Aircraft Speed and Fuel Usage: Empirical Estimates with an Exploration of Environmental Speed Limits

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February 2025

Abstract

This paper uses a Brazilian data set to estimate the relationship between fuel usage and speed for jet passenger aircraft. This exercise appears to be unique, with prior evidence on the fuel-speed relationship coming entirely from engineering models. The regressions generate U-shaped fuel-speed curves like those from the engineering approach, focusing on groups of narrow-body aircraft types (NEO vs. pre-NEO), rather than individual aircraft models. The empirical estimates are used to evaluate the desirability of environmental aircraft speed limits, which would force planes to fly at a speed that minimizes fuel usage, thereby reducing carbon emissions but imposing longer flight times on passengers.

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Jan K. Brueckner and Chrystyane Abreu[*]

1. Introduction

An accepted operational premise for passenger jet aircraft is the existence of a U-shaped curve relating fuel usage and speed. The bottom of the curve, which corresponds to the fuel-minimizing speed, is thought to lie below the typical average speed at which aircraft are flown, in the same way that automobiles traveling on freeways would use less fuel if they were driven slower. Research papers referring to this U-shaped relationship, such as Matsuno and Andreeva-Mori (2020) and Aktrk, Atamtrk and Grel (2014), usually cite for evidence the Base of Aircraft Data (BADA) project of Eurocontrol, Europe's air-traffic management organization.[1] BADA predicts fuel-speed relationships for individual aircraft types using engineering models. By contrast, we are not aware of any published studies that estimate fuel usage as a function of speed using *actual data on aircraft operations.* One purpose of the present paper is present such empirical estimates using a unique Brazilian database offered by the National Civil Aviation Agency. The database,[2] which is public and available monthly, contains detailed information on individual airline flights with at least one endpoint at a Brazilian airport, including aircraft type, fuel usage, average speed, endpoint airports, distance flown, and more. We use data for January 2024.

While our estimated regressions are themselves interesting, a second purpose of the paper is to use our results in a way that relates to growing concerns about the airline industry's

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[*] We thank Alberto Gaggero for helpful comments. The usual disclaimer applies.

[1] See Eurocontrol, 2009 and 2012. Unlike some other researchers, we were unable to secure a license giving access to the database and thus cannot compare our results to theirs. For a textbook explanation of the fuel-speed relationship, see the online book by Leishman (2024), chapter 12, subsection 49.

[2] The database, whose title is simply "Microdata," is avaiable at `https://www.gov.br/anac/pt-br/assuntos/regulados/empresas-aereas/Instrucoes-para-a-elaboracao-e-apresentacao-das-demonstracoes-contabeis/envio-de-informacoes`.

contribution to climate change. Although airlines currently generate less than 3% of the world's carbon emissions, the prominence of the industry has drawn increasing attention to its carbon contribution. Some travelers even try to restrict their airline usage, taking alternate modes where possible or limiting the number of air trips they take, and the French government has banned nonstop flights on routes with a high-speed-rail alternative. Decarbonization of aviation, however, requires larger steps that go beyond such efforts, including development of affordable biofuels and electric or hydrogen powered aircraft, all of which are nonexistent today but might be available farther in the future. A more-immediate decarbonization policy has been analyzed by Brueckner, Kahn and Nickelsburg (2024b), who consider a potential "cash-for-clunkers" program for the airline industry, which would hasten retirement of old, high-polluting planes.

The present paper analyzes another immediate decarbonization policy, which involves a particular restriction on airline operations: an aircraft speed limit designed to reduce fuel usage and hence carbon emissions. The downside of such a restriction is longer trip times, and we use our estimates of the fuel-speed relationship to ask whether the value of lost passenger time could be more than offset by the benefits from reduced emissions, yielding a gain in social welfare. This idea is perhaps fanciful, but it deserves consideration given increasing concerns about aviation's contribution to climate change.

This second exercise complements existing research on airline emissions. Papers on this topic include Brueckner and Abreu (2017, 2020), Brueckner, Kahn and Nickelsburg (2024a,b), Fukui and Miyoshi (2017), Fageda and Teixido (2022), Lee et al. (2021), Miyoshi and Mason (2009), Morrell (2009), Ryerson et al. (2015), Scheelhasse and Grimme (2007), and Schlenker and Walker (2016). Papers that focus more narrowly on aircraft fuel efficiency include Hao et al. (2016), Hao, Hansen and Ryerson (2016), Kwan and Rutherford (2015), and Zou et al. (2014). Also relying on the Brazilian dataset, de Almeida and Oliveira (2023) focus on the determinants of flight speed.

The plan of the paper is as follows. Section 2 discusses the data, and section 3 presents the regression results. Section 4 evaluates environmental aircraft speed limits, and section 5 offers conclusions.

2. Data

As explained above, our Brazilian dataset includes a wealth of information for individual flights. The data show the route, the operating airline, and the aircraft type. In addition, the data give the flight's fuel consumption in liters, the endpoint airports and distance of the route, and the flight duration, measured in gate-to-gate time. As for a speed measure, airborne time divided by flight distance would be ideal, but speed in the dataset is instead computed as gate-to-gate time divided by distance, given that airborne time is not measured. We tried subtracting 20 minutes from gate-to-gate time (capturing taxi time) to approximate airborne time, but this adjustment is somewhat arbitrary and led to unstable results.

To exclude long international routes,[3] we deleted observations with widebody aircraft (A330-200, A330-900NEO, A350-900, B777-300ER or B787-9), and we also deleted observations with turboprops (ATR-42 or ATR-72) or regional jets (EMBRAER-195). These deletions left 10 narrow-body aircraft types. The "pre-NEO" group consisting of the A319, A320-100-200, A321-100-200, B737-300, B737-500, B737-700, and B737-800 aircraft types, and the "NEO" group consists of the A320NEO, A321NEO, and B737-MAX-8 types, which have better fuel efficiency than the pre-NEO types due to technological improvements.

In addition to the aircraft-type exclusions, a desire to focus on more-typical flights and possibly rule out data errors led us to drop observations where distance, speed, and fuel usage were below 5th percentile values in each case. These values are 349 km for distance, 318 km/h for speed, and 2316 liters for fuel. All of these exclusions led to a regression dataset of 43,157 observations on 707 directional routes. Note that flights in different directions on a route are treated as distinct given that the wind angle affects fuel usage.

The dependent variable for the regressions is fuel consumption in liters by the flight. The focal independent variables are speed and speed-squared, which a generate a quadratic curve able to capture the expected U shape of the fuel-speed relationship. The distance variable is used in log form, whose concavity ensures that the fuel use from an extra km of distance is decreasing in distance. The log form thus captures the benefits of longer flights, where the flight's cruise portion increasingly dominates the fuel-intensive take-off phase, leading to a

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[3] This exclusion left only three endpoints outside of South America, all in Florida.

concave relationship and thus a fuel usage per km that declines with distance.[4]

An additional variable is the flight's load factor, measured as revenue ton-kilometers divided by available ton-kilometers. The variable thus counts both passengers and freight in generating a weight-based load-factor measure, with a higher value expected to raise fuel usage. We also computed the directional heading of a flight using the latitude-longitude coordinates of the endpoint airports, dividing the headings into eight catergories: N, NW, W, SW, S, SE, E, and NE. We began by using dummy variables for each of the directions, with E as the default, but found that cleaner results emerge using a single dummy indicating a W or NW heading, denoted W_NW, which captures the direction of the prevailing winds in Brazil. The coefficient of W_NW is thus expected to be positive. Finally, the dummy variable NEO indicates that the aircraft type for the observation is one of the three NEO models from above.

We found that estimating regressions for individual aircraft types led to unsatisfactory results, sometimes leading to large and counterintuitive predicted fuel-usage differences for similar types. While this approach apparently gave too much freedom for the emergence of inter-type differences in each and every regression coefficient, a more-constrained approach led to better results. This approach divides the aircraft into pre-NEO and NEO groups, while allowing the regression intercept and the linear and quadratic speed coefficients to differ (via NEO interaction terms) between the two groups. With no other interactions present, the coefficients for log_distance, W_NW and load_factor are forced to be the same across the aircraft-type groups. The results thus show (average) differences in fuel usage between the pre-NEO and NEO groups, but not between individual aircraft types.

Table 1 shows summary statistics for the sample. Mean fuel consumption is 6103 liters, and ranges between the cutoff value of 2316 and a maximum of 22,989. Mean speed is 561 km/h, ranging between the cutoff value of 318 and 821. Flight distance has a mean of 1297 km and varies between the cutoff of 349 and a maximum of 6096, while about 12 percent of the observations have a West or Northwest direction of flight. The mean load factor of 0.66

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[4] To capture distance effects, we also tried a regression specification with fuel usage per km as dependent variable and distance on the right-hand side, expecting a negative distance coefficient. Although expectations were partly confirmed, this specification had various other drawbacks, leading us to use the one described in the text.

indicates that planes are on average about 2/3 full, with a few totally empty or fully loaded.

About 39% of the observations involve an aircraft in the NEO group. Within that group, the A320NEO and B737-MAX-8 planes are most common, accounting for 20 and 15% of the sample observations, respectively, with the newer A321NEO representing only 4%. The most common aircraft in the pre-NEO group are the A320-100-200 and B737-800 types, representing 18 and 20% of the sample observations. While the overall shares of the A319 and A321-100-200 types are non-negligible, the B737-300, -500, and -700 types are rarely observed, with the first two types accounting for only a handful of observations.

3. Regression results

Table 2 presents the regression results. The regressions are run at the route level, with aircraft types distinguished only by the NEO dummy variable. The specification in column 1 captures the difference between pre-NEO and NEO aircraft only through a difference in the intercept via the NEO dummy. The negative NEO coefficient reflects the better fuel efficiency of aircraft in this group. The speed and speed-squared coefficients are significantly negative and positive, respectively, yielding a positive second derivative for the quadratic speed relationship and thus a U-shaped curve. The log_distance coefficient is naturally positive, and the positive and significant W_NW coefficient shows greater fuel usage flying into the prevailing winds, with a difference of 326 liters. The significantly positive load_factor coefficient shows that more fully loaded planes consume more fuel, with a 0.1 (10 percentage point) increase in load_factor raising fuel consumption by 20 liters, an effect that appears small.

Using the speed and speed-squared coefficients, the fuel-minimizing aircraft speed can be computed, as shown at the bottom of Table 2. The value, which is the same for pre-NEO and NEO planes given the specification, equals 631.4 km/h, which is equivalent to 392.4 miles/h.

The specification in column 2 of Table 2 introduces interaction terms between NEO and the speed variables, allowing both the intercept and speed effects to differ between the pre-NEO and NEO aircraft groups. As can be seen, the log_distance, W_NW, and load_factor coefficients change only slightly, while the NEO coefficient becomes positive, flipping the previous negative sign. However, with NEO also appearing in the interactions, the NEO effect at a given speed equals the NEO intercept coefficient plus the two interaction coefficients multiplied by that speed or its square and summed. Evaluating at the mean speed of 561 km/h, the NEO effect is −1199, similar to the value in column 1.

The uninteracted speed and speed-squared coefficients in column 2 pertain to pre-NEO aircraft. The linear speed effect for NEO planes is given by the uninteracted plus interacted speed coefficients, while the quadratic effect is given by the uninteracted plus interacted speed-squared coefficients. Referring to the estimates, the NEO speed effect comes thus from a more-negative linear term and a slightly more positive quadratic term. The result is a slightly higher min_speed for the NEO group, 639 km/h as opposed to 619 km/h for the pre-NEO group, as seen at the bottom of the column.

Figure 1 shows the combined effect of all these differences by plotting fuel-speed curves for both the pre-NEO and NEO groups, with the associated numbers shown in Table 3. To generate the plots, the non-speed portion of the regression is evaluated by first multiplying the log_distance, W_NW and load_factor coefficients by the sample-mean values of these variables from Table 1, and then adding the regression constant from column 2. For the NEO group, the resulting value is incremented by the NEO coefficient from column 2. Then, the speed portion of the regression is evaluated at different speed values, as seen in figure, doing so both for the pre-NEO and NEO groups. For the pre-NEO group, the uninteracted linear and quadratic speed coefficients are used, while for the NEO group, the sum of the uninteracted and interacted coefficients is used for both the linear and quadratic terms.

As can been from the figure, the NEO curve is below the pre-NEO curve, reflecting the greater fuel efficiency of the former group, and the bottom of the curve is slightly farther to the right for the NEO group, reflecting the different min_speed values in column 2 of Table 2.

The gap between the two curves is perhaps larger than expected. While NEO aircraft are said to a offer 10-15% fuel-efficiency improvement over their predecessors, moving from the pre-NEO to curve to the NEO curve at a speed of 625 km/h yields a larger 24% reduction in fuel usage. However, the curves in Figure 1 are derived from a statistical rather experimental procedure, where factors other than speed cannot be held constant. In other words, they do not come from a comparison of fuel usage by pre-NEO and NEO aircraft flown on a given route at the same speed under the same weather conditions. As a result, a divergence from the 10-15% differential could arise.

Both curves show substantial variability of fuel usage across different speeds. Slowing from the maximum sample speed of 821 km/h (achieved in the NEO group) to the NEO min_speed reduces NEO fuel consumption by 1722 liters, a decrease of 8.9%. For the pre-NEO group, slowing from the maximum speed in this group (782 km/h) to the pre-NEO min_speed reduces fuel consumption by 1219 liters, or 7.5%. Such reductions in fuel usage will be the focus of the next section, which explores environmental aircraft speed limits.

While the regressions in columns 1 and 2 use robust standard errors, the regression in column 3 uses standard errors clustered at the (directional) route level. Such clustering reflects likely correlation in the regression error terms within routes due to common unobserved characteristics. Clustering often reduces the significance level of estimated coefficients, a result than can be seen by the loss of significance of the interaction coefficients and the coefficients for NEO and load_factor. The uninteracted speed coefficients retain significance, however, as do the log_distance and W_NW coefficients.

It should be reiterated that the results in Table 2 and Figure 1, which rely on operational data and not engineering models to generate the fuel-speed relationship, appear to be unique. Offering them is thus a major contribution of the paper.

4. Evaluation of environmental speed limits

The U-shaped fuel-speed curves in Figure 1 suggest the possibility of imposing environmental speed limits on aircraft. Speed limits would reduce fuel usage and thus carbon emissions, but at the cost of longer flight times, which would disadvantage passengers. Since the net impact from this trade-off, and thus the desirability of speed limits, is not at all clear a priori, the analysis in this section carries out the required calculations.

Two parameters are needed in this exercise: the environmental damage per liter of jet fuel used, and the value of passenger time per hour. To compute environmental damage, we start with a carbon damage value of $190 per metric ton, using a recent US Environmental Protection Agency value cited by Brueckner, Kahn and Nickelsburg (2024b). Since one gallon of jet fuel produces 9.75 kg or 0.00975 metric tons of carbon (see Brueckner and Abreu, 2017), the environmental damage per gallon is $\$190 \times 0.00975 = \$1.85$. Multiplying by 0.264 gallons per liter yields carbon damage of $0.49 per liter.

For the value of time in air travel, we use the US Federal Aviation Administration value of $47.10 per hour (an average across business and leisure passengers), and deflate it by the ratio of Brazilian to US GDP per capita, equal to 0.14.[5] The result is a Brazilian value of time in air travel of $6.62/h.

Table 4 shows the calculations based on these numbers, with the first column giving values for the NEO group of aircraft and the second column pertaining to the pre-NEO group. The calculations apply to the subsets of aircraft in the NEO and pre-NEO groups that are flying faster than the min_speed value for their group, which contain 38% of NEO aircraft and 31% of pre-NEO planes. Referring to the first column, the first entry shows the previous NEO min_speed value of 631.4 km/h. The second entry shows that imposing a speed limit equal to the min_speed would reduce the speed across flights in the NEO group by an average of 46.0 km/h. Using flight distance values, lower speeds would then increase the average NEO flight times by an average of 0.26 h (about 15 minutes), as seen in the third entry. Using the average NEO passenger count of 158 and applying the $6.62 value of time, the value of time lost to all passengers on a flight from the speed limit has an average of $274.67 per flight, as seen in the fifth entry in the first column.

Turning to emissions, application of the regression coefficients in Table 2 yields an average reduction in fuel usage from the speed limit of 161.3 liters, as seen in the sixth entry. This number is not particularly large because the excess speed of 46.0 km/h is modest, with unrestricted speeds lying not far above the min_speed. Applying the $0.49 damage value per liter then yields carbon-emission damages that average $78.80 across NEO flights. Since this number is less than the average value of the time loss from the speed limit, the limit is welfare reducing, with an average net welfare change per flight of −$195.87, as seen in the last entry.[6]

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[5] The FAA value, which is for 2015, is available at `https://www.faa.gov/sites/faa.gov/files/regulations_policies/policy_guidance/benefit_cost/econ-value-section-1-tx-time.pdf`. The GDP ratio (in constant 2015 dollars) is from the World Bank at `https://data.worldbank.org/indicator/NY.GDP.PCAP.KD`.

[6] Note that other losses, such as a possible reduction in airline profit, are not considered in reaching this

The second column of Table 4 repeats these calculations for the pre-NEO aircraft group, which yields numbers similar to those for the NEO group. The conclusion is then that aircraft speed limits in Brazil are not at all desirable, with value-of-time losses about 3.5 times as large as the gains from lower emissions. The verdict would be even more dramatic in a richer country like the US, where the emission reductions would be the same but value-of-time losses higher by a factor of 7 (= 1/0.14, using the previous GDP factor).

If all NEO planes were flying at the maximum observed speed of 812 km/h, instead of closer to the min_speed, then the loss-gain relationship from a speed limit would be reversed. For such a flight, the extra flight time from a speed limit would be 0.48 h while fuel usage would fall by 1722 liters. Assuming 158 passengers, the value of lost time would then be \$440.35, while the reduction in emission damages would be \$840.83, a larger value. For the pre-NEO group (which has a lower maximum speed), the outcome is similar, with the two numbers given by \$517.13 and \$595.60, respectively. These reversals are clearly due to the convexity of the fuel-speed curve, with a speed reduction leading to a small decline in fuel usage near the bottom of the curve but a much larger reduction starting from a high speed. However, since such high speeds are uncommon, with slower flying the norm, the smaller reduction in fuel usage due to a speed limit is more than offset by the time loss.

5. Conclusion

This paper has used a Brazilian dataset to estimate the relationship between fuel usage and speed for jet passenger aircraft. This exercise appears to be unique, with prior evidence on the fuel-speed relationship coming entirely from engineering models. The regressions generate U-shaped fuel-speed curves like those from the engineering approach, focusing on groups of narrow-body aircraft types (NEO vs. pre-NEO), rather than individual aircraft models. The empirical estimates are used to evaluate the desirability of environmental aircraft speed limits, which would force planes to fly at a speed that minimizes fuel usage, thereby reducing carbon emissions but imposing longer flight times on passengers. Using outside estimates of the value of time and carbon-emissions damage, the analysis shows that speed limits are not desirable,

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welfare value.

with the gains from lower emissions dominated by the time lost from slower flights.

While the fuel-speed relationships from BADA's engineering models are frequently cited, and while the airlines themselves have vast operational experience on the connection between speed and fuel usage, the present paper has offered a new exploration of this important relationship by exploiting a unique dataset, following its use by de Almeida and Oliveira (2023) for a somewhat different purpose. We hope that our work prompts additional research on aviation topics using nontraditional data sources and empirical approaches.

Table 1: Summary statistics

Variable	*Mean*	*Std. Dev.*	*Min*	*Max*
fuel (liters)	6102.754	2988.579	2316	22989
speed (km/h)	560.8073	107.4507	318.11	821.16
distance (km)	1296.691	762.3967	349	6096
load_factor	.6586375	.1415288	0	1
W_NW	.1194708	.3243454	0	1
NEO	.3924508	.4883019	0	1
A319	.0740784	.2619014	0	1
A320_100_200	.1811989	.3851873	0	1
A321_100_200	.1096462	.3124518	0	1
B737_300	.0001622	.0127348	0	1
B737_500	.0001622	.0127348	0	1
B737_700	.0418009	.2001362	0	1
B737_800	.2005005	.4003795	0	1
A320NEO	.2029103	.4021709	0	1
A321NEO	.0414301	.1992852	0	1
B737_MAX_8	.1481104	.3552135	0	1

Observations = 43,157

Table 2: Fuel-usage regressions

VARIABLES	(1) fuel	(2) fuel	(3) fuel
speed	-57.59**	-56.61**	-56.61**
	(0.687)	(0.664)	(4.442)
speed^2	0.0456**	0.0457**	0.0457**
	(0.000595)	(0.000632)	(0.00407)
speed × NEO	–	-9.564**	-9.564
		(1.450)	(8.195)
$\text{speed}^2 \times \text{NEO}$	–	0.00606**	0.00606
		(0.00137)	(0.00792)
NEO	-1,152**	2,260**	2,260
	(10.34)	(374.0)	(2,048)
log_distance	6,057**	6,046**	6,046**
	(38.28)	(38.09)	(267.5)
W_NW	326.3**	361.4**	361.4**
	(19.00)	(18.92)	(126.1)
load_factor	200.4**	205.5**	205.5
	(36.91)	(36.49)	(185.7)
Constant	-18,610**	-19,124**	-19,124**
	(203.2)	(247.7)	(1,625)
Observations	43,157	43,157	43,157
R^2	0.875	0.878	0.878
min_speed	631.4	–	–
min_speed_pre_neo	–	618.7	618.7
min_speed_neo	–	638.7	638.7

Columns 1 and 2: robust standard errors in parentheses.
Column 3: standard errors clustered by route in parentheses.
** $p<0.01$, * $p<0.05$

Table 3: Numbers underlying the fuel-speed curves

Speed	*fuel* *pre-NEO*	*fuel* *NEO*
450	6942.1	6133.8
475	6583.6	5677.3
500	6282.2	5285.5
525	6038.0	4958.5
550	5850.9	4696.2
575	5720.9	4498.7
600	5648.0	4365.9
625	5632.3	4297.9
650	5673.7	4294.6
675	5772.2	4356.1
700	5927.8	4482.3
725	6140.6	4673.3
750	6410.5	4929.0
775	6737.5	5249.5
800	7121.6	5634.7
825	–	6084.7

Table 4: Evaluation of environmental speed limits

	NEO	*pre-NEO*
min_speed (km/h)	631.4	618.7
avg excess speed (km/h)*	46.0	49.0
avg time difference with speed limit (h)	0.26	0.24
avg passengers	158	162
avg value of lost time ($) (= pax × lost time (h/pax) × 6.62 ($/h)	274.67	260.29
avg fuel difference with speed limit (liters)	161.3	153.2
avg decrease in emissions damage ($) (= fuel diff (l) × 0.264 (gal/l) × 1.85 ($damage/gal)	78.80	74.84
avg welfare change from speed limit ($) (= avg damage decrease − avg value of lost time)	−195.87	−185.45

*averages are across individual flights

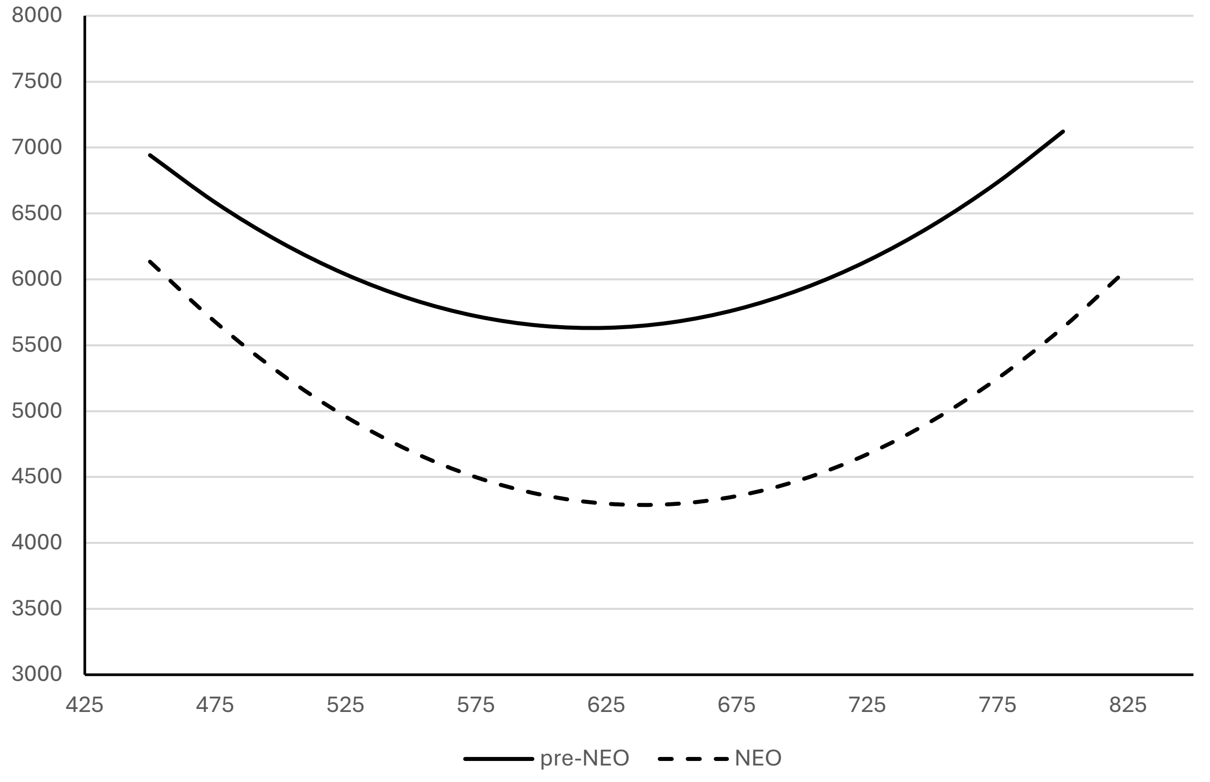

Figure 1: Fuel usage (liters) vs. speed (km/h)

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