Decarbonizing Aviation: Cash-for-Clunkers in the Airline Industry

by

Jan K. Brueckner
University of California, Irvine
jkbrueck@uci.edu

Matthew E. Kahn
University of Southern California
kahnme@usc.edu

Jerry Nickelsburg
UCLA
jerry.nickelsburg@anderson.ucla.edu

March 2024, revised July 2024

Abstract

The durability of the transportation capital stock slows down the pace of decarbonization since newer vintages feature cutting-edge technology. If older vintages were to be retired sooner, the social cost of travel would decline. This paper analyzes and explores the viability of a potential cash-for-clunkers program for the airline industry, which would help to hasten decarbonization of aviation. Focusing on US aviation, our estimation and calculations show that airlines can be induced to scrap rather than sell older planes upon retirement with a payment that is less than the forgone carbon damage.

Decarbonizing Aviation: Cash-for-Clunkers in the Airline Industry

by

Jan K. Brueckner, Matthew E. Kahn, and Jerry Nickelsburg[†]

1. Introduction

With the transportation sector contributing 29% of total US carbon emissions in 2021, decarbonization of the sector is a major policy goal. Since a first-best carbon tax is politically infeasible, automobile CAFE standards constitute a major current US policy tool serving this goal, with subsidies for purchase of electric vehicles recently also becoming important. Commercial aviation, a smaller but rapidly growing part of the transportation sector, accounts for 8% of its emissions and 2-3% of overall US emissions.[1] But unlike in the case of automobiles, US government intervention designed to reduce aviation emissions is mostly absent, although small efforts to spur production of sustainable (nonpolluting) aviation fuels, which are currently unaffordable, have begun.[2]

A different and faster-acting policy for addressing aviation emissions could mirror the automobile "cash-for-clunkers" program, which operated briefly in 2009. The program provided a voucher for purchase of a new fuel-efficient vehicle in return for scrappage of an old vehicle. Its intention was both to boost automobile production during the downturn of the Great Recession and to eliminate the carbon emissions from old fuel-inefficient vehicles. The program was very popular, exhausting its $3 billion budget in less than 60 days and leading to scrappage of almost 700,000 vehicles.[3]

† We thank Calvin Ryan for excellent research assistance and thank (without implicating) Bill Branch, Lucas Davis, Alberto Gaggero, Kangoh Lee, Lisa Ward, Cliff Winston and several referees for comments.

1 See `https://www3.epa.gov/otaq/documents/aviation/420f15023.pdf`

2 See `https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuels.`

3 See Li, Linn and Spiller (2013), Davis and Kahn (2011), Mian and Sufi (2012), and Green et al. (2020). By contrast, CAFE standards, by raising new-car prices, may keep older cars in use, as analyzed by Gruenspecht (1982) and Stavins (2006). In a different vein, Knittel (2011) argues that, even though car producers (like aircraft manufacturers) can achieve higher fuel efficiencies than before, consumer demand for large vehicles (which Anderson and Auffhammer (2014) argue serves a self-protection motive) offsets this effect. Also see Alberini, Harrington and McConnell (1995, 1996) for analyses of vehicle retirement programs that preceded the cash-for-clunkers program.

In this paper, inspired by the automobile program, we analyze and explore the viability of a potential cash-for-clunkers program for the airline industry, which would pay an airline to scrap rather than sell older planes retiring from its fleet. Like the automobile program, an airline program addresses the environmental downside of the durability of capital stocks, which slows the decarbonization of the economy. By paying their owners not to pollute, both programs would prevent ongoing emissions from aging durable capital goods that are in use for too long from an environmental viewpoint, given the availability of new cutting-edge technology. A similar program could be implemented for other durable, polluting capital goods, such as buses, railroad locomotives, and ships, and the idea could even be applied to induce scrappage of aging consumer appliances such as refridgerators, air conditioning systems, and hot water heaters.[4] An airline cash-for-clunkers program would be especially appropriate in the US, where airline fleets contain many old fuel-inefficient aircraft that should be scrapped rather than transferred to another airline upon retirement. In 2019, for example, aircraft in our main US sample were around 3.5 years older on average than planes in an alternate European sample, as discussed further below.

Even though the target of an airline program is not an individual car owner but a carrier solving a complex fleet optimization problem, the incentives created are very similar, and the outcome would mirror the achievements of the automobile program. Currently, older aircraft being retired by major US airlines are often transferred to carriers in developing countries or to domestic start-ups, continuing to generate emissions long after these retirements.[5] Under a cash-for-clunkers program, the government would pay US airlines to scrap rather than sell these older planes, thus terminating the emissions that would otherwise be ongoing. Such a "clunkers" payment is worthwhile, however, only if the forgone carbon damage from scrappage of the plane exceeds the payment's magnitude. We establish that this relationship is generally satisfied in our calculations, showing the potential attractiveness of the program.[6]

[4] Although the context is somewhat different, our program can be viewed as an industrial policy targeted at distortions in the supply chain for air travel services, as in Aghion et al. (2004).

[5] This pattern mirrors the sale of US used cars to buyers elsewhere, as studied by Davis and Kahn (2011) and Newman et al. (2024). That phenomenon, along with sale of old planes, resembles filtering in the market for housing (another durable capital good), as analyzed by Sweeney (1974) and others.

[6] Davis, Fuchs and Gertler (2014) show that this relationship was not satisfied for a Mexican subsidy program

To see the logic of an airline cash-for-clunkers program more clearly, suppose that an older plane has a market value of \$2.5 million and a scrap value of \$1.2 million, the amount that a scrapping company would pay.[7] Then, in the absence of any intervention, the plane would be transferred to another airline rather than scrapped, and to reverse the airline's decision, the government would need to pay it \$1.3 million, the difference between the market and scrap values. The resulting scrappage rather than transfer of the old aircraft would reduce carbon emissions over the plane's previous remaining life, with the reduction E equal to the difference (in present value terms) between its emissions and those of a newer, more fuel-efficient plane operated in its place. The cost of achieving this reduction is the \$1.3 million cash-for-clunkers payment, and dividing this cost by E then gives the cost per ton of forgone emissions. If this cost is low compared to the social cost of carbon emissions, then the cash-for-clunkers program offers an attractive way of decarbonizing aviation.[8] A similar logic can be applied to leased aircraft, as explained further below.

Our analysis operationalizes this idea, relying on several sources of data. We collect the market values of aircraft from proprietary airline bluebooks, estimate forgone carbon damage using data from the US Bureau of Transportation Statistics, and estimate unobservable aircraft scrap values through a logit analysis of airline scrap vs. sell decisions for retiring planes. Individual aircraft histories are needed in the exercise, and they come from a public website. An overview of the methodology is presented in section 2, with further details given in later sections.

The literature on automobile decarbonization is large and includes contributions by Li, Timmins and Von Haefen (2009), Knittel (2011), Klier and Linn (2010), Anderson and Auffhammer (2014), and Holland, Mansur and Yates (2021), along with those cited in previous

designed to induce households to replace old refridgerators.

[7] See Hahn (1995) for a theoretical analysis of scrappage, and Sallee (2024) for examples of the benefits of timely scrappage of various capital goods. A different approach is to simply ban new consumer products with low energy efficiency, as studied by Buettner and Kesselring (2024).

[8] Huang and Kahn (2024) carry out a similar analysis of federal funding to local transit agencies designed to encourage replacement of diesel buses with electric models. They argue that the funding formulas involve a number of inefficiencies. Calel et al. (2021) rank wind projects in India and find the marginal set of decarbonization projects that would not have been carried out without an offset-generated subsidy (analogous to plane scrappage that would not have occurred without a clunkers payment), arguing subsidies are wasted on inframarginal projects.

footnotes. The literature on decarbonization of the airline industry is, by contrast, small but growing. Brueckner and Abreu (2017, 2020) and Fukui and Miyoshi (2017) study how airline fuel usage responds to fuel prices and thus can predict the reductions in carbon emissions from potential fuel taxes. Fageda and Teixido (2022) study the impact of actual taxes by studying the operational responses of European carriers to their inclusion in EU's Emissions Trading System, which taxes airlines by requiring the purchase of emission permits. de Almeida and Oliveira (2023) and Brueckner, Kahn and Nickelsburg (2024) quantify other airline operational responses to higher fuel prices, which include slower flying, lower aircraft utilization, and faster retirements of old planes.[9]

The plan of the paper is as follows. Section 2 presents preliminaries: data on the evolution of aircraft fuel-efficiency along with a discussion of the sources of improvement; a theoretical model showing that airline decarbonization is too slow; and an overview our empirical methodology. Section 3 discusses data, while section 4 provides further details of our strategy. The empirical results are presented in section 5, and section 6 offers conclusions.

2. Preliminaries

2.1. The evolution of aircraft fuel efficiency

The continual improvement in aircraft fuel efficiency over time, which makes carbon emissions from old planes higher than those from new planes, provides the rationale for an airline cash-for-clunkers program designed to spur scrappage of the old models. This favorable fuel-efficiency trend is shown in Figures 1 and 2. The figures plot gallons per seat-mile, an inverse measure of fuel efficiency, against aircraft vintage (year first built) for individual plane types, with Figures 1 and 2 showing narrow-body and wide-body aircraft, respectively (narrow body vintages start earlier, in the 1960s). The gallons per seat-mile numbers are drawn from Table 2 of Brueckner et al. (2024), and they are averages across airline/year appearances of an aircraft type in their 1991-2019 data set. As can been seen, the trend of gallons per seat-mile is downward for both classes of aircraft.[10] Gallons per seat-mile for narrow-bodies started near

[9] Gosnell, List and Metcalfe (2020) show the effectiveness of pilot-directed airline incentives to conserve fuel through actions such as slower flying and taxiing on one engine.

[10] Changes in fuel-saving operational practices that differ across aircraft types could in principle affect fuel-

0.0300 in the 1960s with aircraft types like the 727-100 and DC-9-10, while it had fallen to near 0.0100 by 2020 with the introduction of types such as the 737 Max 9 and A321-200neo.[11] Early wide-bodies (built around 1970) had gallons per-seat mile near 0.0200, but this inverse efficiency measure had fallen to around 0.0120 by 2020 with the emergence of the 787 and A350 types.[12]

Instead of showing fuel efficiency by individual aircraft types, Figure 3 shows average gallons per seat mile across all aircraft types in use in a given year, using data from the six largest US carriers in 2019 and their predecessors acquired through mergers (the data is again from Brueckner et al., 2024). Again, the trend is notably downward.

The improvement in fuel efficiency seen in Figures 1-3 has arisen from two main sources: improvements in jet-engine technology and (more recently) use of lighter composite materials in the fabrication of aircraft bodies and wings. Jet engines produce thrust in two ways: first, through the expulsion of burned fuel, and second, through the air volume pushed past the engine by fan blades powered by the fuel combustion. The emergence of "high-bypass" engines, where the volume of thrusting-producing air that bypasses the combustion chamber is large, led to gains in fuel efficiency. These gains have continued to grow as engineering advancements have continually raised engine "bypass ratios."[13] In step with engine improvements, lighter and stronger composite materials have recently begun to replace aluminum in the construction of aircraft bodies and wings, and the consequent lightening of planes has raised their fuel efficiency. Boeing led the way in this materials revolution with its 787 wide-body models, and Airbus soon followed with its A350 wide-body models.

A third source of increased fuel efficiency has been the installation of winglets, the upward-pointing extensions to aircraft wingtips that were added to existing planes in recent decades and are now standard on new aircraft. Winglets convert the wingtip vortex created as an aircraft

efficiency comparisons, but there is no evidence supporting this conjecture.

[11] A few narrow-body types are not shown in Figure 1 to avoid label overlaps, and one type is not shown in Figure 2. See the table notes.

[12] Among narrow-body planes, regressions show that gallons per seat-mile falls with seat capacity, so that larger narrow-bodies are more fuel efficient. However, among wide-body planes, no relation between fuel efficiency and capacity exists, evidently because these aircraft are all large.

[13] Wikipedia offers a good discussion of jet-engine technology in its article "Turbofan" (https://en.wikipedia.org/wiki/Turbofan).

passes through the air to a form of usable thrust, thereby reducing fuel consumption.[14]

2.2. Theoretical analysis

Building on the evidence of fuel-efficiency improvements just presented, this subsection develops a simple theoretical model showing that airline decarbonization is too slow, with new, more fuel-efficient aricraft not adopted soon enough. The model establishes the need for a cash-for-clunkers program to spur such adoption.

While fuel consumption is constant over an aircraft type's life, we assume that maintenance cost realistically rises as the type ages according to the common function $m(a)$, where a is age and $m'(a) > 0$. Let F_i denote annual fuel consumption for the ith aircraft in the sequence, with $F_{i+1} < F_i$ holding for all i, and suppose that the fuel price and carbon emission per gallon are constant over time, equal to f and c, respectively. With little loss of generality, we focus on a simple setting with just two aircraft types and a fixed retirement time H for the second type. The social planner's problem is then to choose the year T at which the first type ceases and the second type begins to operate, so as to minimize social costs.[15]

Letting r denote the discount rate and γ denote the social cost of carbon emissions, the present value of these costs is given by

$$\int_0^T [(f + \gamma c)F_1 + m(t)]e^{-rt}dt \ + \ \int_T^H [(f + \gamma c)F_2 + m(t - T)]e^{-rt}dt. \tag{1}$$

Using Leibniz's rule, the planner's first-order condition for choice of T is

$$G(T) \ = \ (f + \gamma c)F_1 \ + \ m(T) \ - \ [(f + \gamma c)F_2 \ + \ m(0)] \ - \int_0^{H-T} m'(s)e^{-rs}ds \ = \ 0, \tag{2}$$

where $G(T)$ is the derivative of (1) with e^{-rT} factored out. The (positive) difference between the first two terms is the current cost increase from postponing T (recall $F_1 > F_2$ and $m(T) >$

[14] See the Wikipedia article "Wingtip device" (`https://en.wikipedia.org/wiki/Wingtip_device`).

[15] For simplicity, intensity of use of the aircraft (miles flown per year) is not a decision variable in the model, nor is it captured in the main empirical analysis, although in a robustness check, we do consider a drop in intensity of use after transfer of a plane. The empirical analysis of Brueckner et al. (2024) does focus on use intensity, and their theoretical model also incorporates it. Although age per se plays no role in their model, airlines in reality tend to use newer planes more intensively than older ones, a consequence of their higher capital cost, greater capability and greater fuel efficiency.

$m(0)$), while the second term is the present value of reductions in maintenance-cost from having a younger type-2 aircraft at each future operating time. Since $G'(T) > 0$, an interior solution T^* to (2) represents a global cost minimum (the G function thus slopes up).

The objective function of a cost-minimizing airline, which ignores carbon damage, differs from (1) by the absence of γc. Its first-order condition for T thus involves an (upward-sloping) function $\widehat{G}(T)$ that is lower than G by the amount $\gamma c(F_1 - F_2)$ and thus intersects the horizontal axis to the right of G's intersection, at $T^{**} > T^*$. By not internalizing the reduction in carbon damage from switching to the type-2 aircraft, the cost-minimizing airline then operates the type-1 plane longer than the planner.[16] The present value of the additional carbon emissions from the delayed switch equals $E \equiv c(F_1 - F_2)(e^{-rT^*} - e^{-rT^{**}})/r$, and multiplying by γ gives the social cost of these emissions. While this cost could be eliminated by a carbon tax, which would charge the airline γc per unit of fuel, a cash-for-clunkers program would have a similar effect by hastening retirement of the type-1 aircraft.[17]

Finally, it is important to note that the foregoing analysis concerns operation, not ownership, of the aircraft, with changes in ownership having no effect on the conclusions. If the type-1 aircraft changes hands during its life, it is easily seen that the second owner will choose the same $T = T^{**}$ as before, thus also operating the aircraft too long.[18]

2.3. Overview of methodology

Evaluating an airline cash-for-clunkers program requires two main pieces of information. First, we need to compute the reduction in emissions when a particular aircraft type is scrapped and a newer plane takes its place. Since scrappage occurs immediately, the present value of

[16] To put the foregoing analysis in broader context, note its similarity to models of forest rotation, where aging trees are harvested and new ones planted, (see, for example, Samuelson, 1976). The difference in the aircraft context is the presence of an emissions externality that makes rotation of aircraft too infrequent.

[17] Jacobsen and Van Benthem (2015) analyze the scrappage impacts of carbon taxes.

[18] If technological subsidies were present in the model that make both aircraft types more fuel-efficient, then the conclusions remain the same: the switch from the type-1 to type-2 aircraft will still occur too late. But suppose that in response to the subsidies, aircraft manufacturers announce plans for type-3 aircraft that is much more fuel efficient than both existing types but that is available only after a date $\widehat{T}$ beyond T^{**}. In response to this news, the airline may choose to operate the high-polluting type-1 plane even longer than originally planned, switching to the type-3 aircraft at $\widehat{T}$. In this situation, the incentives provided by a clash-for-clunkers program could lead to short-term usage of the type-2 plane before the switch to type 3, reducing carbon damage relative to case where the type-2 plane is skipped.

these emissions is found by setting $T^* = 0$ in the above formula, yielding $E = (F_1 - F_2)(1 - e^{-rT^{**}})/r$. Using the fuel efficiency data from Brueckner et al. (2024) shown in Figures 1 and 2, we know F_1 for the retiring aircraft along with F_2, which equals fuel usage by a new, more fuel-efficient plane of the same capacity. Then, using aircraft history data (discussed below), we can compute the remaining life of the old plane had it not be scrapped, which gives T^{**} and thus E.

The second main piece of needed information is the amount of the payment required to induce scrappage rather than sale of a retiring aircraft. To estimate the size of this "clunkers" payment, we use the market value information from aircraft bluebooks, along with observed retirements from the aircraft history data, which also show whether a retiring plane was transferred to another airline or scrapped. In deciding whether to scrap an aircraft, the airline compares its market value and scrap value, which is unobserved by us. We assume that scrap value depends on aircraft characteristics X such as its type and age, being equal to $X\beta$, where β is a coefficient vector. We estimate β and hence scrap value by running a logit regression with dependent variable equal to a scrappage dummy and right-hand side equal to $-P + X\beta$, where P is the plane's market value. For an aircraft i that is likely to be sold upon retirement, for which $P_i > X_i\widehat{\beta}$, the size of the clunkers payment required to induce scrappage is the difference $P_i - X_i\widehat{\beta}$, where $\widehat{\beta}$ is the estimate of β.

A similar logic applies when the retiring aicraft is leased rather than owned by the airline, as is the case for around 40% the US fleet.[19] For a leased plane, retirement means that the airline simply returns the plane to the lessor, who then decides whether it should be scrapped or leased to a new operator (the history data then show a transfer to another carrier). In this situation, the leasing company rather than the airline gets the clunkers payment in return for scrapping the plane rather than leasing it again. Note that, in the absence of a cash-for-clunkers program, the leasing company would compare the present value of future lease payments to the plane's scrap value in making its scrap/lease decision. Since this present value should equal the market value of the aircraft, the comparison is the same as the one made by an aircraft

[19] See `https://centreforaviation.com/analysis/reports/aircraft-leasing-in-equilibrium-at-just-over-half-the-world-fleet-675212`

owner. Our analysis is then applicable to either owned or leased aircraft. Accordingly, instead of using the transparent term "sale" in referring to the fate of a retired aircraft, we say that the plane is "transferred" to another airline, which happens either through sale or a new lease.

The last step is to combine these two pieces of information, the emissions reduction from scrappage of a plane and the size of the required clunkers payment. For an aircraft i that is likely to be transferred to another airline upon retirement, the combination yields the cost per ton of forgone emissions, equal to $(P_i - X_i\widehat{\beta})/E_i$. If this cost is less than the social cost per ton of carbon emissions, then a clunkers payment for aircraft i is worth making. If this relationship holds for most retiring aircraft that are likely to be transferred, then a cash-for-clunkers program is generally attractive, and this attractiveness will be heightened if the cost per ton of forgone emissions is especially low. In the actual computation, we inflate the clunkers payment by the marginal cost of public funds, recognizing that the payment uses funds raised through distortionary taxation, while also deriving the marginal value of public funds for the clunkers program.

The issue of "additionality" arises in an airline cash-for-clunkers program. Since the logit prediction is imperfect, planes that are judged as likely to be transferred upon retirement (thus receiving a clunkers payment) might actually have been scrapped in the absence of the program. Such payments therefore do not generate additional emission reductions relative to the status quo, thus not satisfying the additionality criterion. The additionality issue is related to the choice of which planes are "likely" to be transferred on retirement, thus being recipients of a clunkers payment. Our baseline approach is to target aircraft with an estimated scrappage probability less than 0.5 as likely to be transferred (a condition equivalent to $P_i > X_i\widehat{\beta}$ from above). However, to reduce potential violations of additionality, the required scrappage probability can be set lower to better ensure that clunkers payments go only to planes highly unlikely to be scrapped, an exercise we carry out in a sensitivity analysis.

Actual implementation of the program would proceed as follows. Each year, the government would ask an airline to identify the planes it intends to retire in the subsequent year without divulging its sell/scrap decisions. The government would used its own logit scrappage regression (perhaps built on a longer data set than ours) to identify which of the retiring planes are likely to be transferred along with the size of the clunkers payment required to induce scrappage. Then, assuming that the payment is justified in terms of forgone emissions, the government would offer it to the airline, leading to scrappage of the identified planes.

If pursued on a large scale, both in the US and elsewhere, a cash-for-clunkers program could notably reduce the supply of used aircraft and raise their prices. This effect would in turn put upward pressure on the size of the clunkers payments required to induce the scrappage rather than transfer of old planes. As a result, institution of the program may in turn reduce its own viability, although some equilibrium where the program still successfully operates would presumably emerge.

If the program were implemented on a smaller scale (say in the US only), then used aircraft prices would rise by less. But with used prices still higher and program coverage only partial, the result could be lower aircraft scrappage elsewhere in the world, partly offsetting the benefits of the US program. This possibility points to the desirability of global implementation of a cash-for-clunkers program.

It seems unlikely that a program would create moral hazard. Buying used planes simply to capture the clunkers payment upon their retirement loses money because the purchase price would exceed the eventual payment. Moreover, it seems unlikely that the program would generate selection into retirement. The reason is that program does not affect the proceeds from retiring an aircraft. For targeted planes, the airline's proceeds from scrappage equal what it would have received by selling the retiring plane, with the shortfall relative to the sale price exactly offset by the clunkers payment. With proceeds unaffected, aircraft retirement is neither more nor less attractive than before.

3. Data

The empirical analysis in this paper relies on three data sources. The first is the *AVITAS BlueBook of Jet Aircraft Values*, an annual source to which we were given free access for the years 2015, 2017, and 2019. For each aircraft type in a given year, the bluebook shows the market value (denoted $market\_val$) according to the aircraft's vintage, or year of manufacture. For example, for the Boeing 737-300, the 2015 bluebook shows the market value in 2015 for aircraft of this type for different years of manufacture, which range between 1984 and 1999. The blue book also gives the aircraft type's characteristics, including seat capacity (denoted *capacity*), range in miles (*range*), number of engines (*engines*), and a widebody dummy (*widebody*), all of which are independent of year of manufacture. Aircraft age in years (denoted *age*) is generated by subtracting the year of manufacture from the current year (2015, 2017, or 2019).

The second data source, which was also used in Brueckner et al. (2024), is the T2 data set of the U.S. Bureau of Transportation Statistics (BTS).[20] This source provides annual fuel usage (denoted *gallons*) by aircraft type, airline, and year, along with annual seat-miles by aircraft type, airline and year. Using both variables, an inverse measure of fuel efficiency, gallons per seat-mile (*gallons_seat_mile*), can be computed by aircraft type, airline and year.

The third data source, which is used in the cash-for-clunkers analysis, is the Planespotters.net website, whose information was supplemented and cross checked with Planelist.net and Airfleets.net. The Planespotters website tracks of usage of each aircraft, identified by the manufacturer's serial number, over all the years since its manufacture. We collected the Planespotters data for a long period, the years 1991-2019, in order to generate an adequate picture of aircraft lifespans. Planespotters yields 5,108 US aircraft histories, and in each year, the website indicates the passenger airline or other air carrier operating the aircraft or whether it has been scrapped or written off (as would occur in the case of a crash). Scrappage means that the aircraft is sold for scrap, held as a source of spare parts, or possibly stored.

The coding of carriers uses a *focal* set of passenger airlines, which are individually identified, with carriers outside this set not being identified but coded as other OECD passenger carriers, non-OECD passenger carriers, cargo carriers of any country, or other carriers (private service, air taxi, medevac or military transport). The focal US carriers are the six largest ones in 2021: American, Delta, United, Southwest, Alaska and JetBlue, which account for 80% of domestic US revenue passenger miles.

To predict the scrappage vs. transfer decisions of airlines upon retirement of aircraft, the cash-for-clunkers analysis relies on a logit scrappage regression for planes that are retired over

[20] `https://www.transtats.bts.gov/Fields.asp?gnoyr_VQ=FIH`

the years 2015-2019, as explained further below. These are the years for which we have (or can interpolate, as explained below) market values. Retirement in one of these years (say t) means that, in year $t-1$, an aircraft is operated by a focal carrier, while in year t, it is either operated by a non-focal carrier (indicating a transfer) or scrapped, with $t = 2015$, 2016, 2017, 2018, or 2019. The retirement year of an aircraft within this period, equal to one of these years, is denoted *retire_yr*. Focusing on aircraft that retired over this period greatly reduces the number of relevant aircraft histories.

An additional requirement for a focal-carrier retirement is that the aircraft is operated by a focal carrier in each consecutive year of the 2014-2018 period prior to its retirement. Aircraft occasionally cycle between focal and non-focal carriers, with a plane starting out operated by a focal carrier, then shifting to a non-focal carrier, and then shifting back to the same (or a different) focal carrier, and we exclude these patterns near retirement.

Airlines operating a large number of aircraft of a given type may face a stronger incentive to scrap rather than sell a retired plane, which then can be used as a source of spare parts for the remaining aircraft. Accordingly, we create a variable denoted *type_count*, which gives the annual count for an aircraft of a particular type in an airline's fleet.[21] The count is created by looking across an airline's aircraft histories in a given year and summing by type, with only counts for 2015-2019 needed.

As explained further detail below, the market value of a plane is an important factor in the scrap vs. sell decision. We have market values for the years 2015, 2017, and 2019, but using all the retirements over the 2015-2019 period in the logit regression requires imputing the missing market values for 2016 and 2018. We do so by setting, for planes of a given type and age, the 2016 market value equal to the average of the 2015 and 2017 values, and setting the 2018 value equal to the average of the 2017 and 2019 values. In the few cases where the data structure rules out this interpolation, we set the missing 2016 or 2018 value equal to the value in the previous year.

The full set of aircraft histories starting at 1991 is used to estimate the average lifespan

[21] Table 6 in Brueckner et al. (2024) shows, for some airlines and aircraft types, the share of retired planes used for parts. The number is positively correlated with the peak count of that type in the carrier's fleet.

of aircraft types. In doing so, note that the few rare histories where an aircraft is scrapped and later returns to service (having been stored) are not present in the data set, having been removed. Then, the interval between the year of manufacture (which may predate 1991, the earliest history year) and the year of scrappage (if it is observed) is computed. The resulting lifespan is averaged within aircraft types, yielding a type-specific average lifespan (denoted *avg_life*). The expected remaining life for an aircraft not scrapped upon retirement (denoted $remain\_life$) is then equal to the average lifespan minus the retirement year ($avg\_life-retirement\_yr$). The *remain_life* variable is used to compute carbon emissions from continued operation of a retired aircraft, required in the cash-for-clunkers analysis, as explained below.

4. Details of our procedures

4.1. Logit regression

An airline's scrappage decision depends on the difference between an aircraft's market value and its scrap value. The scrap value captures the proceeds from selling the plane for scrap or else the aircraft's value as a source of spare parts. Scrap value thus depends on a subset of the aircraft's characteristics and on *type_count*, which captures the benefits of using the plane for spare parts. Crucially, while the market value is observed, the scrap value is unobserved and must be estimated. Let the scrap value be written as $X\beta$, where X is vector containing the relevant set of determining variables, and let P denote market value. Then, a retired plane will be scrapped rather than transferred when

$$P \;<\; X\beta \;+\; \epsilon, \tag{3}$$

where ϵ is an error term that captures the unobserved determinants of scrap value. The probability of scrappage is then

$$Prob\,(\epsilon > P - X\beta) \;=\; 1 \;-\; Prob\,(\epsilon < P - X\beta) \;=\; 1 \;-\; F(P - X\beta), \tag{4}$$

where F is the cumulative distribution function of ϵ. If ϵ has the logistic distribution, then

$F(z) = exp(z)/(1 + exp(z))$, and

$$Prob\,(\epsilon > P - X\beta) = 1 - \frac{exp(P - X\beta)}{1 + exp(P - X\beta)}$$
$$= \frac{1}{1 + exp(P - X\beta)} = \frac{exp(-P + X\beta)}{1 + exp(-P + X\beta)}. \quad (5)$$

Based on the final expression in (5), β can be estimated using a logit regression with $-P+X\beta$ on the right-hand side.[22] Note that the coefficient of P must be constrained to equal -1 when running the regression.

The logit regression is run using two different specifications, with the scrappage dummy *scrap* being the dependent variable. In the first specification, X includes the variables *capacity*, *age* and *type_count*, along with year dummy variables. Aircraft with large seat capacities are likely to have high scrap values, as are planes where *type_count* is large, making their spare-parts value high. Older planes may have lower scrap values, although such a vintage effect could be absent. Holding capacity and age constant, it appears that scrap value would not further depend on aircraft characteristics such as range and fuel-efficiency (inversely measured by *gallons_seat_mile*), so that these characteristics are omitted from the logit regression.

Under a second specification, *capacity* is dropped as a covariate, while aircraft-type dummy variables are added to the logit regression. These variables capture capacity as well as any other unobserved aircraft features that influence scrap value. The *age* variable and *type_count*, which vary independently of the aircraft dummies, continue to appear as covariates.

From the logit post-estimation sample, the fitted value $-P+X\widehat{\beta}$ (denoted *fitted_val*) and the fitted probability of scrappage (denoted *prob_scrap* and equal to (5) evaluated at *fitted_val*) are recovered. They are used in the cash-for-clunkers calculation, which is explained in next section.

4.2. The cash-for-clunkers calculation

Under a cash-for-clunkers program, the government would pay an airline to scrap an old plane rather than sell it for ongoing usage, thus avoiding the carbon emissions from continued

[22] We experienced probit convergence problems in some cases, thus using logit instead.

operation. Aircraft that would be targeted are those likely to be transferred rather than scrapped, having $prob\_scrap < 0.5$. The remaining aircraft in the logit post-estimation sample are thus dropped, with calculations proceeding on those planes likely to be transferred rather than scrapped. A probability smaller than 0.5 could be used instead to better avoid violations of additionality (clunkers payments going to planes that would have been scrapped anyway), and we explore such values in a sensitivity analysis below. With $prob\_scrap < 0.5$ thus holding for the targeted aircraft, $fitted\_value < 0$ also holds, implying $-P + X\widehat{\beta} < 0$ or $P > X\widehat{\beta}$. To induce scrappage of these aircraft, the government would need to pay the airline the difference between P and the estimated scrap value $X\widehat{\beta}$, or an amount equal to $-fitted\_value$. Let this payment be denoted $clunkers\_pmt$.

To decide whether the payment is worthwhile, the foregone carbon emissions must be calculated. Let D denote the annual carbon emissions from continued operation of the retiring aircraft (represented by cF_1 in the theoretical model) and let T denote its remaining life after being transferred. Then, scrappage of the retiring aircraft eliminates own carbon emissions equal to

$$own\_emissions \quad = \quad \int_0^T De^{-rt}dt \quad = \quad D(1 - e^{-rT})/r, \tag{7}$$

where r again is the discount rate.

But as seen in the model of section 2, the proper emissions measure is the forgone emissions, which is the difference between the emissions from the old retiring plane and those from the new plane that would replace it in the world aircraft fleet. This emissions difference equals $\Delta D \equiv D - \widetilde{D}$, where $\widetilde{D}$ is annual emissions from the new plane (cF_2 in the model). Letting $\widetilde{D} = \delta D$, for some $\delta < 1$, it follows that $\Delta D = (1 - \delta)D$, with δ's magnitude discussed below. Forgone emissions is then equal to

$$E \quad = \quad (D - \widetilde{D})(1 - e^{-rT})/r \quad = \quad (1 - \delta)D(1 - e^{-rT})/r, \tag{8}$$

which is analogous to the similar expression in the theoretical model.

The next step is to produce an estimate of D. We note from Brueckner and Abreu (2017) that each gallon of jet fuel burned generates 9.75 kg of CO_2 of carbon. Then, using the annual *gallons* value for the retiring aircraft type and 10^{-3} metric tons (*mtons*) per kg, the estimate of D in metric tons equals

$$\widehat{D} \;=\; gallons \;\times\; 9.75\ kg/gallon \;\times\; 10^{-3}\ mton/kg. \tag{9}$$

Setting r equal to the typical value of 0.05, replacing T in (8) by $remain\_life$, and replacing D by $\widehat{D}$ then yields the following estimate of forgone emissions:

$$\widehat{E} \;=\; (1-\delta)\widehat{D}\,[1 \;-\; exp(-0.05 \times remain\_life)]/0.05. \tag{10}$$

In our calculations, $\widehat{D}$ is computed and multiplied by a realistic value of $1-\delta$ for each aircraft with $prob\_scrap < 0.5$. Then, using the $remain\_life$ value for the aircraft, E in (10) is evaluated. For an aircraft i, the ratio of the clunkers payment and E_i, equal to $(P_i - X_i\widehat{\beta})/E_i$ is then computed, giving the cost per dollar of emissions forgone for that aircraft under the clunkers program. To evaluate whether making the clunkers payment is worthwhile, the result is then compared to the social cost of carbon. In doing this calculation, we actually inflate the clunkers payment by an estimate of the marginal cost of public funds, as explained below.

Aircraft that are transferred to a non-OECD passenger airline or a cargo carrier may end up being utilized less intensively over a longer lifespan than by a US passenger airline. In this case, the forgone emissions must be adjusted, but our verdict on the desirability of cash-for-clunkers payments is mostly robust to any such adjustment, or to a change in the discount rate, as shown below.

5. Empirical findings

Before turning to the main findings of interest, we report the results of estimating an hedonic aircraft price function, making use of the bluebook market-value and plane-characteristics data and information on *gallons_seat_mile* by aircraft type. The results are shown in Table A2 in the appendix, with Table A1 showing the frequency of aircraft types in the regression data set (standard errors are clustered by type). From the estimated coefficients, we see that larger, newer, longer-range, and more fuel-efficient aircraft have higher market values. Other things equal, widebody aircraft and those with more engines have lower values, although the larger capacity and range of such planes raises value.[23] Market values do not vary significantly across the three sample years, and the values of Airbus planes are no different from those of other manufacturers (mainly Boeing), holding characteristics constant.[24] Although these results match expectations, we are not aware of any other estimated hedonic aircraft price functions in the literature.

5.1. The logit scrappage regression

Table 1 gives the summary statistics for the US logit data set, which is the data set used to run the logit scrappage regression. Since the aircraft in this data set are those retiring over the 2015-2019 period, the set of aircraft types (which contains 13 types) is smaller then the set of all the types for which we have information, which is shown in Table A1 in the appendix. Table 1 shows the aircraft types represented, their frequencies (number of retired aircraft), and the mean values of a number of variables. For the US case, 757-200 aircraft are the type experiencing the most retirements over the 2015-2019 period, with 737-300s and MD-82s being the next most-retired planes. The 1.0 mean value of *scrap* shows that the single retired 737-700 was scrapped, as were all of the more numerous 767-200ERs and 767-300s. In addition, 737-500s, 747-400s and MD-82s were almost always scrapped rather than transferred upon retirement. Average market values range from a high of $11.8 million for the lone 737-700 to a low of $1.0 million for MD82s. Average ages at retirement are all over 20 years, except for the 737-700, for which *retire_age* equals 18 years. The data show that this plane (operated by Southwest) suffered nose-wheel damage and was used for parts for the carrier's large fleet of this type (410 planes, as seen in type-count column). The number of individual aircraft observations in the data set equals 585, the sum of the frequencies. Of the 126 aircraft out this

[23] Recalling that the dependent variable is in logs, a 1-year increase in age reduces value by 9%, a 10-seat increase in capacity raises value by 4%, and a 100-mile increase in range raises value by 2%. Holding capacity fixed, a 4-engine aircraft is worth 56% less than a 2-engine plane, reflecting greater maintenance costs and fuel usage, although *gallons_seat_mile* mostly captures the latter effect. While a widebody aircraft is worth 41% less than a narrow-body plane, the coefficient is hard to interpret in an other-things-equal fashion because of the presence of other covariates (capacity, range) that already capture widebody features. Since the coefficient is large, the *widebody* effect is not given by the coefficient α but instead equals $exp(\alpha) - 1$, and similarly for the *engines* effect.

[24] Aircraft-type dummies are not used in the hedonic regression because the goal is to gauge the effect of aircraft characteristics, which vary by type, on market values.

total that were not scrapped (21.6%), 37 were transferred to an OECD (possibly US) passenger airline, 26 went to a non-OECD passenger carrier, and 63 went to a cargo airline.

In addition to collecting scrappage data for the US, we also collected a smaller European data set (with 203 retirement observations) for a focal-carrier group consisting of Air France, KLM, Iberia, Lufthansa, SAS, TAP, Ryanair, and EasyJet. Our initial intention was to pool the data sets for the logit regression, but we chose not to do so because the US and Europe exhibit very different aircraft scrappage environments. The scrappage rate over the 2015-2019 period is much lower for the European case than for the US case, 17.2% vs. 78.4%, possibly reflecting an EU policy environment (including airline coverage by the EU's ETS) that encouraged carriers to unload their older planes before they were ready to scrap. Intensity of aircraft usage may also be higher in the US than in Europe, making scrappage upon retirement more likely (hard evidence is lacking, though). This apparent European tendency to sell older planes (presumably to carriers outside the EU) is reflected in younger fleets. The average age of aircraft in 2019 among the 689 aircraft operated by our set of European carriers is 11.3 years versus 14.7 years among the 2,954 planes operated in 2019 by our set of US carriers. Because of the difference in scrappage behavior, we do not report the European logit results (which are available on request), nor do we carry out European cash-for-clunkers calculations.[25]

Table 2 shows the result of the US logit regression, with the first regression relying only on aircraft characteristics, while column 2 includes type dummies. In both regressions, the standard errors are clustered by type. Recall that the estimated coefficients should be viewed as reflecting the contribution of a variable to an aircraft's scrap value. As can be seen in the first regression, a larger *capacity* and a higher *type_count* both raise scrap value, as expected. The marginal effects of a 10-unit increase in *capacity* or *type_count* are 0.05 and 0.03, respectively, indicating 3 and 5 percentage-point increases in the probability of scrappage. The *age* coefficient is negative but statistically insignificant, possibly a result of small age variation across observations, although the coefficient gains significance when clustering is dropped (an action that may be preferred anyway given the small number of clusters). The insignificant

[25] Of 203 aircraft in the European data, 168 (82.8%) were not scrapped, with 156 being transferred to an OECD (possibly European) passenger airline, 11 going to a non-OECD passenger carrier, and 1 to a cargo airline.

year dummy coefficients show no variation in scrap value across the period. Despite the parsimonious specification, the percent of correct logit predictions is a high 84.44%, as seen at the bottom of the table.

In the second regression, where *capacity* is dropped and the aircraft type dummies added, the *type_count* coefficient loses significance, while the *age* coefficient is again insignificant (both conditions persist without clustering). The year dummy coefficients are again insignificant. As for the type dummies, coefficients for the aircraft types that are always scrapped (see above) cannot be estimated, so these type dummies are omitted and viewed as the reference group. Relative to this group, the negative dummy coefficients for the remaining types naturally show that they all have lower scrap values. This second logit regression has a somewhat higher rate of correct predictions than the first one, at 87.01%, which makes it the preferred specification.

5.2. Cash-for-clunkers calculations

As explained above, the cash-for-clunkers calculations are done only for the US case. Based on the second logit regression in Table 2, the set of aircraft retiring in the 2015-2019 period that have $prob\_scrap < 0.5$ (thus being candidates for clunkers payments) consists of 65 planes out of the 585 in the US logit sample.[26] This relatively small number reflects the low rate at which US planes were transferred upon retirement.[27]

The first panel of Table 3 shows the elements of the clunkers calculations for this group (the second panel is discussed below). For these 65 planes, the values of the key variables in the calculations are averaged within aircraft types across airlines and retirement years, with the results shown in the table. The number of planes of each type is shown along with type-average of $market\_val$, in millions of dollars. The table then shows the type-average annual *gallons* and the type-average $remain\_life$. The type-average of own carbon emissions from continued operation ($own\_emissions$, based on (7) and (9)) is also shown, as is the type-average cash-for-clunkers payment ($-fitted\_val \times 10^6$ to yield actual dollars). The clunkers payments are

[26] Two 737-400 aircraft with negligible remaining lifespans were dropped as unrepresentative in creating the first panel of Table 3. Several other planes with negative remaining lifespans, which prevent calculation of $own\_emissions$, were also dropped.

[27] As noted above, since $prob\_scrap$ only indicates the likelihood of scrappage, it need not exactly predict actual scrappage. In fact, 21% of the 65 aircraft with $prob\_scrap < 0.5$ were actually scrapped. In these cases, the clunkers payment would be made when the plane would have been scrapped anyway, violating additionality.

large, ranging from just below \$1 million per aircraft for 757-200s to over \$7 million per plane for A320-200s.

In the next column, the value of $1-\delta$ for the aircraft is shown, which multiplies *own_emissions* to get forgone emissions E from (10) (not shown). These $1-\delta$ values reflect the fuel-efficiency of a new aircraft that would replace the scrapped plane in the world fleet, chosen to be as similar as possible in capacity and range. For the 737-400, which has *gallons_seat_mile* equal to 0.0167 (see Table 2 of Brueckner et al., 2024), the new plane would be a 737 Max 8, a somewhat larger 737 version that has *gallons_seat_mile* of 0.0109. The value of δ (the ratio of alternative to own *gallons_seat_mile*) for the 737-400 would then be $0.0109/0.0167 = 0.65$, so that $1-\delta = 0.35$. For the other aircraft types in the first panel of Table 3, new-plane alternatives are the 777-300 for the 747-400 (a somewhat-smaller large widebody plane with *gallons_seat_mile* of 0.0159 vs. 0.0173), the A321-200neo for the 757-200 (a similar-size narrowbody aircraft with *gallons_seat_mile* of 0.0107 vs. 0.0143), the 787-9 for the 767-300ER (a similar-size medium widebody with *gallons_seat_mile* of 0.0124 vs. 0.0154), and the A320-200neo for the A320-200 (a re-engined version of the same aircraft model with *gallons_seat_mile* of 0.0111 vs. 0.0136).

The last two columns of Table 3 contain the ultimate results of the analysis in this paper. They show the cost per ton of forgone emissions under the cash-for-clunkers program, equal to $clunkers\_pmt/[(1-\delta) \times own\_emissions]$. The second-to-last column shows cost per ton without a cost-of-public-funds (COPF) adjustment, while the last column applies such an adjustment. Following Finkelstein and Hendren (2020), we use a value of 0.3 for the cost of public funds, so that the clunkers payment is raised by a factor of 1.3.

For each of the five aircraft types in first panel of Table 3, the cost-per-ton values with the COPF adjustment lie well below recent estimates of the social cost of carbon emissions, indicating the attractiveness of a cash-for-clunkers program as a means for decarbonizing aviation. For example, the range of social-cost estimates for the year 2020 surveyed in the 2021 report of the US government's Interagency Working Group on Social Cost of Greenhouse Gases led to a representative value of \$51 per metric ton.[28] This value is at least twice as large as the

[28] The \$51 value assumes a 3% discount rate. See Figure ES-1 at `https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf?source=email`.

cost-per-ton values for all the aircraft types in the first panel of Table 3, and at least four times as large for three types.

An aggregate cost per ton of forgone emissions for the 65 planes can also be computed. Total forgone emissions equals *own_emissions* times $1-\delta$ times the number of planes of a given type, summed across the types, which yields 24.9 million tons. Using a similar summation, the aggregate outlay (adjusted by the COPF) on clunkers payments equals \$190.3 million. Division then yields a cost per ton of forgone emissions equal to \$7.64. Without adjusting for the COPF, the aggregate outlay equals \$146.4 million, and the cost per ton of forgone emissions is \$5.88.

Using the unadjusted cost per ton, along with a \$51 social cost of carbon, the marginal value of public funds used in a cash-for-clunkers program (MVPF; Hendren and Sprung-Keyser, 2020) is 8.67 (= 51/5.88). Using instead the US Environmental Protection Agency's more recent and much higher \$190 value for the social cost of carbon emissions, the MVPF is 32.31. These numbers are higher than all of the MVPF values in the computations of Hahn, Hendren, Metcalfe and Sprung-Keyser (2024), which derive individual MVPF values for 96 government climate policies. It should be noted, however, that our MVPF numbers do not take into account some second-order benefits and costs of an airline cash-for-clunkers program, which the more-comprehensive approaches surveyed by these authors might have considered. These include benefits from lower ground-level pollution from scrappage of old planes, which would generate health benefits for residents near airports, as analyzed by Schlenker and Walker (2016). In addition, while the program would presumably increase production of new aircraft, the carbon impact this activity is not considered. These omission may approximately cancel one another, however, so that our MVPF numbers may not diverge substantially from the values resulting from a more comprehensive approach.

The numbers in Table 3 can be used to produce the McKinsey (2009) abatement-cost curve in Figure 4, which shows the marginal cost of forgone carbon emissions at different levels of forgone emissions. The cost per metric ton of forgone emissions for the given aircraft type is graphed against the total tons of forgone emissions (in units of 10^5) from scrapping the different plane types, taking account of the number of each type. The initial long flat segment is at height \$2.09, the cost per ton of forgone emissions for 757-200s, and the length of the segment equals forgone emissions per aircraft times the number of such planes (24). Scrapping all these planes would yield a total of 13.8 million metric tons of forgone emissions (138×10^5), which gives the position of segment's right endpoint. The next short segment is at height \$8.97, the cost per ton for 747-400s, and the length of the segment is again forgone emissions per aircraft times the number of planes (2 in this case). The remaining segments of the curve are for 767-300ERs (19 planes), 737-400s (12 planes), and A320-200s (8 planes), respectively, as shown. Scrappage of all the planes would results in forgone emissions of 24.9 million metric tons (249×10^5), which determines the position of the curve's ultimate endpoint. The fact that the curve lies below a horizontal line at height \$51 indicates that the costs per ton of forgone emissions are all below the \$51 social-cost value and therefore worth incurring.

Figure 4 highlights the cost-per-ton differences across aircraft types, whose sources can be identified. The low 2.09 value for 757-200s is due to the relatively low clunkers payment for this type (which reduces the cost-per-ton numerator), along with relatively high forgone emissions (which raises the denominator). This latter factor is due to a middling value of *remain_life* (leading to relatively high own emissions) along with the high fuel efficiency of the A321-200neo replacement aircraft, which leads to a relatively large value of $1 - \delta$. By contrast, the large cost-per-ton value for the A320-200 is mainly due to the type's high clunkers payment. The type's long remaining life cannot raise *own_emissions* enough to offset this cost factor. It should be noted that the low *gallons* value for the 737-400s (all 12 of which were operated by Alaska Airlines) reflect apparently low utilization of the 9 aircraft that were retired in 2017. Possibly, these planes were retired early in the year. The value of *own_emissions* is then relatively low, and while this factor is offset somewhat by the highest $1 - \delta$ value among all types, the clunkers payment for this type is also low, with the net result being an above average cost-per-ton of forgone emissions.

Since the fitted values and scrappage probabilities differ somewhat under the first logit regression in Table 2, which does not include type dummies, the cash-for-clunkers numbers that emerge are somewhat different, as seen in the second panel of Table 3. Moreover, an additional plane type (767-300s) emerges as a cash-for-clunkers candidate, although the number of eligible aircraft falls to 54. However, the main implications of the second panel of Table 4 are the same as before. Although cash-for-clunkers payments per aircraft are large, the costs per ton of forgone emissions are again well below the $51 social-cost value.

5.3. Robustness checks

As discussed earlier, clunkers payments may be directed to some aircraft that would be scrapped anyway, violating additionality. To reduce the likelihood of this outcome, a more stringent cutoff for the probability of scrappage can used, smaller than the 0.5 probability underlying the numbers in Table 3. Table 4 repeats the calculations using a probability half as large, equal to 0.25. As can be seen, the number of targeted planes drops from 65 to 43, and the sizes of the required clunkers payments rise, except for the 747-400s, where the number of planes is unchanged. Nevertheless, the cost per ton of forgone emissions for each aircraft type remains below a $51 social cost per ton. Therefore, imposing a more stringent cutoff to better ensure additionality does not change the conclusions of the analysis.[29]

Other robustness checks are shown in Table 5. As mentioned above, aircraft that are transferred upon retirement may be operated less intensively than by the selling carrier, which would reduce forgone emissions and raise the cost per ton of such emissions. To show the effect of lower utilization, the first column of Table 5 shows the cost per ton of forgone emissions (with the COPF adjustment) when *own_emissions* in Table 3 is multiplied by 0.6, as would occur when utilization by the purchasing carrier is only 60% of utilization by the selling airline. This change, which raises the Table 3 values by 1/0.6, yields costs per ton that remain well below a $51 social cost of carbon emissions. The second column of Table 5 shows the effect of raising the discount rate from 0.05 to 0.07, which also reduces the magnitude of forgone emissions. The increases in cost per ton are smaller than in the first column, again leading to values that lie well below the $51 social cost.

6. Conclusion

This paper has analyzed a potential cash-for-clunkers program for the airline industry, which would help to hasten decarbonization of US aviation. Our estimation and calculations

[29] Out of the 43 targeted planes, 8 would have been scrapped anyway, a smaller share than with the less-stringent scrappage-probability cutoff (21 out of 65).

show that airlines can be induced to scrap rather than sell older planes upon retirement at a cost per ton of forgone emissions that is substantially less than the social cost of these emissions. The program yields forgone carbon emissions of 24.9 million tons for a total COPF-adjusted outlay on clunkers payments of $190.3 million, yielding an adjusted cost per ton of $7.64, which is well below current social cost estimates. Moreover, the marginal value of a dollar of public funds used in the program is 8.67 at carbon cost of $51, a large value compared to other climate programs.

Based on results from Li, Linn and Spiller (2013), an airline program would be much more cost-effective at reducing emissions than was the automobile cash-for-clunkers program. Their findings show an emissions reduction ranging between 9 and 28.2 million tons of carbon depending on uncertain estimates of the volume of new-vehicle sales prompted by the program. With a $3 billion cost, their unadjusted cost per ton of forgone emissions then ranges from $92 to $288, values well above our unadjusted cost of $5.88.

As explained earlier, a government operating an airline cash-for-clunkers program would ask an airline to list the planes it intends to retire in the subsequent year without divulging its sell/scrap intentions. Using an updated logit scrappage regression, the government would then identify the planes on this retirement list likely to be transferred to another airline and would compute the size of the clunkers payment required to induce their scrappage, making the payment only if the emissions reduction is worth more. One advantage of this program structure relative to that of automobile program is that the cost of the clunkers payment would be incurred only when it has a reasonable chance of making a difference (satisfying additionality), with planes unlikely to be scrapped being the ones targeted. With its blanket approach, the automobile cash-for-clunkers program lacked such a criterion.

While we have analyzed a cash-for-clunkers program targeted at aircraft that are retiring, the same approach could be used to accelerate the retirement of planes that are several years away from leaving an airline's fleet. Since the current market value of such an aircraft would equal the profit it generates up to the retirement date plus the market value at that date, a clunkers payment equal to the difference between the current market value and scrap value would again induce scrappage. As before, a payment would only be made if the resulting gain from lower emissions is larger. After trying a retirement-date clunkers program, the government could consider enlarging the program in this fashion.

As in the case of the automobile cash-for-clunkers program, manufacturers (here plane builders) are a source of political support since scrappage raises the demand for new output. While the political viability of the automobile program (as well as that of electric-vehicle subsidies) was further ensured because consumers received the outlays, taxpayers may object to making payments to the airlines for environmental purposes, although the likelihood of such objections is hard to predict. A related consideration is that the possible targeting of particular aircraft types would direct payments only to those airlines where these types are concentrated. An example from the past would be MD-80 aircraft and their variants, which were disproportionately operated by American Airlines. However, while pickup truck owners may have rebelled if clunkers payments went to owners of Ford F-150s but not Chevrolet Silverado owners, targeting of particular plane types would presumably be less controversial.

As noted earlier, by reducing the supply of used aircraft, a cash-for-clunkers program would raise their prices to an extent that depends on the elasticity of aircraft demand. Going forward, these higher prices would in turn raise the required clunkers payments in subsequent rounds of the program, leading to a higher cost per ton of forgone emissions. However, since our results show that this cost is already low across plane types, the cost is likely to remain below the social cost of forgone emissions despite higher used aircraft prices caused by the program. A related point is that, while the alternative of subsidizing the manufacture of new aircraft could lead to more scrappage by reducing used-plane prices, a clunkers program is a more direct (and likely politically more palatable) way of achieving this outcome.

Higher used prices along with the need to buy newer, more-costly planes might also retard the growth of aviation in the developing world, leading to smaller airline fleets in these countries. While such an effect is environmentally efficient, developing-country governments may wish to partly mitigate it by subsidizing aircraft acquisition for their carriers.

As noted above, the paper has been silent about two other possible effects of an airline cash-for-clunkers program: the benefits of lower ground-level pollution around airports, and carbon emissions generated by increased production of new aircraft.[30] However, adding these potentially offsetting effects would be unlikely to change our conclusion that money directed to a program would be well spent.

[30] Strict maintenance requirements (a component of our theoretical model) mean that old planes are no less safe than new ones. As a result, there appears to be no safety benefit from a cash-for-clunkers program.

Table 1: Summary statistics for US logit data set

aircraft type	*# retired*	*scrap*	*retire_yr*	*market_val*	*capacity*	*retire_age*	*type_count*
737-300	112	0.85	2017.4	2.56	126	24.3	75.5
737-400	36	0.17	2016.9	3.69	147	22.7	17.2
737-500	15	0.93	2016.3	1.61	110	24.7	9.2
737-700	1	1.00	2018.0	11.80	126	18.0	410.0
747-400	40	0.95	2017.2	10.36	416	22.8	14.4
757-200	141	0.74	2016.2	6.42	200	25.1	89.1
767-200ER	3	1.00	2015.0	3.23	181	27.7	3.0
767-300	15	1.00	2017.2	4.07	218	27.1	10.2
767-300ER	35	0.37	2017.2	6.82	218	26.7	43.2
A320-200	25	0.68	2016.2	7.46	150	22.5	61.6
MD-82	83	0.98	2016.3	1.00	143	27.0	53.5
MD-83	36	0.78	2016.9	1.20	143	25.0	50.0
MD-88	43	1.00	2018.6	1.20	143	29.4	106.2

The logit data set consists of observations on aircraft that were retired (transferred to a non-focal carrier or scrapped) over the 2015-2019 period. The table gives mean values by *aircraft type* of variables in this data set other than # retired. The variable *scrap* is a dummy variable that takes the value 0 if an aircraft was scrapped upon retirement and 1 if the plane was transferred, and *type_count* is the number of planes of the given type in an airline's fleet. Units are $millions for *market_val* (the aircraft market value), seats for *capacity* and years for *retire_age*.

Table 2: US logit results

VARIABLES	scrap	scrap
market_val	-1	-1
capacity	0.0427**	–
	(0.00530)	
retire_age	-0.127	-0.0589
	(0.0881)	(0.102)
type_count	0.0274**	0.00318
	(0.00639)	(0.0228)
d2015	-0.331	1.682
	(0.480)	(2.271)
d2016	0.663	2.206
	(0.852)	(1.804)
d2017	-0.597	0.945
	(0.506)	(1.355)
d2018	-0.890	0.0811
	(0.489)	(1.191)
d737_300	–	-19.81**
		(6.739)
d737_400	–	-22.86**
		(8.638)
d737_500	–	-20.64*
		(8.624)
d747_400	–	-5.197
		(8.644)
d757_200	–	-17.33*
		(7.039)
d767_300ER	–	-18.85*
		(7.647)
dA320_200	–	-17.44*
		(7.464)
dMD_82	–	-19.85**
		(7.694)
dMD_83	–	-21.91**
		(7.350)
Constant	0.317	24.94**
	(2.702)	(7.467)
Observations	591	591
% correct	84.44%	87.01%

Standard errors clustered by *type* in parentheses

** p<0.01, * p<0.05

Table 3: Cash-for-clunkers calculations

Using US logit results with *type* **FEs** (yielding 65 aircraft)

								cost per ton of forgone emissions	
type	*#planes*	*market_val*	*gallons*	*remain_life*	*own_emissions*	*clunkers_pmt*	$1-\delta$	*w/o copf adj.*	*w/ copf adj.*
737-400	12	3.78	0.96e+07	3.6	260,960	$1,279,819	0.35	14.01	18.22
747-400	2	24.00	3.70e+07	9.6	2,771,644	$3,060,717	0.16	6.90	8.97
757-200	24	8.66	4.78e+07	5.5	2,309,157	$928,602	0.25	1.61	2.09
767-300ER	19	8.06	4.25e+07	3.6	1,482,417	$2,317,174	0.19	8.23	10.69
A320-200	8	15.73	3.49e+07	10.0	2,564,992	$7,319,435	0.18	15.85	20.61

Using US logit results without *type* **FEs** (yielding 54 aircraft)

								cost per ton of forgone emissions	
type	*#planes*	*market_val*	*gallons*	*remain_life*	*own_emissions*	*clunkers_pmt*	$1-\delta$	*w/o copf adj.*	*w/ copf adj.*
737-400	8	4.56	0.44e+07	6.0	224,879	$318,101	0.35	4.04	5.25
747-400	4	20.65	3.70e+07	8.1	2,412,074	$3,899,903	0.16	10.11	13.14
757-200	19	8.56	4.75e+07	5.2	2,045,333	$1,067,951	0.25	2.09	2.72
767-300	1	8.60	4.51e+07	8.07	2,918,988	$2,173,909	0.19	3.92	5.10
767-300ER	13	8.32	4.25e+07	3.8	1,515,265	$1,218,870	0.19	4.23	5.50
A320-200	9	14.89	3.49e+07	9.3	2,393,084	$8,668,231	0.18	20.12	26.16

To generate the numbers in the tables, retiring aircraft with a scrap probability greater than 0.5 are excluded from the logit post-estimation samples, leaving planes where scrappage is unlikely. In addition, a few aircraft with negative or negligible remaining lives are excluded. Then, calculations are undertaken using the formulas below for individual aircraft. Finally, the results for each variable are averaged within aircraft types across airlines and retirement years.

units are $ millions for *market_val* and metric tons for *own_emissions*

gallons is annual gallons of fuel consumed by the type

$$remain\_life = avg\_life - retire\_age$$

$$own\_emissions = gallons \times (9.75\ kg\ CO_2/gallon) \times (10^{-3}\ metric\ tons/kg) \times [1 - exp(-.05 * remain\_life)]/.05;$$

δ equals the fraction of *own_emission* generated by the replacement aircraft, so that $(1-\delta) \times own\_emissions$ equals forgone emissions.

$$clunkers\_pmt = -fitted\_val \times 10^6 = (-market\_val + X\widehat{\beta}) \times 10^6$$

$$cost\ per\ ton\ of\ forgone\ emissions\ w/o\ COPF\ adjustment = clunkers\_pmt/[(1-\delta) \times own\_emissions]$$

COPF adjustment adds 1.3 multiplicative factor

Table 4: Cash-for-clunkers calculations for aircraft with scrappage probability < 0.25

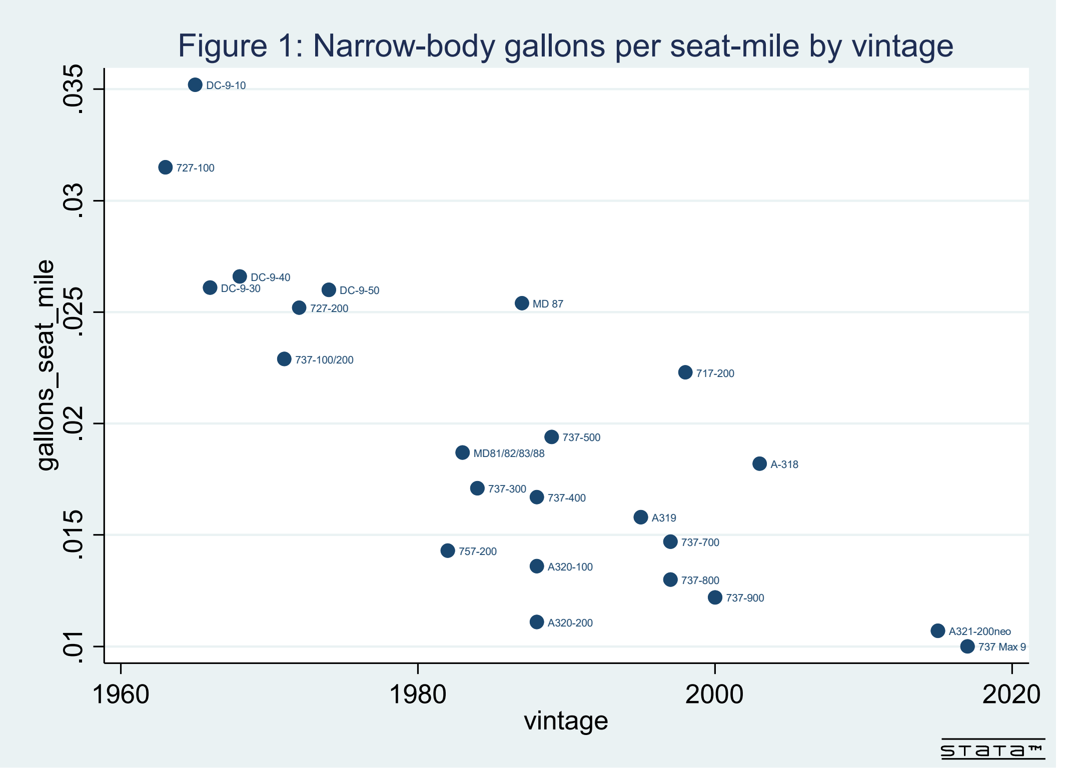
Using US logit results with *type* FEs (yielding 43 aircraft)

								cost per ton of forgone emissions	
type	*#planes*	*market_val*	*gallons*	*remain_life*	*own_emissions*	*clunkers_pmt*	$1-\delta$	*w/o copf adj.*	*w/ copf adj.*
737-400	9	4.46	0.44e+07	5.6	209,735	$2,506,739	0.35	34.19	44.39
747-400	2	24.00	3.70e+07	9.6	2,771,644	$3,060,717	0.16	6.90	8.97
757-200	11	9.62	3.59e+07	7.5	2,191,722	$2,394,945	0.25	4.37	5.68
767-300ER	14	8.24	4.09e+07	3.7	1,478,879	$2,808,845	0.19	10.00	13.00
A320-200	7	17.17	3.49e+07	11.1	2,810,410	$8,687,276	0.18	17.17	22.32

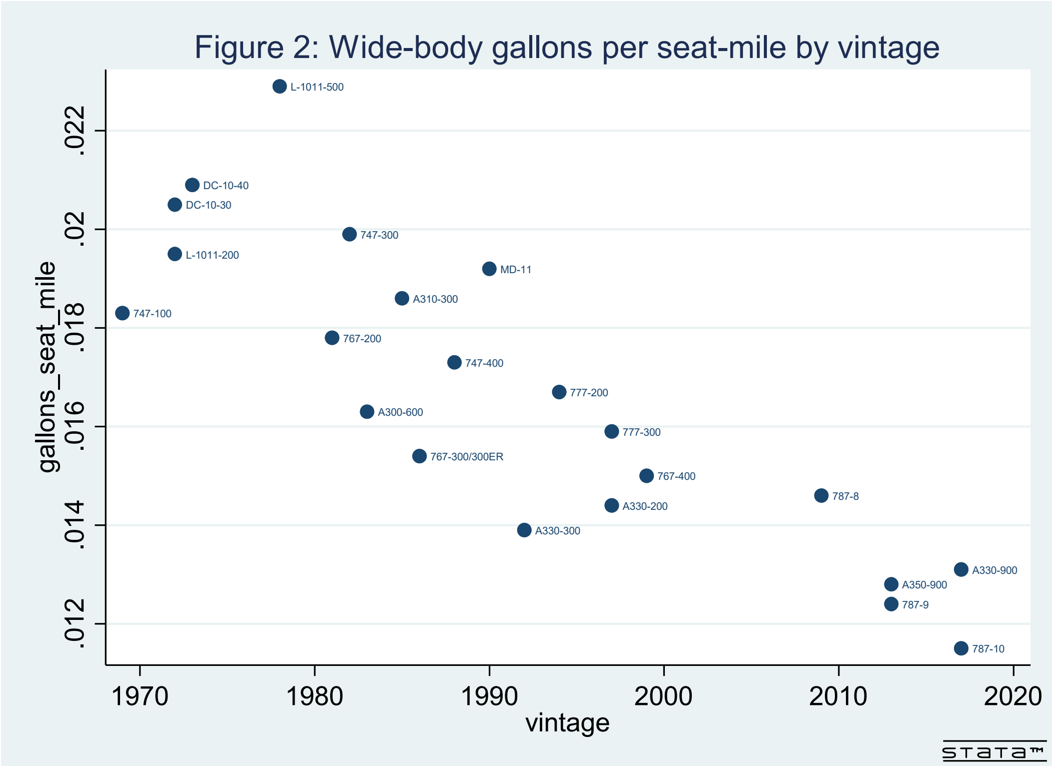
Table 5: Other robustness checks

	cost per ton of forgone emissions w/copf adjustment	
type	*60% post-retirement utilization*	*7% discount rate*
737-400	30.36	18.84
747-400	14.95	9.80
757-200	3.49	2.22
767-300ER	17.82	11.15
A320-200	34.35	22.69

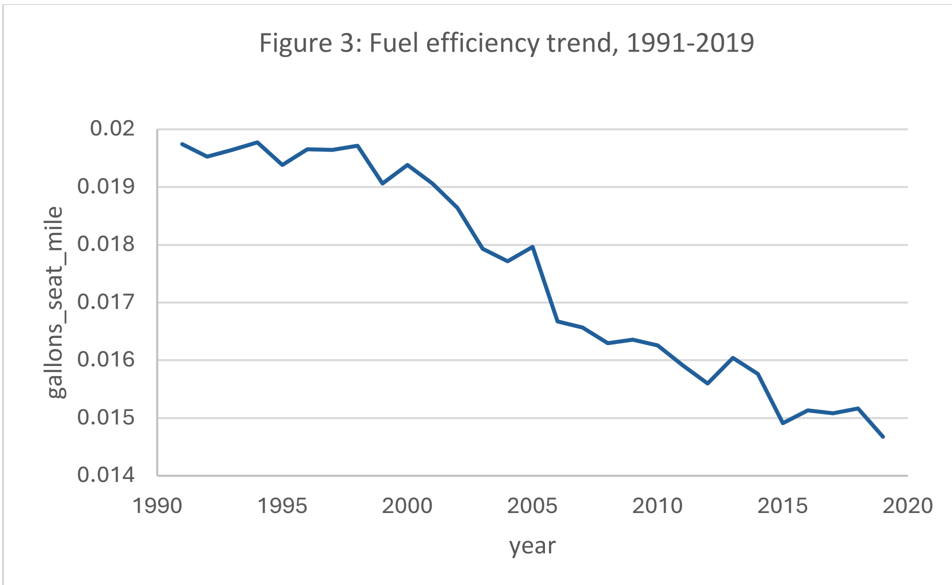
This table shows the cost per ton of forgone emissions when post-transfer utilization of retired aircraft is lower than at the selling US carrier, and when a higher discount rate is applied in computing *ownemissions*.



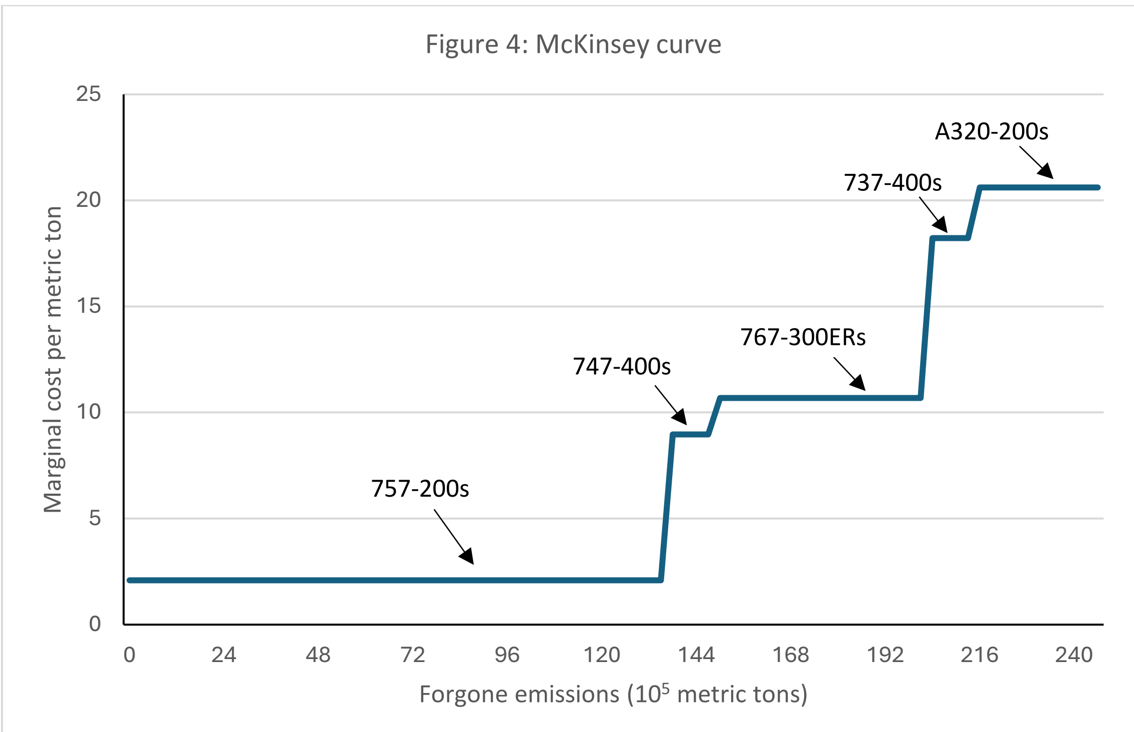
This figure shows an inverse measure of fuel efficiency (gallons per seat-mile) for narrow-body aircraft of different vintages, starting with 1960. Aircraft labels are shown. Note that three aircraft types are not shown since their labels overlap in the figure with those of other planes. The types are the 757-300 (vintage = 1998, gallons per seat-mile = 0.0131), MD-90 (vintage = 1996, gallons per seat-mile = 0.0158), and 737 Max 8 (vintage = 2016, gallons per seat-mile = 0.0109).



This figure shows an inverse measure of fuel efficiency (gallons per seat-mile) for wide-body aircraft of different vintages, starting with 1970. Aircraft labels are shown. Note that one aircraft type (DC-10-10, vintage = 1970, gallons per seat-mile = 0.183) is not shown since its label overlaps in the figure with that of another plane.



This figure shows the average across airlines and major aircraft types of annual gallons of fuel used per seat mile (a seat flown one mile). The airlines are the focal carriers for this study (American, United, Delta, Southwest, JetBlue, and Alaska) and the large carriers the first three absorbed via mergers (US Airways, Continental and Northwest). The underlying data are from Brueckner et al. (2024).



This figure plots the cost per ton of forgone emissions from the last column of Table 3 against the quantity of forgone emissions. The 757-200 segment, which is at height 2.09, has a length equal to emissions per plane times the number of planes of that type, and similarly for the other segments in the figure.

Appendix

Table A1: Aircraft type frequencies in hedonic data set

type	frequency
717-200	27
737-300	48
737-400	36
737-500	33
737-800	63
737-900	18
737 Max 8	6
737 Max 9	3
747-200B	2
747-300	2
747-400	54
757-200	69
757-200ETPS	68
757-300	21
767-200ER	34
767-300	44
767-300ER	82
767-400ER	12
777-200	42
777-200ER	54
777-300ER	45
787-8	18
787-9	16
A300-600	9
A300-600R	36
A310-300	27
A318-100	21
A319-100	69
A320-200	90
A320-200neo	9
A321-200neo	6
A330-200	63
A330-300	57
A350-900	15
MD-82	51
MD-83	45
MD-88	36
Total	1,394

Repeated aircraft observations are generated by different ages and years.

Table A2: Hedonic aircraft price function

VARIABLES	coefficient	var. mean
capacity	0.00455**	208.78
	(0.000849)	
age	-0.0939**	16.75
	(0.00611)	
range	0.000203**	4347.43
	(4.32e-05)	
gallons_seat_mile	-108.2**	0.016
	(34.83)	
engines	-0.357**	2.08
	(0.0697)	
airbus	0.0700	0.25
	(0.0828)	
widebody	-0.484**	0.44
	(0.125)	
d2017	-0.0228	0.33
	(0.0280)	
d2019	0.0504	0.34
	(0.0438)	
Constant	4.742**	–
	(0.365)	
Observations	1,394	
R^2	0.929	

Dependent variable is log *market_val*, and 2015 is default year

Standard errors clustered by *type* in parentheses

** p<0.01, * p<0.05

References

AGHION, P., BARRAGE, L., HÉMOUS, D., LIU, E., 2024. Transition to green technology along the supply chain. Working paper, INSEAD.

ALBERINI, A., HARRINGTON, W., MCCONNELL, V., 1995. Determinants of participation in accelerated vehicle-retirement programs. *RAND Journal of Economics* 26, 93-112.

ALBERINI, A., HARRINGTON, W., MCCONNELL, V., 1996. Estimating an emissions supply function from accelerated vehicle retirement programs. *Review of Economics and Statistics* 78, 251-265.

DE ALMEIDA, E.E., OLIVEIRA, A.V.M., 2023. An econometric analysis for the determinants of flight speed in the air transport of passengers. *Scientific Reports* 13, article 4573.

ANDERSON, M.L., AUFFHAMMER, M., 2014. Pounds that kill: The external costs of vehicle weight. *Review of Economic Studies* 81, 535-571.

BRUECKNER, J.K., ABREU, C., 2017. Airline fuel usage and carbon emissions: Determining factors. *Journal of Air Transport Management* 62, 10-17.

BRUECKNER, J.K., ABREU, C., 2020. Does the fuel-conservation effect of higher fuel prices appear at both the aircraft-model and aggregate airline levels? *Economics Letters* 197, article 109647.

BRUECKNER, J.K., KAHN, M.E., NICKELSBURG, J., 2024. How do airlines cut fuel usage, reducing their carbon emissions? *Economics of Transportation* 38, article 100358.

BUETTNER, T., KESSELRING, A., 2024. Banning products with low energy efficiency: Market response and adjustment cost. *Journal of the Association of Environmental and Resource Economists*, in press.

CALEL, R., COLMER, J., DECHEZLEPRÊTRE, A., GLACHANT, M., 2021. Do carbon offsets offset carbon? Working paper 398, Centre for Climate Change Economics.

DAVIS, L.W., KAHN, M.E., 2010. International trade in used vehicles: The environmental consequences of NAFTA. *American Economic Journal: Economic Policy* 2, 58-82.

DAVIS, L.W., KAHN, M.E., 2011. Cash for clunkers? The environmental impact of Mexico's demands for used vehicles. *Access Magazine* 1, no. 38, 15-21.

DAVIS, L.W., FUCHS, A., GERTLER, P., 2014. Cash for coolers: evaluating a large-scale appliance replacement program in Mexico. *American Economic Journal: Economic Policy*

6, 207-238.

Davenport, C., Ewing, J., 2024. New pollution rules aim to lift sales of electric trucks. *New York Times*, March 29.

Fukui, H., Miyoshi, C., 2017. The impact of aviation fuel tax on consumption and carbon emissions: The case of the US airline industry. *Transportation Research Part D* 50, 234-253.

Fageda, X., Teixido, J.J., 2022. Pricing carbon in the aviation sector: Evidence from the European emissions trading system. *Journal of Environmental Economics and Management* 111, article 102591.

Finkelstein, A., Hendren, N., 2020. Welfare analysis meets causal inference. *Journal of Economic Perspectives* 34, 146-167.

Gosnell, G K., List, J.A., Metcalfe, R.D., 2020. The impact of management practices on employee productivity: A field experiment with airline captains. *Journal of Political Economy* 128, 1195-1233.

Green, D., Melzer, B.T., Parker, J.A., Rojas, A., 2020. Accelerator or brake? Cash for clunkers, household liquidity, and aggregate demand. *American Economic Journal: Economic Policy* 12, 178-211.

Gruenspecht, H.K., 1982. Differentiated regulation: The case of auto emissions standards. *American Economic Review* 72, 328-331.

Hahn, R.W., 1995. An economic analysis of scrappage. *RAND Journal of Economics* 26, 93-112.

Hahn, R.W., Hendren, N., Metcalfe, R.D., Sprung-Keyser, B., 2024. A welfare analysis of policies impacting climate change. Unpublished paper.

Hendren, N., Sprung-Keyser, B., 2020. A unified welfare analysis of government policies. *Quarterly Journal of Economics* 135, 1209-1318.

Holland, S.P., Mansur, E.T, Yates, A.J., 2021. The electric vehicle transition and the economics of banning gasoline vehicles. *American Economic Journal: Economic Policy* 13, 316-344.

Huang, R., Kahn, M.E., 2024. The unintended consequences of federal funding rules on public transit decarbonization. Unpublished paper.

Jacobsen, M.R., Van Benthem, A.A., 2015. Vehicle scrappage and gasoline policy. *American Economic Review* 105, 1312-1338.

Jacobsen, M.R., Sallee, J.M., Shapiro, J.S., Van Benthem, A.A., 2023. Regulating untaxable externalities: Are vehicle air pollution standards effective and efficient? *Quarterly Journal of Economics* 138, 1907-1976.

Klier, T., Linn, J., 2010. The price of gasoline and new vehicle fuel economy: Evidence from monthly sales data. *American Economic Journal: Economic Policy* 2, 134-153.

Knittel, C.R., 2011. Automobiles on steroids: Product attribute trade-offs and technological progress in the automobile sector. *American Economic Review* 101, 3368-3399.

Knittel, C.R., 2012. Reducing petroleum consumption from transportation. *Journal of Economic Perspectives* 26, 93-118.

Li, S., Timmins, C., Von Haefen, R.H., 2009. How do gasoline prices affect fleet fuel economy? *American Economic Journal: Economic Policy* 1, 113-137.

Li, S., Linn, J., Spiller, E., 2013. Evaluating "cash-for-clunkers": Program effects on auto sales and the environment. *Journal of Environmental Economics and Management* 65, 175-193.

Mian, A., Sufi, A., 2012. The effects of fiscal stimulus: Evidence from the 2009 cash for clunkers program. *Quarterly Journal of Economics* 127, 1107-1142.

McKinsey & Company, 2009. Pathways to a low-carbon economy: Version 2 of the global greenhouse gas abatement cost curve. `http://www.mckinsey.com/clientservice/ccsi/pathways_low_carbon_economy.asp`.

Newman, S.J., Schulte, K., Morellini, M.M., Rahal, C., Leasure, D.R., 2024. Offshoring emissions through used vehicle exports, emissions through used vehicle exports. *Nature Climate Change,* `https://doi.org/10.1038/s41558-024-01943-1`.

Sallee, J.M., 2024. Retiring old capital to foster decarbonization. *Entrepreneurship and Innovation Policy and the Economy* 3, 115-138.

Samuelson, P., 1976. The economics of forestry in an evolving society. *Economic Inquiry* 14, 466-492.

Schlenker, W., Walker, W.R., 2016. Airports, air pollution, and contemporaneous health. *Review of Economic Studies* 83, 768-809.

Stavins, R.N., 2006. Vintage-differentiated environmental regulation. *Stanford Environmental Law Journal* 25, 29-63.

Sweeney, J.L., 1974. A commodity hierarchy model of the rental housing market. *Journal* *of Urban Economics* 1, 288-323.