal to the ratio of the number of events occurring during a policy year, to the number of vehicles of type *a*, o belonging to the basket in the beginning of that policy year. Here *a* stands for vehicle age and *o* for ownership duration. Our focus is on the events described in subsection 5.1 – in section 6.3.2 we discuss how we apply a similar approach to the quality attributes of the replacement vehicles.

Given these definitions, we estimate the following equation *separately for gasoline and diesel* vehicles:

$$Y_{ao,t} = \mathbf{d_t} + \mathbf{d_{ao}} + \mathbf{d_v} + \beta_1\, s_t\, e_o + \beta_2\, s_t\, e_a + \beta_3\, s_t\, e_a\, e_o + \beta_4\, s_{t+1}\, e_{a+1} + \beta_5\, s_{t+2}\, e_{a+2} + \beta_6\, s_{t+3}\, e_{a+3} + \varepsilon_{ao,t}\,, \quad (5)$$

where $\mathbf{d_t}$ denotes a vector of policy year fixed effects, $\mathbf{d_{ao}}$ is a vector of two-way fixed effects capturing the two cross-section identifiers, i.e. vehicle age and length of ownership, and $\varepsilon_{ao,t}$ is the error term. Dummy variable s_t equals 1 in the year in which the policy is effective, dummy variable e_a equals 1 for baskets containing cars with an eligible age, and dummy variable e_o

[12] See Bento et al. (2018), Jacobsen and Van Benthem (2015), and Laborda and Moral (2019) for studies that also use cars that are younger than required by the policy in the control group. By contrast, Alberini et al. (2018) and Li et al. (2013) use cross-region variation to establish a control group.

[13] Car age is defined relative to January 1st of the respective year, which is in line with the eligibility criteria for the policy. A given car will belong to incrementally older baskets when considered in subsequent years.

equals 1 for baskets with cars that are owned by the current owner long enough to be eligible. Coefficient β_3 captures the *intention-to-treat* effect of the policy, and is therefore our coefficient of interest.

The vector of dummies $\mathbf{d_{ao}}$ captures the average ratio for cars of a particular age and ownership duration during the whole length of the panel, and nests the single eligibility condition dummies e_a and e_o. The inclusion of vectors $\mathbf{d_{ao}}$ and $\mathbf{d_t}$ in the specification ensures that all single eligibility conditions are accounted for. In addition, the double difference $e_{ao} = e_a{*}e_o$ is also captured as a special case of d_{ao}. This leaves just s_t e_o and s_t e_a as necessary additional interaction terms to ensure consistency of the estimator.[14]

The panel structure with yearly baskets of car age and ownership duration does not directly control for differences between vintages – cars built in a particular year – in the outcome variable.[15] If the programme targets older vintages for a specific reason, such as an outdated emissions abatement technology, vintage effects are potentially correlated with the policy. The probability of scrap might also be different for specific vintages due to underlying vehicle quality differences. Moreover, the size of a particular vintage might be relatively small, because new car sales were low in the year the vintage was new (due to e.g. unfavourable economic circumstances). Therefore, we include the vector of vintage dummies $\mathbf{d_v}$ in our model.[16]

The penultimate three terms in Eq. (5) are lagged policy effects, interactions between lagged subsidy dummy variables s_{t+1} to s_{t+3}, and age eligibility dummy variables e_{a+1} to e_{a+3}. Controlling for such lagged effects is important because the policy potentially shifts scrappage, sales and replacements over time and because extra scrappages and sales due to the policy reduce the number of cars in eligible baskets in the years after the policy. Important for the identification strategy is that a substantial part of the total group of eligible cars – about 30% – is within one year of the policy cut-off. This implies that one year after the policy roughly 30% of cars of eligible age are considered unaffected by the policy, and after two years 60%.

[14] When we take $\mathbf{Y_{ao,t}}$ to equal the scrappage rate for a basket, our specification comes close to the empirical hazard rate defined in Laborda and Moral (2019). The number of cars in a given basket declines over time, following a survival function. The two-way fixed effect $\mathbf{d_{ao}}$ controls for the survival rate of cars of different ages, averaged over owners who possess them for a similar amount of time. The empirical scrappage rate might also be a non-linear function of its determinants – see e.g. Bento et al. (2018), Jacobsen and Van Benthem (2015), Laborda and Moral (2019) and Li et al. (2013).

[15] Vehicle age and vintage are closely interlinked. However, age changes over time, while vintage remains unaffected by it. For example, while the age of a vehicle will be *a+1* in *t+1*, its vintage will remain *v*.

[16] Together with $e_{ta} = s_t$ e_a,, d_v is a subset of the total set of d_{ta} dummies that could have been included.

Furthermore, general equilibrium effects could potentially lead to biased coefficients when the policy that targets the older vintages also affects the same outcome variable amongst younger vintages. However, the small scale of the programme and the open EU car market make it unlikely that the policy systematically affected the scrappage of younger cars in the Netherlands.

How much earlier are participating vehicles traded?

To estimate the environmental benefits of the policy (see Section 8), we need to know how many days earlier old vehicles are traded due to the subsidy programme. For this purpose, we use a similar triple-difference approach to the one presented above. Specifically, our empirical model follows Eq. (5), but this time the dependent variable is the *remaining* duration of ownership, counted in days from the beginning of the period (May 29th). Furthermore, we do not use the period before the introduction of the scrappage programme (May 2008 – May 2009) in this analysis, because the remaining duration of ownership of many vehicles in that period is also affected by the policy. Therefore, our identification relies on differences between the year of the policy and the years thereafter, in addition to differences between the eligible and ineligible groups.

For many vehicles in our sample, the day of trade is beyond our final observation, i.e. beyond July 2016. Hence, we censor the variable by assigning the value of 1500 days to observations beyond July 2016. This is not only equal to the difference between the date at which the youngest basket of our panel starts (May 29th, 2012) and the end of our period of observation (July 2016), but also to the average holding period observed in our study.

This approach allows us to estimate the intention-to-treat effect of *eligibility* for participation in the scheme on ownership duration. We then infer the impact of *participation* in the scheme on ownership duration by dividing the estimated intention-to-treat effect by the share of participating vehicles in those eligible for the policy.[17]

[17] An alternative approach would be to employ cross-sectional regression models, directly estimating the effect of participation in the scheme on ownership duration. However, the estimates from these models are more prone to bias, as participating car-owner combinations may be inherently different from those not participating in the scheme. For example, participating vehicles may be of lower quality and their owners more willing to forgo them. We describe this approach in more detail and present results from estimated models in Appendix B.

6. Empirical analysis

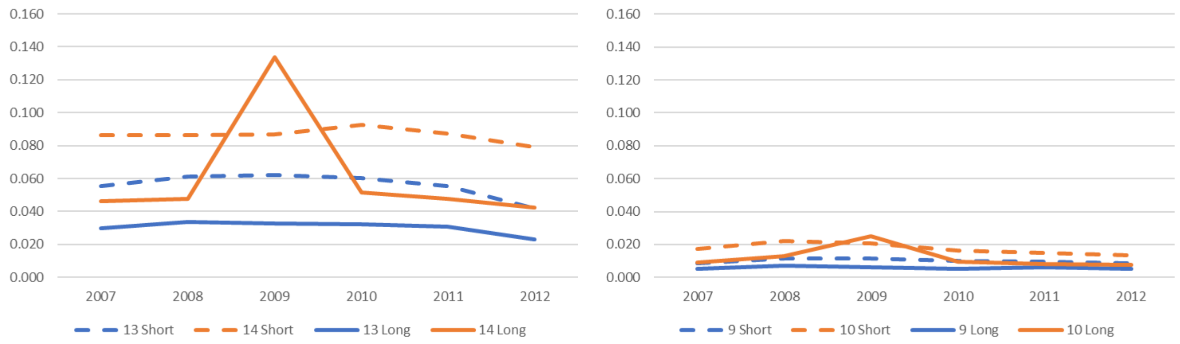
6.1. Descriptive analysis

To illustrate the effect of the policy, we start with a graphical analysis comparing old vehicles that are barely eligible to participate in the programme with vehicles barely ineligible to do so in the period May 2007 – May 2013. The analysis focuses on the scrappage, ownership termination and replacement of old vehicles, and on the purchase of replacement vehicles eligible for the subsidy. The results are presented in Figures 2-5. In each figure, the graph on the left draws on gasoline vehicles and the one on the right on diesel vehicles. Each graph presents trends for one eligible group of cars – based on both policy age and ownership duration – and for three groups that are ineligible for the policy: one group of just ineligible (younger) policy age, one group with a shorter ownership duration and one group with both a younger age and a shorter ownership duration.

The evolution of the scrappage rate for the four groups of vehicles is presented in Figure 2. For both gasoline and diesel vehicles, the subsidy policy has a salient positive effect on scrappage, manifested in the jump of the rate for eligible cars in 2009. Comparing the two graphs, we also directly observe that the average scrap rate for 13- and 14-year-old gasoline cars is roughly 4 times as high as the average scrap rate for 9- and 10-year-old diesel cars. This is mainly due to the difference in the age determining eligibility for the subsidy between the two fuel types. For gasoline and diesel vehicles with long ownership durations, we observe similar trends in the evolution of the scrappage rate outside of the policy period. Vehicles held by their owners for shorter periods exhibit higher scrappage rates, that decline rather sharply in the last year for gasoline cars.

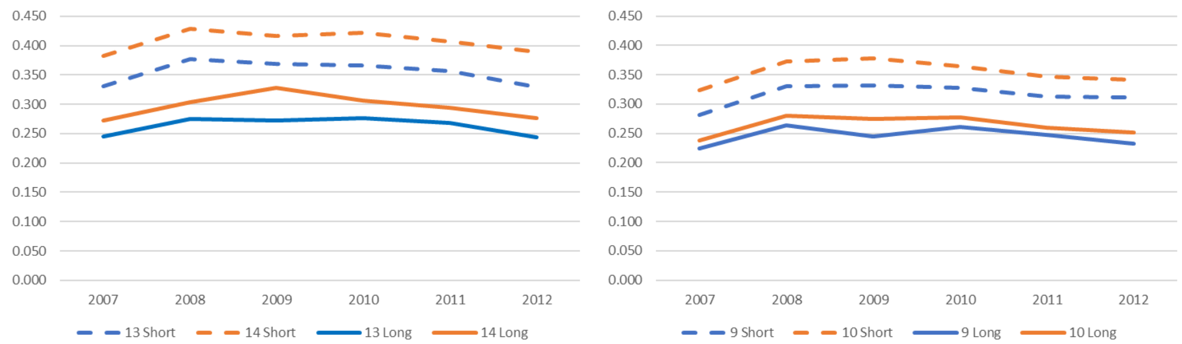
The evolution of the ownership termination rate is shown in Figure 3. In general, vehicles with short ownership durations have a higher turnover than vehicles that have been owned longer by an individual. Outside of the policy period – which is captured by the year 2009 in the graphs – the evolution of the transfer rate is very similar across the compared groups. For gasoline vehicles, the graph is strongly suggestive of a positive impact of the subsidy policy on ownership transfers. This is manifested in the spike of the ownership termination rate in 2009 for eligible vehicles, and in the absence of a spike for ineligible ones. For diesel vehicles, the graph is less revealing of a policy impact: while eligible vehicles do not exhibit the dip in the ownership

Figure 2: Evolution of the scrappage rate for four groups of vehicles



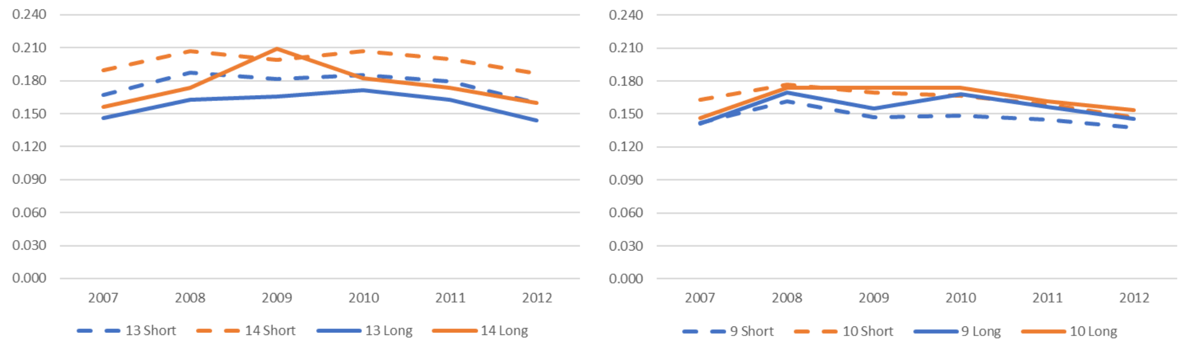
Note: The graphs present the evolution of the vehicle scrappage rate in the period May 2007 to May 2013 in the Netherlands for four groups of vehicles. This rate is defined as the ratio of the number of vehicles scrapped during a policy year over the number of vehicles in a group in the beginning of that policy year. The graph on the left draws on gasoline vehicles and the one on the right on diesel vehicles. Each graph presents trends for one barely eligible group of cars – based on both policy age and ownership duration – shown by the solid orange line – and for three groups that are ineligible for the policy: one group with a younger policy age (solid blue line), one group with a shorter ownership duration (dashed orange line) and one group with both a younger age and a shorter ownership duration (dashed blue line). Ownership durations that are eligible for the policy are equal to or longer than 454 days (about 15 months); durations shorter than that are ineligible. The just eligible policy age is 14 years for gasoline vehicles, and 10 years for diesel vehicle, while the just ineligible vehicle age is 13 years for gasoline vehicles and 9 years for diesel vehicles. The Dutch scrappage scheme was introduced in May 2009 and ended by May 2010.

Figure 3: Evolution of the ownership termination (selling) rate for four groups of vehicles



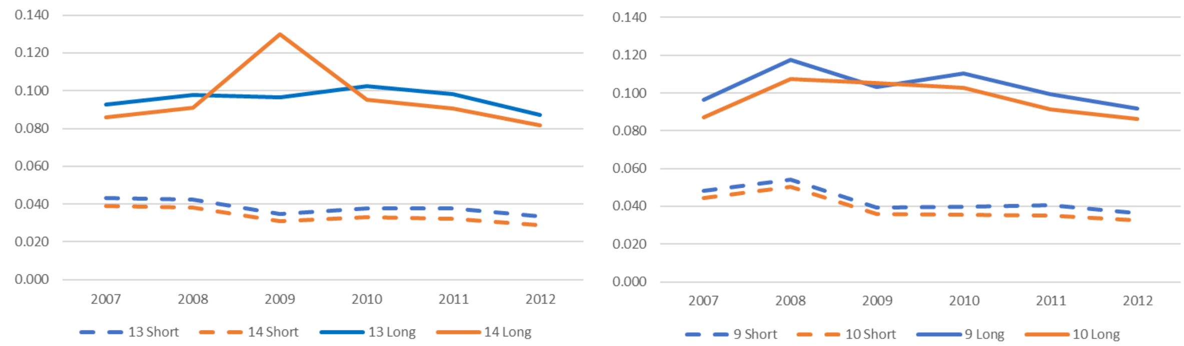
Note: The graphs in Figure 3 present the evolution of the vehicle ownership termination (deregistration) rate in the period May 2007 to May 2013 in the Netherlands for four groups of vehicles. This rate is defined as the ratio of the number of vehicles sold (deregistered) by their owners during a policy year over the number of vehicles in a group in the beginning of that policy year. The graph on the left draws on gasoline vehicles and the one on the right on diesel vehicles. Each graph presents trends for one barely eligible group of cars – based on both policy age and ownership duration – shown by the solid orange line – and for three groups that are ineligible for the policy: one group with a younger policy age (solid blue line), one group with a shorter ownership duration (dashed orange line) and one group with both a younger age and a shorter ownership duration (dashed blue line). For details on the definition of eligible and ineligible vehicle ages and ownership durations, see notes to Figure 2. The Dutch scrappage scheme was introduced in May 2009 and ended by May 2010.

Figure 4: Evolution of the replacement rate for four groups of vehicles



Note: The graphs present the evolution of the vehicle replacement rate in the period May 2007 to May 2013 in the Netherlands for four groups of vehicles. This rate is defined as the ratio of the number of vehicles replaced during a policy year over the number of vehicles in a group in the beginning of that policy year. The graph on the left draws on gasoline vehicles and the one on the right on diesel vehicles. Each graph presents trends for one barely eligible group of cars – based on both policy age and ownership duration – shown by the solid orange line – and for three groups that are ineligible for the policy: one group with a younger policy age (solid blue line), one group with a shorter ownership duration (dashed orange line) and one group with both a younger age and a shorter ownership duration (dashed blue line). For details on the definition of eligible and ineligible vehicle ages and ownership durations, see notes to Figure 2. The Dutch scrappage scheme was introduced in May 2009 and ended by May 2010.

Figure 5: Evolution of the share of replacement vehicles eligible to participate in the policy



Note: The graphs present the evolution of the share of replacement vehicles in the period May 2007 to May 2013 in the Netherlands for four groups of vehicles. This share is defined as the ratio of the number of qualifying *replacement* vehicles purchased during a policy year over the number of vehicles in a group in the beginning of that policy year. Qualifying replacement vehicles are gasoline vehicles built after 2000 and diesel vehicles built after 2004 (as a proxy for diesel vehicles with a pre-installed particulate filter). The graph on the left draws on gasoline vehicles and the one on the right on diesel vehicles. Each graph presents trends for one barely eligible group of cars – based on both policy age and ownership duration – shown by the solid orange line – and for three groups that are ineligible for the policy: one group with a younger policy age (solid blue line), one group with a shorter ownership duration (dashed orange line) and one group with both a younger age and a shorter ownership duration (dashed blue line). For details on the definition of eligible and ineligible vehicle ages and ownership durations, see notes to Figure 2. The Dutch scrappage scheme was introduced in May 2009 and ended by May 2010.

termination rate observed in 2009 for younger vehicles, they neither exhibit the slight increase in the rate observed for vehicles held by the same owner for a shorter period.

We now turn to the evolution of the replacement rate for the four vehicle groups, which is presented in Figure 4. For gasoline vehicles, similar trends are observed outside of the policy period for all four groups. The positive effect of the policy on replacement is shown by the spike of the rate in 2009. For diesel vehicles, trends are rather similar between vehicles with longer ownership durations. The positive effect of the policy on replacement is manifested in the absence of a dip in the rate in 2009, which is visible for all three groups of ineligible vehicles.

Figure 5 presents the fraction of replacement vehicles that fulfil the conditions of the policy. The graph on the left draws on replacements when *the vehicle sold* is a gasoline one, while that on the right on replacements when *the vehicle sold* runs on diesel.[18] Similar to the replacement rate, the positive effect of the policy on the share of eligible replacement vehicles is manifested in the spike of the share in 2009 for gasoline vehicles and the absence of a dip in the share in the same year for diesel vehicles.

6.2. Regression results

Tables 3 and 4 present the results of the regression discontinuity analysis following Eq. (4), and Tables 5 and 6 present the results of the triple-difference analysis following Eq. (5). Tables 3 and 5 show how the results vary for different specifications estimating the effect of the policy on scrappage. Tables 4 and 6 present the results of the preferred specification for the observed outcome variables that are relevant according to our theoretical framework.

6.2.1. Regression Discontinuity

We first present the 'local' estimates following from the regression discontinuity analysis. Table 3 shows the effect of the policy on the scrappage rate. Columns (1) and (5) focus on cars with *both* a duration length of 60 days around the threshold (i.e. between 394 and 514 days), and an age around 2 years from the threshold (12-15 years for gasoline cars and 8-11 years for

[18] To determine the eligibility of replacement diesel vehicles, we rely on the year in which the EURO 4 air emissions standard was introduced, i.e. 2005. This way we likely overestimate the number of eligible diesel vehicles, as the installation of a particulate filter became mandatory only in 2009. However, we prefer this approach, as many of the replacement diesel vehicles participating in the programme were built before 2009.

Table 3: Policy effect on Scrappage (Regression Discontinuity)

	Gasoline				Diesel			
	Both PP (1)	Age PP (2)	Dur PP (3)	Dur Long (4)	Both PP (5)	Age PP (6)	Dur PP (7)	Dur Long (8)
Treatment	0.051***	0.053***	0.052***	0.044***	0.007**	0.012**	-0.004	-0.002
	(0.004)	(0.007)	(0.007)	(0.010)	(0.003)	(0.005)	(0.006)	(0.011)
Obs	63456	31421	28860	2886	23744	12079	10388	10388
R^2	0.024	0.031	0.008	0.005	0.009	0.011	0.003	0.005

Note: The columns differ in the sample used in the analysis. Columns (1) and (5) present results of models using cars with both an ownership duration length of 60 days around the threshold (394-514 days), and an age around 2 years from the threshold (12-15 years for gasoline cars and 8-11 years for diesel cars). For the models of columns (2) and (6), we only use cars that are *eligible in terms of ownership duration* (60 days above the threshold) and whose age is around 2 years from the threshold. Columns (3), (4), (7) and (8) show results from models using cars that are *eligible in terms of age* (2 years above the threshold) and have an ownership duration length of 60 days around the threshold (394-514 days). Columns (1)-(3) and (5)-(7) use a dummy for scrappage in the 12 months following the start of the policy. In the models of columns (4) and (8), this period is extended to 48 months. In all specifications we have included interactions between the distance of age and ownership duration to the respective threshold and a dummy indicating whether the car-owner combination is below or above the threshold. ***, **, * denote significance at the 1, 5 or 10 percent level, respectively. Robust standard errors are reported in parentheses below the parameter estimates.

diesel cars). In these models, eligibility is determined by both the age and the ownership threshold. In columns (2) and (6), we only consider cars with a marginally eligible ownership duration length (between 454 and 514 days), such that eligibility is determined by the age of the car. For the results shown in columns (3) and (7), we have only used cars of eligible age (14-15 years for gasoline and 10-11 years for diesel) such that the ownership threshold determinesThe ownership duration length might be regarded as being close to a random draw, under the reasonable assumption that the implementation of the policy could not have been predicted by Identification is also based on the ownership threshold for the results shown in columns (4) and (8), but this time we study long-run effects until 28 May 2013.

Results show that irrespective of the dimension of identification, the policy causes 5 percentage points more eligible gasoline cars to be scrapped. This effect amounts to more than a doubling of the scrappage rate, which was 4.8 percent for 14-year-old cars in the year before the policy. The effect on diesel cars is much smaller and only significant when we include cars that are

Table 4: Choice Margins (Regression Discontinuity)

	Gasoline				Diesel			
	Scrapped (1)	Sold (2)	Replaced (3)	Type (4)	Scrapped (5)	Sold (6)	Replaced (7)	Type (8)
Treatment	0.052***	0.018	0.030***	0.030***	-0.004	0.009	0.012	-0.003
	(0.007)	(0.012)	(0.010)	(0.005)	(0.006)	(0.019)	(0.015)	(0.008)
Obs.	28860	28860	28860	28860	10388	10388	10388	10388
R^2	0.008	0.002	0.008	0.005	0.003	0.001	0.000	0.002

Note: In all specifications we include only cars that are marginally eligible based on age, i.e. gasoline cars of 14 and 15 years, and diesel cars of 10 and 11 years. Randomisation is over duration length only, i.e. ineligible cars are those with an ownership duration between 13 and 15 months (60 days short of the threshold) and eligible those with a duration between 11 and 13 months. The columns differ in the dependent variable used. Columns (1) and (5) use a dummy for scrappage in the 12 months following the start of the policy as dependent variable. Columns (2) and (6) similarly use a dummy for ownership termination, whereas columns (3) and (7) a dummy for replacement. Columns (4) and (8) use a dummy indicating whether the replacement car is of one of the types eligible for the policy (as determined by building date). All specifications include interactions between the distance of age and ownership duration to the respective threshold and a dummy indicating whether the car-owner combination is below or above the threshold. ***, **, * denote significance at the 1, 5 or 10 percent level, respectively. Robust standard errors are reported in parentheses below the parameter estimates.

ineligible based on their age. However, our preferred specification is the randomization based on ownership duration length, which shows an insignificant result for 10- and 11-year-old diesel cars. Although the effect of the policy for gasoline cars becomes smaller over time, we still observe extra scrap for eligible cars 3 years later (column 4). This suggests that not all extra scrappage during the policy comes from short-term intertemporal substitution. Comparing the estimates in columns (3) and (4), we can infer that only 15% of the extra scrappage of 14- and 15-year-old gasoline vehicles during the policy would otherwise have occurred before 29 May 2013. The remaining 85% would have been scrapped later. For diesel vehicles, we find no long-run effect.[19]

Table 4 shows the effect of the policy on the various decision margins identified earlier. In all columns we focus on the preferred specification with randomisation over the ownership duration (see also columns 3 and 7 in Table 3). For gasoline vehicles, the table shows that the effect on scrappage is by far the largest. The effect of the policy on the replacement of eligible

[19] Note that the effect sizes reported in Table 3 are sensitive to the inclusion of the interaction variables between the distance of age and ownership duration until the respective threshold and a dummy indicating whether the car-owner combination is below or above the threshold. If these dummies are not included, the estimated effect sizes are larger, 0.079 for gasoline and 0.019 for diesel; in line with the results in Table 5.

gasoline cars is 3 percentage points, an increase of 17 percent relative to the average replacement ratio for 14-year-old gasoline cars in the year before the policy. Interestingly, the policy does not appear to influence ownership terminations. This suggests that – for marginally eligible gasoline cars – extra replacement and scrappage originate from owners that would have anyway discarded their car in the year of the policy. However, note that this part of the analysis focuses on individuals owning their vehicle for a short period (11-15 months at the time the subsidy was introduced). It is not surprising that those participating in the programme from this group are those with low transaction costs, and thus with a higher propensity to trade. We also find a 33% increase in the fraction of qualifying replacement cars.[20] For diesel vehicles, no statistically significant effects are found.

6.2.2. Triple Difference

While the regression discontinuity estimates of the previous section focus on the effects of the policy on marginally eligible cars, the triple-difference model of Eq. (5) also considers the effects of the scrappage subsidy policy on inframarginal cars. In Table 5, we present our triple-difference estimates for the effect of the policy on scrappage, while in Table 6 results for all four choice margins of interest.[21] In contrast to Tables 3 and 4, the unit of observation in Tables 5 and 6 is a *basket* containing multiple cars for a period of *one policy year*. In total, there are 2300 such potential baskets, spanning 5 years, 20 vehicle ages and 23 groups of ownership duration lengths. For gasoline vehicles, we leave out the youngest six vehicle age categories; this reduces the number of baskets considered to 1610. For diesel vehicles, we remove the youngest two ages, thus 2070 baskets are used in the analysis. As the number of underlying individual observations varies by basket, we weight observations by the size of the basket.

Focusing on the results presented in Table 5, the estimated effect on scrappage is insensitive to the adopted specification. Our results do not change if we include lagged terms (columns 2

[20] The relative effects presented are based on benchmark ratios observed for eligible 14-year-old gasoline cars in the year before the policy was implemented. These benchmarks are a 4.8 percent scrappage rate, a 17.3 percent replacement rate, and a 9.1 percent share of cars satisfying the policy condition for the replacement of a gasoline car.

[21] Appendix A discusses the local schemes in the cities of Amsterdam and The Hague that partly overlap with the national scheme this paper studies. We estimate that maximum 5% of the owners of eligible vehicles reside in those two cities. The bias potentially caused by the lack of data on the cars participating in these local schemes is further limited by the fact that the scheme in The Hague started 8 months before the national scheme, and the Amsterdam scheme ended 8 months after the national one. When participation in these schemes is approximately uniform over time – or when both schemes have a similar participation pathway over time (e.g. participation is front- or back-loaded) – extra scrappage due to these local schemes will also be captured in our counterfactual.

Table 5: Policy effect on Scrappage (Triple Difference)

	Gasoline				Diesel			
	Base (1)	Lagged (2)	Before (3)	After (4)	Base (5)	Lagged (6)	Before (7)	After (8)
Treatment	0.083***	0.083***	0.081***	0.085***	0.025***	0.025***	0.025***	0.026***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.002)	(0.002)	(0.002)	(0.002)
Relative effect	99%	99%	96%	101%	78%	78%	78%	81%
Obs	1610	1610	644	1288	2070	2070	828	1656
R2	0.847	0.848	0.904	0.882	0.689	0.693	0.787	0.761

Note: All specifications use the *scrappage rate* (number of scraps during the year over number of vehicles in a basket in the beginning of the year) as dependent variable and include the following set of dummies: i) Ownership duration; ii) Policy age; iii) interaction between Ownership duration and Policy Age; iv) Car vintage; v) Year; vi) interaction between Car eligibility and Treatment Period; and vii) interaction between Ownership eligibility and Treatment period. In columns (2)-(4) and (6)-(8), we additionally include dummies that capture the potential lagged effects on vintages that were eligible for the policy (controlling thus for intertemporal substitution). Columns (3) and (7) only use observations before 28 May 2010; Columns (4) and (8) only use observations after 29 May 2009. The specifications for gasoline cars include only cars of 12 years and older, while the specifications for diesel cars include cars of 8 years and older. *Control groups:* Columns (1-4) use gasoline cars aged 12 and 13 years and older gasoline cars with an ownership duration length shorter than 1 year and 3 months as control groups. Columns (5)-(8) use diesel cars of 8 and 9 years old, and older diesel cars with an ownership duration length shorter than 1 year and 3 months as control groups. ***, **, * denote significance at the 1, 5 or 10 percent level, respectively. Robust standard errors are reported in parentheses below the parameter estimates.

Relative effect*:* We use a weighted average over a year before and a year after the policy as the *benchmark scrappage rate* for determining the relative effect. This yields an annual rate of 8.4 percent for gasoline cars, and 3.2 percent for diesel cars.

and 6), or remove the period after (columns 3 and 7), or before the policy (columns 4 and 8) from the analysis. Comparing these results with those from the regression discontinuity analysis, we observe that the *average* effect estimated for gasoline cars in Table 5 is about 60% higher than the *marginal* effect in Table 3. For diesel cars, we find a statistically significant effect, amounting to a 78% increase in the scrappage rate, whereas the marginal effect in Table 3 was insignificant. In both cases, the average eligible car is much more responsive to the policy than the marginal one. This is an intuitive finding, as the subsidy net of residual value is higher for the (older) average eligible car than for the marginal one, and therefore the incentive for it to participate in the programme is stronger.

Table 6: Choice Margins (Triple Difference)

	Gasoline				Diesel			
	Scrapped (1)	Sold (2)	Replaced (3)	Type (4)	Scrapped (5)	Sold (6)	Replaced (7)	Type (8)
Treatment	0.083***	0.033***	0.037***	0.040***	0.025***	0.014***	0.014***	0.015***
	(0.005)	(0.003)	(0.003)	(0.002)	(0.002)	(0.004)	(0.003)	(0.002)
Relative	99%	10%	22%	61%	78%	5%	9%	20%
Absolute	69100	27900	30500	33000	8300	4600	4700	4900
Obs.	1610	1610	1610	1610	2070	2070	2070	2055
R2	0.848	0.753	0.810	0.864	0.693	0.551	0.520	0.650

Note: Specifications differ in the dependent variable used. All dependent variables are expressed as ratios of the number of events during a 12-month period over the number of vehicles in a basket in the beginning of the period. These events are: (i) vehicle *scrappages* in columns (1) and (5); (ii) vehicle *ownership terminations* (i.e. sales) in columns (2) and (6); (iii) vehicle *replacements* in columns (3) and (7); and (iv) purchases of replacement cars of types eligible for the policy (as judged by building date) in columns (4) and (8). In the year of the policy, replacement vehicles eligible for the subsidy are gasoline vehicles built after 2000 and diesel vehicles built after 2004 (used as a proxy for diesel vehicles with a pre-installed particulate filter). Although coefficients are not reported in the table, all specifications include the following set of control variables: i) Ownership Duration; ii) Policy Age; iii) Vintage; iv) Year; v) the interaction between Car Eligibility and Treatment Period; vi) the interaction between Ownership Eligibility and Treatment Period; and vii) interactions between lagged subsidy dummy variables and age eligibility dummy variables for the 3 years after the policy. The specifications for gasoline use only cars aged 12 years and older, while the specifications for diesel cars use cars aged 8 years and older. Columns (1-4) use gasoline cars aged 12 and 13 years and older gasoline cars with an ownership duration length shorter than 1 year and 3 months as control groups. Columns (5)-(8) use diesel cars aged 8 and 9 years old, and older diesel cars with an ownership duration length shorter than 1 year and 3 months as control groups. ***, **, * denote significance at the 1, 5 or 10 percent level, respectively. Robust standard errors are reported in parentheses below the parameter estimates.

Relative effect: The treatment effect is compared with a benchmark for the respective variable. This benchmark is based on a weighted average over a year prior to and a year after the policy. We use 8.4 percent *per year* as the benchmark *scrappage rate* for gasoline cars, and 3.2 percent for diesel cars; 32.0 percent *per year* as the benchmark ownership *termination* rate for gasoline cars, 29.5 percent for diesel cars; 16.6 percent *per year* as the benchmark *replacement* rate for gasoline cars, 16.3 percent for diesel cars; and 6.6 percent for the share of cars satisfying the policy condition for the replacement for gasoline cars, and 7.5 percent for the replacement for diesel cars.

Absolute effect: The rounded absolute effect is computed by multiplying the treatment effect with the number of observations. On 29 May 2009, approximately 832,000 gasoline cars and 328,000 diesel cars with an age up to 25 years old were potentially eligible for the policy.

The estimated effects of the policy on the four choice margins of interest are shown in Table 6. The effects are larger than those shown in Table 4, and for diesel cars – as well as for ownership terminations for both fuel types – they are now statistically significant. Furthermore, the estimated effect on replacement is not statistically different from the effect on ownership

Table 7: Earlier trading of old vehicle due to the policy

	Gasoline		Diesel	
	Days (1)	log(Days) (2)	Days (3)	log(Days) (4)
Treatment	-30.87***	-0.057***	-15.22***	-0.019***
	(2.59)	(0.005)	(3.55)	(0.007)
Obs	1288	1288	1656	1656
R2	0.821	0.703	0.577	0.449

Note: The dependent variable measures the average number of remaining days until a car is sold in specifications (1) and (3) and its log transformation in specifications (2) and (4). To limit the influence of extreme values on our estimates, we set the maximum number of remaining days to 1500, i.e. slightly more than 4 years and a month. Although the related coefficients are not reported in the table, all specifications include the following set of control variables: i) Ownership Duration; ii) Policy Age; iii) Vintage; iii) Year; iv) interaction between Age Eligibility and Treatment Period; v) interaction between Ownership Eligibility and Treatment Period. Specifications for gasoline cars use only vehicles aged 12 years and older, while specifications for diesel ones use only cars aged 8 years and older. ***, **, * denote significance at the 1, 5 or 10 percent level, respectively. Robust standard errors are reported in parentheses below the parameter estimates.

terminations both for diesel and gasoline vehicles. These estimates can be compared with each other because all fractions have the same denominator.

6.2.3. Policy impact on early trading of vehicles

The estimated average number of days that eligible cars are traded earlier is presented in columns (1) and (3) of Table 7. To estimate the impact of *participation in the scheme* on early trading, we need to divide these point estimates by the share of participation, which is 8.63% for gasoline cars and 2.66% for diesel cars. These computations reveal that participating gasoline cars are sold on average almost a year (358 days) earlier due to the programme, whereas diesel cars slightly more than 1½ year (572 days) earlier. For comparison, Sandler (2012) estimates that cars participating in California’s Vehicle Buyback Programme are scrapped some 3.8 years earlier, whereas Li et al. (2013) find only little intertemporal shifting in response to the US CARS programme.

6.2.4. Policy impact on replacement car characteristics

The environmental impact of the policy does not only depend on the early removal of polluting vehicles from the fleet, but also on the environmental performance of the cars by which they are replaced. We now turn to the effects of the policy on environmentally relevant characteristics of replacement cars, focusing on fuel type, age, weight, and tailpipe emissions

Table 8: Policy effect on weight and emissions of replacement cars

	Gasoline			Diesel		
	Weight (1)	CO_2 (2)	NOx (3)	Weight (4)	CO_2 (5)	NOx (6)
Treatment	-18.080***	-6.274***	-0.002	-26.070**	-2.470**	-0.085***
	(3.631)	(0.673)	(0.009)	(13.210)	(1.078)	(0.032)
Relative	-2%	-4%		-2%	-1%	-33%
Obs.	1610	1606	1605	2055	1939	1930
R2	0.443	0.581	0.074	0.043	0.178	0.014

Note: The estimates presented in the table illustrate the effect of the policy on: (i) Columns (1) and (4): the replacement vehicle's weight (in kg); (ii) Columns (2) and (5): the replacement vehicle's CO_2 emissions (in g/km); and (iii) Columns (3) and (6): the replacement vehicle's NO_x emissions (in g/km). All specifications include the control variables mentioned in the notes of Table 6. The specifications for gasoline cars use only cars aged 12 years or older, while the specifications for diesel cars use cars aged8 years or older. Columns (1)-(3) use gasoline cars aged 12 and 13 years and older gasoline cars with an ownership duration length shorter than 1 year and 3 months as control groups. Columns (4)-(6) use diesel cars of 8 and 9 years old, and older diesel cars with an ownership duration length shorter than 1 year and 3 months as control groups. ***, **, * denote significance at the 1, 5 or 10 percent level, respectively. Robust standard errors are reported in parentheses below the parameter estimates.

Relative effect: Based on a weighted average over the years right before and after the policy, we use the following benchmark values: (i) weight: 1051 kg for replacements for gasoline cars, 1425 kg for diesel cars; (ii) CO_2 emissions: 165 g/km for replacements for gasoline cars, 166 g/km for diesel cars; and (iii) NO_x emissions: 0.098 g/km for replacements for gasoline cars, 0.256 g/km for diesel cars.

of CO_2 and NO_x. To estimate these effects, we rely again on the triple difference approach, but this time our dependent variable is defined as the average value of a characteristic over *all replacement vehicles* bought by car owners in a basket.

The estimated effects are presented in Tables 8 and 9, separately for replacements for gasoline and diesel cars. The effects of the policy on the weight, CO_2 and NO_x emissions of replacement vehicles are presented in Table 8, while those on their age and fuel type in Table 9. Our estimates reveal that the policy led to the purchase of younger, lighter, cleaner and more fuel-efficient replacement vehicles. However, it is unclear whether this result is due to participants choosing cleaner vehicles than those they were planning to purchase, or due to them purchasing earlier the 'clean' vehicle they would anyway buy.

Table 9: Policy effect on fuel type and age of replacement cars

	Gasoline		Diesel	
	Diesel purchase (1)	Age (2)	Diesel purchase (3)	Age (4)
Treatment	-0.006	-357.8***	-0.043***	-104.0***
	(0.004)	(23.7)	(0.014)	(32.7)
Relative		-11%	-8%	-4%
Obs.	1610	1610	2055	2055
$R2$	0.323	0.677	0.158	0.165

Note: The estimates presented in the table illustrate the effect of the policy on: (i) Columns (1) and (3): the fraction of replacement vehicles powered by diesel; and (ii) Columns (2) and (4): the age of the replacement vehicle (in days). All specifications include the control variables mentioned in the notes of Table 6. The specifications for gasoline use only cars aged 12 years and older; the specifications for diesel cars use only cars aged 8 years and older. Columns (1)-(2) use gasoline cars aged 12 and 13 years and older gasoline cars with an ownership duration length shorter than 1 year and 3 months as control groups. Columns (3)-(4) use diesel cars of 8 and 9 years old, and older diesel cars with an ownership duration length shorter than 1 year and 3 months as control groups. ***, **, * denote significance at the 1, 5 or 10 percent level, respectively. Robust standard errors are reported in parentheses below the parameter estimates.

Relative effect: Based on a weighted average over the years right before and after the policy, we use: (i) 3340 days as the benchmark age of cars bought as replacements for gasoline cars and 2651 days for cars bought as replacements for diesel cars; and (ii) 6.4 percent as the benchmark fraction of diesel cars bought as replacements for gasoline cars, and 56.5 percent as the benchmark for replacements for diesel cars.

As shown in Table 8, reductions of CO_2 emissions range from 3 g/km for replacements of old diesel vehicles to 6 g/km for replacements of old gasoline ones. These reductions are both in absolute and in percentage terms (1% and 4% respectively) rather small. For NO_x, we only find evidence of an emissions reduction for diesel car replacements. However, this reduction is considerable, amounting to a third of benchmark emissions.

The small reduction of CO_2 and the large reduction of NO_x emissions estimated for diesel car replacements could mainly be attributed to participants switching from diesel to gasoline cars. Gasoline cars emit less NO_x, but more CO_2 per km than comparable diesel cars. This is confirmed by the estimates presented in Table 9, which reveal that the policy induced a 4 percentage-point reduction in the share of diesel cars purchased as replacements of old diesel vehicles.

Another channel through which emissions are reduced is the purchase of younger replacement vehicles. Younger vehicles generally have more advanced pollution control systems installed and are more fuel efficient than older vehicles, and thus generate less CO_2, NO_x and other air emissions. The effect of the policy on vehicle age is presented in Table 9, which shows that the replacement for a gasoline vehicle is almost a year younger (about 11%) than the average age of a gasoline replacement vehicle without the policy, while the replacement for a diesel vehicle is about 3½ months younger (4%). The strong effect of the policy on the age of gasoline car replacements has likely been an important driver of the reduction of CO_2 emissions.

Note, however, that a replacement vehicle of younger age is not necessarily also a vehicle of more recent vintage. It is indeed likely that participants purchase a vehicle of the same vintage with what they would have purchased without the policy, but now do so earlier. For example, a participant aiming to buy in 2011 a used vehicle built in 2003, now buys the same vehicle in 2010.

7. Quantifying participant types in the Dutch programme

In this section, we estimate the shares of the various participant types identified in Section 3 for the Dutch scrappage programme. To this end, we juxtapose the observed participation of 80,300 old cars in the programme – 71,600 gasoline cars and 8,700 diesel cars – with the estimated absolute effects of the programme presented in Table 6. We acknowledge the uncertainty surrounding point estimates, but as the purpose of this analysis is to illustrate the relative size of the various participant types, we prefer for brevity reasons to limit its scope to point estimates.

We start by focusing on the extent to which the subsidy scheme induced selling and scrapping the old vehicle, disregarding changes in buying behaviour. Table 10 presents the outcome of allocating the total number of paid subsidies to the three participant types defined in Section 3.2. We estimate the number of potential free-riders (type III) by subtracting the number of individuals who changed their scrappage decision due to the policy from the total number of individuals who received the subsidy. The total change in selling behaviour due to the subsidy – the sum of types I and II – is approximated by the number of extra scrappages. As shown in columns (2) and (6) of Table 6 (see row *absolute effects*), 69,100 owners of an eligible gasoline car and 8,300 owners of an eligible diesel car scrapped their car earlier to receive the subsidy.

Table 10: Types of participants in the Dutch scrappage subsidy programme, selling side

	Gasoline			Diesel			Average
	Total	Type	%	Total	Type	%	%
Subsidy receivers	71,600			8,700			
Early traders (II)		27,900	39%		4,600	53%	40%
Counterfactual traders (I)		41,200	58%		3,700	43%	56%
Total additional scrappage	69,100			8,300			
Potential free-riders (III & IV)		2,500	3%		400	5%	4%

Note: Counterfactual traders, early traders, and free-riders are defined in Section 3.1 as types I, II and III respectively. The numbers for 'Early traders' and 'Total additional scrappage' are those presented in the row "Absolute" of columns (1) and (2) (gasoline), and (5) and (6) (diesel), of Table 6. The number of potential free-riders is computed by subtracting the 'Total additional scrappage' from the number of 'Subsidy receivers'. The number of 'counterfactual traders' results from subtracting 'Early traders' from 'Total additional scrappage'. The column "Average" presents the average share of each category in the total number of programme participants, weighted by the percentage of old gasoline (89% of participants) and diesel car owners (11% of participants).

The bottom row of Table 10 shows that 3% of subsidy receivers discarding a gasoline car and 5% of subsidy receivers discarding a diesel car cannot be accounted for in the extra scrappage. Therefore, this is our estimate of the share of *potential* free-riders on the subsidy.[22] We say 'potential', because some of these individuals may have *bought a different replacement car* due to the subsidy scheme (type IV in Section 3.3). These estimates reveal that the design of the Dutch scheme was very effective in limiting free-riding.[23]

To complete our estimation of the sizes of participant types from Section 3.2, we distinguish between individuals trading their car earlier due to the programme (early traders, type II), and individuals who would have also traded it without the policy (counterfactual traders, type I). We estimate the effect of the policy on two indicators of trade in Table 6 – on ownership terminations (columns 1 and 5) and on replacements (columns 3 and 7) – but the estimated effects are not statistically different from each other. We use the more conservative (lower) estimate of ownership terminations to quantify the size of the category of *early traders*: 27,900

[22] Even when allowing for the possibility of a small underestimate of the number of free-riders, due to not fully factoring in the effect of the local schemes discussed in Appendix A, the extent of free-riding is very unlikely to exceed 10%.

[23] When multiplying the number of eligible vehicles with the fraction of scrap observed before and after the policy (see the note below Table 6), we find that 69,900 eligible gasoline cars and 10,600 eligible diesel cars would have been scrapped without a policy, yielding 80,500 potential free-riders competing for a scarce subsidy. Instead, it took almost a year to deplete the budget – as compared to one month in the case of the US 'Cash for Clunkers' programme (Li et al., 2013) – with free-riders accounting for only 4% of programme participants.

owners of an eligible gasoline car and 4,600 owners of an eligible diesel car. This implies that about 40% of the participants in the scrappage scheme traded earlier than otherwise planned.[24] To determine the number of counterfactual traders, we simply subtract early traders from the total number of those scrapping their car earlier to receive the subsidy. This completes the categorisation of participants in the programme across the types identified in Section 3.2.

We now turn our attention to how the Dutch scrappage scheme affected the type of replacement car purchased, or the so-called *type adjusters* (type IV) introduced in Section 3.3. Two behavioural channels cause the purchase of *additional* qualified replacement vehicles. First, individuals are induced by the policy to buy *a different* replacement car than the one they intended to buy (type IV), and second, individuals would have purchased a car *of the same age* at a later point in time but *trade early* due to the policy (type II).[25] The challenge is to disentangle these two effects. To this end, we start by observing that the intention-to-treat effect in columns (4) and (8) of Table 6 is given by:

$$\beta_{Type} = dQ/N, \tag{6a}$$

where N denotes the number of cars in a basket right before the introduction of the programme and dQ the number of *extra* qualifying replacements due to the policy. Intuitively, dQ includes *pure* type adjusters, denoted by dT and defined as type IV in Section 3.3, who already planned to trade but *buy a car of a younger age* due to the policy. However, by definition, also all early traders, denoted by dR, must have bought an additional qualifying replacement car. As discussed in Section 3.3, it is also possible that some participants *both* adjust the type of car bought *and* trade early: this group is subsumed in the group of early traders (dR). Following these definitions, we obtain:

[24] Li et al. (2013) estimate a larger percentage of early traders in the US CARS programme, amounting to about 55% of participants. However, due to the different duration of the two programmes (one month for the US CARS programme vs. about a year for the Dutch scrappage scheme) early trading is not directly comparable between their study and ours. Early traders in the US CARS programme just needed to bring their car replacement decision forward by a few weeks, while in our empirical setting by several months. Furthermore, both Li et al. (2013) and Mian and Sufi (2012) show that the effect of the US CARS programme completely vanishes when considering intertemporal shifting of car purchases over a longer period (within a year or less from the start of the programme).

[25] Note that in Section 3 the definition of the eligibility of the replacement car is based on its *age*, not its vintage. Let us take as an example individuals who were planning to buy a 2003 gasoline vehicle in 2011 without the policy. When these individuals now purchase the *same vehicle* in early 2010, they are considered by our setup as *type adjusters*, because they buy a younger vehicle. If they buy instead a 2002 gasoline vehicle in early 2010, they are considered early traders.

$$dQ = dR + dT. \tag{6b}$$

Combining Eqs. (6a) and (6b) yields:

$$\beta_{Type} = \left(\frac{1}{N}\right)[dR + dT], \tag{6c}$$

and defining β_{Sell} as the extra trade induced by the policy ($\beta_{Sell} = dR/N$):

$$\beta_{Type} = \beta_{Sell} + \left(\frac{1}{N}\right)dT. \tag{6d}$$

As shown in Equation (6d), we can estimate the number of pure type-adjusters by comparing the effect on additional trade with the effect on extra qualifying replacement cars. We only observe a difference in the intention-to-treat effect for owners of retired gasoline vehicles, and not for owners of retired diesel ones. The effect for gasoline vehicles is in the range of 0.3-0.6%, depending on whether extra replacements or extra transfers are used as a measure of early trading. This effect translates to 2500-5000 *pure* type-adjusters among the potential free-riders and counterfactual-traders. Our estimate of 2500 potential free-riders among gasoline vehicle owners is at the lower bound of this range. Therefore, some – or even all – individuals who are classified as free-riders when only selling behaviour is considered, may have had to change their purchasing behaviour to receive the subsidy.

In addition to pure type-adjusters, some early traders may have bought a different car than originally intended. A logical prerequisite for the existence of type adjusters within early traders is the presence of *pure* type adjusters among those who intended to trade anyway in the period the subsidy was offered. Therefore, we do not expect type adjusters within early traders of *diesel* cars. On the other hand, we cannot rule out the existence of type adjusters among early traders of gasoline cars. This implies that the 2500-5000 *pure* type adjusters mentioned in the previous paragraph may best be viewed as a low-bound estimate of the total number of gasoline car owners who opted for a newer than intended vehicle to participate in the programme.

The differences in participation in the scheme between diesel and gasoline car owners illustrate that a strict buying criterion lowers participation – an insight also provided by our model in Section 3.3. The participation of diesel cars is relatively low when contrasting the 28% of cars eligible for the subsidy to the 11% of cars scrapped under the scheme. This low participation can be explained by two factors. First, the lax eligibility requirement on the age of *replaced* diesel vehicles seems ineffective, based on the absence of significant effects for owners of 10-year-old eligible diesel cars from the regression discontinuity analysis in Table 4, most likely because these cars are more valuable than the subsidy offered. The effective set of potentially participating diesel cars is therefore smaller than the eligible set.[26] The second factor is the relatively strict requirement on replacement diesel cars. Absent the policy, only 33% of replacers of 14-year-old or older diesel vehicles would buy a replacement diesel vehicle meeting the requirements of the policy. By contrast, about 53% of replacers of 14-year-old or older gasoline vehicles meet the laxer condition on replacement gasoline vehicles also without the policy.[27]

8. Environmental benefits of the policy

To evaluate the effectiveness of the Dutch scrappage subsidy programme – or simply to compare it with other programmes – it is insightful to estimate the environmental benefits of the early scrappage of polluting vehicles and of their replacement with cleaner ones. Besides these benefits, the total welfare effects of the scrappage programme depend on: i) the economic value lost due to the early scrappage of a functional vehicle; ii) potential climate and environmental damages due to extra vehicle production; iii) the societal costs of financing the scrappage subsidies; and iv) redistributive benefits when the recipients of the subsidy are predominantly lower-income households. In what follows, we focus solely on the environmental benefits from savings of tailpipe emissions of CO_2 and air pollutants.

The tailpipe emissions saved from the scrappage of an old vehicle and its replacement with a cleaner one are equal to the product of emissions saved per kilometre and the number of kilometres for which this reduction in emissions applies (see also Alberini et al., 1996). The latter is determined by: i) how much earlier the old vehicle is scrapped and replaced by a

[26] We note that the distribution of eligible diesel cars is skewed towards the youngest cars. For example, 10-year-old diesel cars make up more than 25% of the total population of eligible diesel cars, whereas 14 years and older diesel cars are only 29% of the total group of eligible diesel cars.

[27] Most diesel car owners participating in the scheme side-stepped the strict buying criteria on replacement diesel vehicles through switching fuel type, mostly through buying a gasoline replacement vehicle. We observe that more than 80% of diesel cars participating in the scheme were replaced by a gasoline car, as compared to 44% in the counterfactual. Intuitively, fuel switching usually involves high transaction costs. This is because diesel and gasoline engines have different characteristics, which make them more suitable for different consumer needs. The higher fuel efficiency and longer endurance of diesel engines, as well as the beneficial tax treatment of diesel fuel, make diesel vehicles particularly suitable for individuals making intensive use of the vehicle (Grigolon et al., 2018; Miravete et al., 2018). Therefore, most diesel car owners would be unwilling to switch to a gasoline vehicle to participate in the programme.

cleaner vehicle; ii) the kilometres driven in the *replacement* vehicle, in case its environmental performance is different from that of the vehicle that would have been bought in the counterfactual; and iii) the kilometres driven by the prospective next owner(s) of the scrapped vehicle in a vehicle of different environmental performance (see also Lenski et al., 2010).

In this section, we assume that the last two behaviour changes described in the previous paragraph have a negligible effect on emissions, and we focus solely on the first one. Given our conclusion in Section 7 that 3-7% of the participants scrapping a gasoline vehicle might have bought a cleaner car than originally intended due to the policy, it may seem counterintuitive that we assume away the effect of the second behaviour change. However, the estimates in Table 8 reveal no effect of the policy on the NOx emissions of replacement vehicles and only a very small effect (4%) on their CO_2 emissions. Given that NOx and CO_2 emissions savings account for the lion's share of the environmental benefits of the programme, as we will see below, our assumption might only have led to a very small underestimation of those benefits. Disregarding the third behaviour change mentioned above stems from our inability to determine whether the prospective owners of earlier scrapped vehicles ultimately buy vehicles with different environmental performance.[28]

For each participating scrapped vehicle *i*, we therefore formulate the environmental benefits (b_i) from participation in the programme as:

$$b_i = \sum_{p=1}^{P} S_p\left[km_i\left(r_{p,i}^o - r_{p,i}^n\right)\right]. \quad (7)$$

In Eq. (7), we sum over the monetised value of the change in emissions (r) of a number of pollutants (*p*) over the extra distance that would have been travelled in the old vehicle. The shadow price per kilogram of emissions of pollutant *p* is denoted by S_p. Variable km_i represents the additional kilometres that the participating car would have travelled in the absence of the programme. The change in emissions per km of pollutant *p* is equal to the difference between those of the scrapped vehicle ($r_{p,i}^o$) and those of the replacement vehicle ($r_{p,i}^n$).

[28] One channel through which prospective owners of a participating car could be affected by the programme is through changes (increases) in the prices of cars with comparable environmental performance. However, the Dutch car market is integrated in the European one (the potential next owner could also be living abroad), and only slightly more than 80,000 cars were scrapped through the programme. Such general equilibrium effects seem therefore unlikely. In addition, even in the presence of such general equilibrium effects, it is unclear whether the next owner would buy a replacement car with better or worse environmental performance as a substitute.

To estimate b_i, we need to operationalise the terms in Eq. (7). Unlike Sandler (2012), we do not observe the usage history of the cars participating in the programme, and more generally of any car scrapped before 2014. We therefore construct the counterfactual number of kilometres travelled in the old vehicle by combining our estimate of the number of days vehicles are traded earlier (see Table 7), with an estimate of the number of kilometres old vehicles of a given class are on average driven *per day*.

We mainly base our estimate of kilometres travelled per day on usage data for vehicles scrapped after January 1st, 2014.[29] Vehicle classes are defined on the basis of fuel type, age and weight (9 weight classes).[30] These vehicle classes correspond to emission classes that are discussed later in this section. We select the final and the penultimate odometer reading for each scrapped car, and compute the average vehicle kilometres travelled (VKT) per day between the dates of the two readings.[31] The resulting distribution of VKT over cars in the same age group is skewed, due to a long tail of cars with very high VKT. Figure 6 presents the median daily VKT for gasoline and diesel cars of different ages. Computing a weighted average based on the age distribution of vehicles participating in the programme, we find a daily VKT of 26 km for gasoline vehicles and of 50 km for diesel vehicles, i.e. 9,500 and 18,000 km per year respectively. To estimate the additional kilometres that scrapped gasoline cars would have been travelled in the absence of the programme (km_i in Eq. (7)), we multiply the vehicle class-specific median daily VKT with the estimated number of days that cars are sold earlier due to the policy: 358 days for gasoline cars and 572 days for diesel cars (see Table 7).[32]

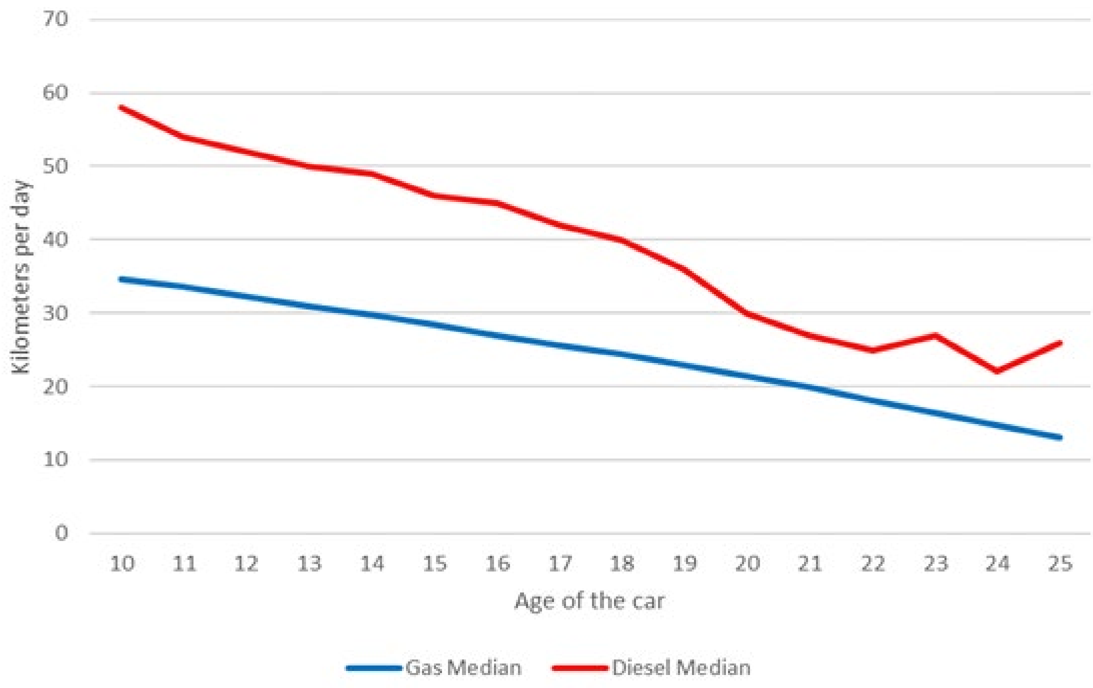
[29] We use a dataset with about 510,000 observations on cars scrapped as of 1 January 2012. This includes a limited number of observations on the usage of vehicles scrapped in 2012 and 2013, but most observations concern vehicles scrapped from 2014 onwards. This is because historical data on odometer readings of cars in the Netherlands were required to be kept as of 1 January 2014. We excluded from our dataset all observations relating to dealers and taxis to ensure that the used odometer readings pertain to household driving behaviour. We also drop observations with more than 750,000 kilometres driven within 3 years' time.

[30] The weight classes follow the classification of the Netherlands Environmental Assessment Agency (PBL): i) <= 850 ii) (850,1000); iii) [1000,1100); iv) [1100,1150); v) [1150,1300); vi) [1300,1400); vii) [1400,1500); viii) [1500,1600); ix) >= 1600.

[31] The last observation is the last odometer reading recorded for each vehicle. As penultimate observation, we chose the odometer reading on the date closest to 1 year before the last observation. We remove observations with a difference of less than 6 months or more than 3 years between odometer readings. In total, 2% of the observations are dropped due to this reason.

[32] These calculations reveal that scrapped gasoline vehicles travel on average about 9000 kilometres less due to the programme, and diesel vehicles 28,000 less. Sandler (2012) estimates that participating vehicles in California's Vehicle Buyback Programme would have travelled about 24-25,000 kilometres extra without it, while Li et al. (2013) estimate that vehicles participating in the US CARS programme would have travelled an additional 96,000 kilometres. Our results show that the gasoline cars that participated in the Dutch programme were closer to their counterfactual end-of-life than cars participating in US programmes.

Figure 6: Vehicle Kilometres Travelled



Note: The figure shows the median vehicle kilometres travelled per day for gasoline and diesel cars of different ages. The age of the vehicle is that at which the penultimate odometer reading is observed.

The final parameters in Eq. (7) that need to be estimated are the monetized emissions of CO_2, NO_X, CO, NMVOC and PM_{10} per kilometre travelled for the old and the replacement vehicle ($r^o_{p,i}$, $r^n_{p,i}$). We observe both the cars scrapped due to the programme and the cars replacing them. Although the dataset obtained from RDW also includes information on the emission intensities of many individual cars, the emissions data for the vehicles participating in the programme have many gaps. Besides being incomplete, the reported emission intensities in the RDW dataset refer to type-approval emissions of new vehicles at the time of purchase, which differ from real-world emissions, especially when cars have been used for multiple years. Therefore, we rely on the average emission intensities by fuel type, vintage and weight class computed by the Netherlands Environmental Assessment Agency (PBL) and TNO (Geilenkirchen et al., 2020). These emission factors correct for the average wear-and-tear of vehicles in each vintage that systematically affect emission performance (see also Jacobsen et al., 2023).

The main results of our analysis are presented in Table 11. The table summarizes the weighted average emissions of the vehicles scrapped in the programme and of their replacements, as well as the estimated environmental benefits implied by emissions savings. To calculate these

Table 11: Emission intensities and shadow prices

	Gasoline			Diesel			Shadow prices
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Old vehicle (g/km)	Replacement vehicle (g/km)	Benefit (€)	Old vehicle (g/km)	Replacement vehicle (g/km)	Benefit (€)	Estimate 2021 (€/kg)
CO_2	209.781	193.620	17	177.340	188.938	-36	0.11
NO_X	1.227	0.054	256	0.671	0.124	382	25.03
CO	6.512	3.440	2	0.343	2.821	-5	0.07
NMVOC	0.858	0.211	13	0.071	0.174	-7	2.28
PM_{10}	0.012	0.002	5	0.099	0.006	146	58.00
Total			292			480	

Note: Columns (1) and (4) report the average emission intensities of participating gasoline vehicles for CO_2, NO_X, CO, NMVOC and PM_{10}, based on Geilenkirchen et al. (2020). Columns (2) and (5) report the average emission intensities of replacement cars, based on information from the same source. Column (7) reports the shadow prices used, based on de Bruyn et al. (2023), in 2010 Euros. Columns (3) and (6) present the average environmental benefit from the scrappage and replacement of old gasoline and diesel cars respectively. Note that replaced and replacement cars may be of different fuel types. The absolute change in emissions per vehicle class (defined by a unique combination of fuel type, vintage and weight class) is valued using the shadow prices from column (7). The sum of the benefits per pollutant is presented in the final row and provides an estimate of b_i, defined in Eq. (7).

environmental benefits, we use the shadow prices for the pollutants of interest from de Bruyn et al. (2023). The estimates presented in columns (3) and (6) of the table are averages of values calculated at the participant level. These values are based on the class of the scrapped and of the replacement vehicle, and different emission factors and distance travelled per day for each vehicle class.

Multiple insights can be extracted from Table 11. First, the estimated environmental benefits are close to 30% of the average subsidy for retired gasoline cars and 48% for retired diesel ones. Second, for gasoline cars, the average emission intensity of replacement vehicles is lower than the average emission intensity of replaced vehicles for *all* pollutants. However, this is not the case for replaced diesel vehicles. For CO_2, CO and NMVOC, the average emission intensity of replaced vehicles is lower than that of replacement vehicles. This is because 78 percent of the diesel vehicles that participated in the programme were replaced by gasoline vehicles that generally emit more of these gases and pollutants. Still, there is a substantial gain from nitrogen oxide (NO_X) and PM_{10} emissions savings.[33] Second, saved NO_X emissions are responsible for a major share – 80 percent or more – of the environmental benefits from the accelerated replacement of old gasoline and diesel vehicles.[34]

We reiterate that the computed environmental benefits shown in Table 11 are lower bounds. First, as mentioned above, we exclude potential benefits from participants buying different (cleaner) replacement vehicles due to the programme. Second, in Section 6 we concluded that the policy induced the purchase of slightly lighter (2%) replacement vehicles. Lighter vehicles imply less emissions from mining and processing of materials needed for vehicle manufacturing, as well as lower non-exhaust emissions of particulate matter (OECD, 2020).

9. Conclusions

Scrappage subsidies have been a popular policy instrument to stimulate the replacement of polluting old vehicles with cleaner alternatives and to support trade in times of economic downturns. We focus on the design of vehicle scrappage subsidy programmes and study how eligibility criteria for participation in them affect vehicle trade and the generation of harmful emissions.

To this end, we first develop a theoretical framework accounting for the correlation between the quality of the discarded vehicle and the quality of the replacement vehicle, and describing how consumer behaviour is influenced by the eligibility criteria for participation in a scrappage subsidy programme. Then, we empirically estimate the effects of the eligibility requirements of a real-world programme on consumers' discarding and replacement decisions.

Our empirical analysis concentrates on a nationwide scrappage subsidy programme implemented in 2009-10 in the Netherlands, with differentiated eligibility requirements on gasoline and diesel vehicles. Using a unique combination of datasets on the universe of vehicles in the country in a five-year period and an econometric approach allowing us to establish counterfactual outcomes in the absence of the policy, we study the extent to which the programme removed old cars earlier from the roads, stimulated car trade and increased the sales of cleaner replacement vehicles. We then relate the estimated behaviour changes caused

[33] The Dutch policy saves on average about 10 kg NOx per participating gasoline car, and about 15 kg per participating diesel car. This is less than the savings of 28 kg per car reported by Sandler (2012).
[34] Helm et al. (2023) find that the nitrogen oxide concentration reductions caused by the 2009 German scrappage subsidy programme were responsible for public health benefits exceeding its costs.

by the programme to the participant types defined in our theoretical framework. Finally, we quantify the environmental benefits of the policy.

We find that the programme caused a large increase in the scrappage of old vehicles and their replacement with newer ones. However, we find evidence of an effect on the type of replacement vehicle purchased only for participants scrapping gasoline vehicles. More generally, the effects of the programme vary substantially by fuel type, something we can associate with differences in the stringency of eligibility criteria for participation. For example, the lax requirements on gasoline replacement cars incentivised a small percentage (3-7%) of those scrapping a gasoline car to purchase a cleaner vehicle than what they would have bought without the policy. On the other hand, we do not find evidence that participants scrapping a diesel vehicle purchased a different replacement vehicle than intended. In fact, the stricter purchase criteria of the programme on replacement diesel cars discouraged overall participation of diesel car owners.

Although we find very limited free-riding on the subsidy, we estimate that about 56% of all participants complied with the policy requirements by simply offering their car for scrap instead of selling it on the second-hand market. While the early scrappage of polluting vehicles yields environmental benefits, the behavioural change of these participants was minimal. Our – rather conservative – estimate of the average environmental benefits from early scrappage is approximately € 300 for gasoline vehicles and € 480 for diesel ones.

Strict requirements on the replacement vehicle may particularly discourage lower-income households from participating in scrappage subsidy programmes, as these households usually cannot afford buying newer and more expensive vehicles. By shifting attention in programme design from the adoption of the cleanest technology to the removal of the dirtiest, scrappage subsidy programmes could increase both their welfare benefits and support for the energy transition, without forgoing their environmental effectiveness. Allowing the purchase of a *second-hand* clean replacement product is an example of such a shift in programme design. Such a laxer requirement not only encourages the participation of lower-income households in the scrappage subsidy programme, but also enables them to embark on the energy transition.

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Appendix A: Concurrent scrappage subsidy programmes

A1. In other countries

Several countries introduced vehicle retirement acceleration programmes in 2009 in response to the repercussions of the financial crisis. Grigolon et al. (2016), Heimeshoff and Mueller (2013) and IHS Global Insight (2010a) provide overviews of these policies. Perhaps the most striking difference between the Dutch programme and other contemporaneous scrappage subsidy programmes is its openness to the purchase of second-hand replacement vehicles. Most other programmes required that the replacement vehicle was new. Exceptions to this pattern were the programmes implemented in Spain, where replacement vehicles could be up to 5 years old, and to a lesser extent in Germany, where replacement cars could be up to 14 months old (IHS Global Insight, 2010b). By contrast, vehicles aged up to 9 years old qualified as replacement vehicles in the Dutch programme.

The Dutch programme also differs in terms of other aspects from similar programmes in other countries. The subsidy offered in the Netherlands is closer to the lower end of the distribution of subsidies offered by contemporaneous vehicle retirement acceleration programmes, which range from € 222 per vehicle in Canada to 3288 € per vehicle in the United States (Heimeshoff and Mueller, 2013). Another important feature of the Dutch programme is that eligibility conditions differ between diesel cars and other fuel types (mostly gasoline). That is, the programme conditions on diesel cars in the Netherlands (effectively almost new) is comparable to what most other countries have imposed (see Table 1). For replaced vehicles of other fuel types, the participation constraint is more restrictive in the Netherlands than in other countries. On the other hand, the age restriction on replacement vehicles other than diesel, i.e. that they should first be registered as of 2001, is the least stringent of all concurrent programmes.

A2. Local scrappage programmes in the Netherlands

Two of the largest Dutch cities further incentivised the scrappage of old vehicles by providing complementary subsidies to residents offering their vehicle for scrap. In Amsterdam, the largest city in the Netherlands, residents were eligible for an extra subsidy ranging from 250 € to 1000 € – depending on the vintage, fuel type, and weight of the vehicle – as of 1 October 2009 (Municipality of Amsterdam, 2009a). In The Hague, the third largest city of the country, the extra subsidy was set to a flat amount of 500 €, and became available on 1 July 2009. All participants in the national scrappage programme registered in the municipality for at least 2 years before applying for the subsidy were eligible for it (Municipality of The Hague, 2009a).

Concurrently with increasing the amount of subsidy provided to participants in the national programme, the two cities implemented independent scrappage schemes for residents offering their old vehicle for scrap, without requiring them to have it replaced by another vehicle. On the same date with enacting the additional subsidy for participants in the national programme, Amsterdam launched its own scrappage scheme, which run until the end of 2010. The scrappage subsidy was available for diesel cars built before 1996 (1000 €), and gasoline and LPG cars built before 1990 (500 €). Furthermore, the car should have been owned by the same individual since 1 March 2008 the latest. While the ownership duration condition set in Amsterdam's scrappage scheme was completely in line with that of the national programme, its age eligibility conditions were much stricter. Amsterdam's programme also banned the owner from asking for a parking permit for another vehicle for at least 6 months after the scrappage date, therefore explicitly discouraging the purchase of a replacement vehicle (Municipality of Amsterdam, 2009b). The combined budget for all scrappage subsidies offered by the city of Amsterdam amounted to 5.85 million €.

The local scrappage programme in The Hague was enacted on 1 October 2008 and offered a 1000 € subsidy to residents offering an old vehicle for scrap, under the condition that they had been owning it for at least two years before submitting their application for a subsidy. The scope of the programme was initially limited to vehicles built no later than 1991, but it was in March 2009 expanded to vehicles built until 1995 (Municipality of The Hague, 2008, 2009b). The total budget allocated to the scrappage scheme in The Hague was 5.5 million € (Municipality of The Hague, 2009c). The budget was depleted at the end of June 2010, with an estimated 5,900 vehicles participating in the scheme (van Oort and van der Wal, 2012).

Appendix B: Cross-sectional approach for the estimation of the effect of the programme on remaining ownership length

Our second approach to estimating the effect of participation in the scrappage scheme on ownership duration relies on a cross-sectional regression model of the form:

$$D_i = \alpha\, p_i + \beta_1\, g_i + \beta_2\, l_i + \beta_3\, x_i + \beta_4\, q_i + \boldsymbol{z_i}\,\boldsymbol{\eta} + \varepsilon_i\ , \quad \text{(B1)}$$

where D_i measures the remaining ownership length of vehicle *i*, i.e. the number of days from 29 May 2009 until the date on which its registration ends. We only have data until July 2016, so when an ownership record has not ended by then, the observation is censored.[35] Dummy variable p_i equals 1 when a car participates in the programme, and 0 otherwise. Coefficient α is therefore our parameter of interest, as it reveals the number of days by which cars are scrapped earlier due to the programme. Indicator variables g_i and l_i denote whether the vehicle satisfies the age and the ownership length condition for participation in the programme respectively. Variable x_i measures the length of ownership duration until 29 May 2009 and serves as a proxy variable for consumer's willingness to replace the vehicle. We empirically observe a positive relationship between past and remaining ownership duration: consumers who have owned a vehicle for longer by the time of the introduction of the subsidy, are more likely to keep it for a longer period thereafter. Variable q_i counts the number of owners of vehicle *i* until 29 May 2009 and is a proxy for vehicle quality. We assume an inverse relationship between vehicle quality and the number of past owners, i.e. that the quality of vehicles that have changed hands more times has deteriorated more than that of vehicles that have had fewer owners. Vector $\mathbf{z}_i$ contains a series of control variables explaining differences in lifespan between vehicles: weight and engine displacement, as well as their squared values, a set of vehicle make dummies and a set of vintage dummies.

A potential concern in this model is that participating vehicles would have had a shorter remaining ownership duration also in the absence of the policy due to latent factors, for instance due to being of lower quality or due to their owners being more willing to forgo them. We try to address such concerns about endogenous selection in two ways. First, we use the two proxy variables mentioned above: the number of owners up to the start of the policy as a

[35] Ownership records not ended by July 2016 are removed from the analysis, because their ownership length (more than 7 years) is too long to be considered comparable with that of the vehicles participating in the programme (a few months).

proxy for vehicle quality, and past ownership duration as a proxy for the owner's readiness to sell the vehicle.

Second, we identify groups of vehicles for which selection effects may be stronger and run robustness checks on samples excluding them. The most prominent of these groups is eligible vehicles whose owners chose not to participate in the policy. These owners selected themselves out of the policy because vehicles were of too high quality and/or because they were not yet ready to trade them. In addition, we remove vehicles not satisfying one of the two conditions for participation. We thus compare participating vehicles either with old enough vehicles that have been held for too little by their owners, or with younger vehicles that have been long enough in the possession of their owners.

The results of the cross-sectional models are presented in Table 12. Our baselines estimates indicate that participating gasoline vehicles are forgone by their owners 592 days earlier than their non-participating counterparts, while diesel vehicles 559 days earlier (columns 1 and 4).[36] When comparing participating vehicles with younger vehicles that satisfy the ownership length condition (columns 2 and 5), estimates are higher. This is particularly the case for gasoline vehicles, whose remaining ownership length is estimated to be reduced by 801 days. Diesel vehicles are forgone 617 days earlier. These results point to a strong inverse relationship between vehicle age and remaining ownership duration. This is also confirmed by estimates from models excluding younger vehicles, but including vehicles that have not been long enough under the possession of their owners (columns 3 and 6). These estimates are considerably lower: 469 days for gasoline cars and 515 days for diesel ones.

In general, the estimates for gasoline cars above are considerably larger than that from the triple difference approach presented in Section 8 (358 days), whereas those for diesel cars do not consistently deviate from the estimate in Section 8 (572 days). For gasoline cars, which were the lion's share of vehicles participating in the scheme, the cross-sectional approach therefore leads to a significant overestimate of the benefit of the policy. We suspect that this discrepancy in estimates between diesel and gasoline vehicles could be attributed to weaker selection effects for diesel car owners. The reason for this is the much stricter conditions for

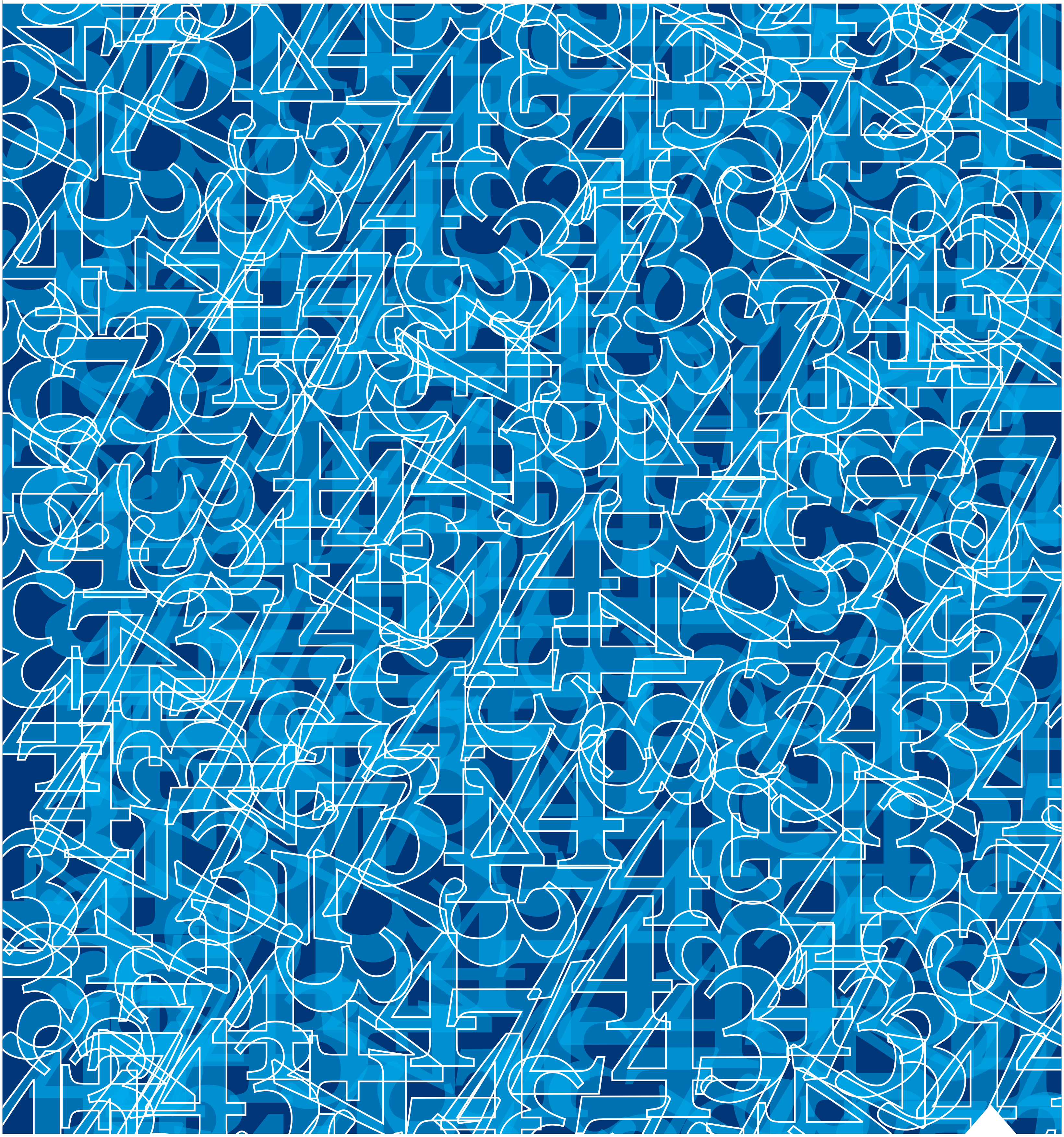
[36] Note that models including eligible non-participants – but excluding vehicles that neither satisfy the age nor the past ownership length condition of the policy, or vehicles that satisfy just one of these two conditions – lead to very similar estimates.

Table 12: Cross-sectional estimate of effect of subsidy on remaining ownership length

	Gasoline			Diesel		
	(1)	(2)	(3)	(4)	(5)	(6)
	All cars built between 1984 and 1997	Eligible duration & excl. eligible non-participants	Eligible age & excl. eligible non-participants	All cars built between 1984 and 2001	Eligible duration & excl. eligible non-participants	Eligible age & excl. eligible non-participants
Participation in the scheme	-591.7***	-801.0***	-468.8***	-558.4***	-617.6***	-514.6***
	(0.962)	(17.47)	(1.911)	(2.182)	(18.90)	(5.463)
Obs	1,586,928	489,602	375,859	594,366	172,889	108,093
R2	0.094	0.153	0.123	0.062	0.062	0.103

Note: All columns present OLS estimates of the impact of participation in the car scrappage subsidy scheme on remaining vehicle ownership length (in days). All specifications include only cars present in the fleet on 29 May 2009, which in addition have changed hands – or have been scrapped – between that date and 21 July 2016. Column (1) uses all gasoline cars first registered between 1984 and 1997, while column (4) all diesel cars first registered between 1984 and 2001. The specifications underpinning the estimates in columns (2) and (5), and (3) and (6) use smaller samples, excluding those who although eligible for the subsidy decided not to participate in the scheme (eligible non-participants). In addition, models of columns (2) and (5) exclude those who are ineligible for the subsidy due to a too short ownership duration (less than 15 months), while columns (3) and (6) exclude vehicles ineligible due to being too young, i.e. built after 1995 for gasoline cars and after 1999 for diesel ones. Symbols ***, **, * denote significance at the 1, 5 or 10 percent level, respectively. Robust standard errors are reported in parentheses below the parameter estimates.

participation on diesel replacement vehicles than on gasoline ones. These stricter conditions imply that owners of low-quality old diesel cars are discouraged to participate in the scrappage subsidy scheme, because they would have to replace them with almost new – and therefore expensive – diesel vehicles.



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