Pass-through of the policy-induced E85 subsidy: Insights from Hotelling’s model

Jinjing Luo and GianCarlo Moschini *

Abstract. We build a structural model of imperfect competition for a retail market that supplies both low-ethanol (E10) and high-ethanol (E85) gasoline blends. The model permits us to study some impacts of the E85 subsidy induced by the U.S. Renewable Fuel Standard, specifically how the pass-through of this subsidy to retail prices is affected by market power. The model is rooted in Hotelling’s horizontal differentiation framework, which is extended to also represent the imperfect substitutability between E10 and E85 (a vertical product differentiation attribute). The model naturally captures two sources of imperfect competition in the fuel market—refueling stations’ market power arising from their spatial location, and limited availability of E85 stations. We derive both analytical and numerical solutions for Nash equilibrium outcomes under various scenarios. In our baseline parameterization, when the penetration of E85 stations is incomplete, we find that the pass-through rate is about 0.7. Complete penetration of E85 stations leads to near complete pass-through, notwithstanding the market power enjoyed by stations because of their spatial location. With monopolistic market power (e.g., collusion), however, with full penetration of E85 stations the pass-through rate is lower. Moreover, when market power only arises from location differentiation (duopoly model with full penetration of E85), the pass-through rate converges to one as the subsidy gets large, whereas it converges to zero if a station has exclusivity in selling E85 (partial penetration of E85) or there is collusion/monopoly power from collusion.

Key Words: E85, ethanol, gasoline, horizontal and vertical differentiation, market power, pass-through.

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* Jinjing Luo is a Ph.D. student and GianCarlo Moschini is a professor and the Pioneer chair in science and technology policy, both with the Department of Economics, Iowa State University, Ames, IA 50011, USA.

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1. Introduction

Over the last decade, the United States has implemented ambitious policies designed to drastically increase the share of renewable energy used for transportation fuels. In particular, the Energy Independence and Security Act of 2007 (EISA) greatly expanded the Renewable Fuel Standard (RFS), which entails a set of nested quantity “mandates” for several forms of renewable fuels. The schedule originally envisioned by EISA contemplated the use of biofuels growing to 36 billion gallons by the year 2022 (Schnepf and Yacobucci 2013). This bold target has had to be scaled back somewhat, by repeated waivers by the Environmental Protection Agency, because of the apparent failure of commercially-viable cellulosic biofuel supply. Still, the non-cellulosic portion of these mandates—mainly corn-based ethanol, but also advanced biofuels such as biodiesel and sugarcane-based ethanol—are still being pursued at the full level envisioned by EISA (21 billion gallons by the year 2022). As these mandate levels have grown over the years, the “blend wall” has materialized. This concept refers to the bottleneck that arises when the total quantity of ethanol to be blended into the gasoline supply exceeds 10%.

To understand the root of the blend wall problem, one must note that ethanol is blended into the fuel supply essentially by way of two distinct blends: low-ethanol E10 fuel (which contains 10% ethanol) and high-ethanol E85 fuel (which contains anywhere from 51% to 83% ethanol, depending on seasonality). E10 can be used by all cars, whereas E85 can be used only by flexible fuel vehicles (FFVs). Insofar as meeting rising EISA’s mandates requires ethanol use in excess of 10% of the total gasoline use, increased consumption of E85 is necessary. By 2013 the RFS required 13.8 billion gallons of ethanol, which constituted 10.3% of gasoline consumption, thus exceeding the E10 blend wall (Stock 2015). It has become apparent, however, that increasing consumers’ use of E85 is problematic (Collantes 2010; Pouliot and Babcock 2014). Specific constraints are due to the low number of FFVs (which at present make up approximately 8.5% of the fleet of cars and light trucks), and the limited availability of E85 service stations (E85 pumps are available at about 3% of stations).1 Furthermore, previous work has found that the majority of FFV drivers actually do not fill up their vehicles with E85.

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1 The Alternative Fuels Data Center of the U.S. Department of Energy reports 3,322 E85 stations in 2017. The total number of gasoline stations in the United States, which has been declining over time, was reported to be 114,474 in 2012 by the U.S. Bureau of the Census.
Demand for E85 depends crucially on the distinctive features of the choice problem faced by FFV drivers. E85 has considerably less energy content than E10—on average, a gallon of E85 only delivers about 80% of the miles of a gallon of E10. Consumers who ultimately care about the cost per mile traveled, therefore, would require the price of E85 to be suitably discounted relative to that of E10 in order to be enticed to buy (Collantes 2010; Pouliot and Babcock 2017). Furthermore, because a tank of E85 delivers fewer miles than E10, consumers face an additional convenience cost because of the need for more frequent refueling stops. All this suggests that, from a vertical product differentiation perspective, E85 is an inferior product relative to E10. Such a conclusion may be partially offset, however, if consumers attached some utility to the consumption of renewable energy per se, perhaps because of their beliefs about the lower carbon emission of ethanol relative to fossil gasoline (i.e., consumers may have “green” preferences).2 But there is also a horizontal differentiation component to E85 demand, which is related to the relative scarcity of E85 refueling stations: other things equal, drivers located farther from an E85 station will be less willing to refill their tank with this fuel (relative to the ubiquitous E10).

The heterogeneity of consumers, vis-à-vis the structural determinants of demand, suggests that E10 and E85 are imperfect demand substitutes. If expanding consumption of E85 is required to overcome the blend wall, the structural determinants of E85 demand will matter in translating price signals into consumption decisions. Such price signals are supposed to be induced by the policy design of the RFS. As shown by Lapan and Moschini (2012), in a competitive setting, a quantity mandate is isomorphic to a combination of a tax (on fossil fuel) and a subsidy (for ethanol) that is revenue neutral. The use of renewable identification numbers (RINs) to enforce the mandates makes this equivalence transparent. These tradable instruments command a price whenever the mandate is binding, which reflects the cost of complying with the RFS at the margin (Korting and Just 2017). The price of RINs quantifies the extent of the subsidy for ethanol and tax for fossil gasoline. Because E85 contains substantially more ethanol and less gasoline than E10, positive RIN prices translate into a policy-induced subsidy for E85, relative to E10.

If the policy-induced subsidy for E85 is fully reflected in retail fuel prices, then consumers would be given the proper market signal: tighter RFS mandates would lead to higher RIN prices, increasing the spread between E10 and E85 RIN prices, ultimately resulting in higher E85 consumption. Recent

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2 Indeed, in an early empirical analysis of E85 demand, Anderson (2012) found that a substantial fraction of FFV drivers were willing to pay a premium for E85 fuel.
empirical work, however, has raised questions on the extent of this pass-through. Knittel, Meiselman, and Stock (2017) find that, whereas RIN price pass-through is fairly complete at the wholesale level, there appears to be little or no pass-through of RIN prices to retail E85 prices. Market power is the chief market imperfection typically invoked to rationalize a less-than-full pass-through of an (exogenous) cost differential. Lade and Bushnell (2019) emphasize the dynamics of the process and, unlike Knittel, Meiselman, and Stock (2017), find that pass-through of E85 subsidy is on average one-half to three-quarters. Li and Stock (2019), utilizing station-level data from Minnesota from 2012 to 2015, estimate the state-level pass-through rate for E85 to be approximately 0.5. Similar to Lade and Bushnell (2019), they also find that indicators of local monopoly for E85 stations correlate with lower pass-through.

As noted by Knittel, Meiselman, and Stock (2017, p. 1082), “… a central question for RFS policy is whether this pass-through occurs at the retail level.” The empirical contributions cited in the foregoing do not provide a conclusive answer, and in fact suggest the possibility that imperfect competition at the retail level may be key. Complete pass-through is a feature of perfect competition, in the sense that goods are priced at marginal costs. The rate by which equilibrium prices are affected by a given cost change, though, in general depends on the elasticities of demand and supply. With constant marginal costs, as maintained below, the E85 subsidy is fully transmitted to retail prices under perfect competition. Under imperfect competition, however, the pass-through rate also depends on conduct parameters for market power and the shape of demand curves (Weyl and Fabinger 2013). In the context of gasoline retail, what pass-through should one expect? And, what are the critical factors affecting the subsidy pass-through rate?

To address these questions, this paper develops a structural model suitable to study the pass-through of the policy-induced E85 subsidy to retail prices. Our model is rooted in Hotelling’s (1929) spatial competition model, a standard approach in industrial organization whereby firms are endowed with some market power by the presumption of product differentiation. This structure captures in a natural way the heterogeneity of consumers, vis-à-vis the locations of refueling stations. We extend this horizontal product differentiation framework to also accommodate consumers’ heterogeneous preferences with respect to E85, a vertical differentiation feature that appears essential to the context being modeled. Consideration of more than one dimension of
product differentiation makes models rather unwieldy.\textsuperscript{3} The model we develop is, inevitably, rather stylized. Yet the model captures important features of the structure of demand for E10 and E85 discussed earlier, and provides a natural way to represent the role of imperfect competition at the retail level. The advantage of a structural model, albeit a stylized one, is that of providing a vehicle by which we can isolate the effects of various factors and assess their contribution towards favoring or impeding pass-through. As such, this paper complements the emerging literature, noted earlier, on the empirical assessment of RIN pass-through to gasoline prices (Knittel, Meiselman, and Stock 2017; Lade and Bushnell 2019; Li and Stock 2019).

To investigate the impact of E85 availability, our benchmark model is a duopoly setting with incomplete penetration of E85 stations—specifically, two stations, only one of which sells E85. As a comparison, we also investigate the duopoly model with only E10 fuel (this is the basic Hotelling’s model), and the duopoly model where both firms sell both fuels (E10 and E85). Except for the basic Hotelling duopoly model, and one of the monopoly models we consider, analytic solutions for the Nash equilibrium are not possible in our extended models. Hence, we solve our models numerically. To that end, we calibrate the values of parameters in the various models and solve for Nash equilibrium results under alternative parameter settings.

Our results show that pass-through is incomplete with incomplete penetration of E85 stations. In the benchmark model, we estimate the pass-through rate to be about 0.7. When firms have no exclusivity of selling E85 (i.e., E85 is offered at all locations), however, the pass-through is near complete even though firms still have some market power from horizontal differentiation. Moreover, our results show that the market generally exhibits lower pass-through when the E85 subsidy is higher, and when market power is higher (the two stations are a monopoly). Our results also show that prices of E10 at both location barely change with the E85 subsidy (under the working assumption that the cost of E10 fuel is constant). Interestingly we show that, in the model with partial penetration of E85 stations, the E10 price at the same location with E85 is higher than the E10 price at the other location in duopoly, whereas the relation reverses in monopoly. For demands, we show that E85 consumption increases with the subsidy, as expected, and the decrease in E10

\textsuperscript{3} Conceptual models include Neven and Thisse (1990), Ferreira and Thisse (1996), and Gabszewicz and Wauthy (2012). Recent applications include Brécard (2014), Di Comite, Thisse and Vandenbussche (2014), Norman et al. (2016), and Pennerstofer (2017).
consumption is larger at stations with both E10 and E85 pumps, no matter whether in duopoly or in monopoly.

The paper is organized as follows. Section 2 provides more details on framing pass-through rate in our setting. In section 3, we specify drivers’ preferences and derive demand functions for various cases of interest. In section 4, we calibrate some of the critical parameters of the model. Section 5 presents the results for the main duopoly models we consider. Section 6 considers the issue of market power further, in the context of a monopolized market. Finally, section 7 concludes the paper.

2. Background

We begin with a simple example that shows how subsidy pass-through works in the context of the simplest Hotelling model of horizontal product differentiation. We then review how the E85 subsidy arises from the basic mechanisms of the RFS. Both of these discussions point to the usefulness of looking at the subsidy pass-through to the spread between E10 and E85 retail prices, a feature that we will then investigate with the analytical model that we develop below.

2.1 A simple motivating example

To motivate the analysis that we propose, consider the textbook linear-city setup where two firms are located at the extreme of a line of unit length, each offering a product to a population of consumers, with unit demand, who are uniformly distributed on the unit segment (see, e.g., Tirole, 1988, pp. 279-280). The two products are perceived as imperfect substitutes, by any one consumer, because of the consumer’s own location. To fix ideas, think of the product sold by firm A at location L0 as E10 gasoline, and the product sold by firm B at location L1 as E85 gasoline (presently we will discuss why this is too simplistic, and how the model needs to be generalized). The two firms compete in prices by setting $p_A$ and $p_B$, respectively. If the consumers’ reservation value for one unit of either good is sufficiently large, so that the market is covered, then the demand functions facing the two firms are easily obtained:

$$q_i = \frac{1}{2} + \frac{p_j - p_i}{2t}, \quad i, j = A, B, i \neq j$$

where $t > 0$ is the “travel cost” parameter. Suppose the firms have constant per-unit costs $c_A$ and $c_B$, respectively. It is readily found that the Nash equilibrium prices are:
In this setting, we ask what the implications would be of a tax/subsidy on these products. Suppose first that a per-unit subsidy \( s > 0 \) is provided to both products. Then it is readily seen that both equilibrium prices decline by exactly the amount \( s \) (i.e., there is 100% pass-through), and the equilibrium quantities are unchanged. Alternatively, suppose that only product B enjoys the per-unit subsidy \( s \). It is easy to see that, in this case

\[
\frac{\partial p^*_A}{\partial s} = -\frac{1}{3} \quad \text{and} \quad \frac{\partial p^*_B}{\partial s} = -\frac{2}{3}
\]

Interestingly, both prices decline in equilibrium. The subsidy-induced decline in product B’s marginal cost provides an incentive to reduce \( p_B \). Furthermore, because prices are “strategic complements” in this setting, this leads firm A to also reduce its price. In equilibrium, although the subsidy does not apply to both products, the subsidy to product B reduces both prices.

If the purpose of the subsidy is to incentivize consumption of product B, then from the demand functions above it is clear that what matter is the net effect of the subsidy on the price difference \( (p^*_A - p^*_B) \). When the subsidy only applies to product B, the pass-through rate on this price difference is:

\[
\frac{\partial (p^*_A - p^*_B)}{\partial s} = \frac{1}{3}
\]

Thus, we conclude that, in this imperfectly competitive setting, the effectiveness of the subsidy to promote use of product B is blunted by the exercise of market power from horizontal differentiation, and by the fact that prices are strategic complements.

This model is clearly too simplistic to capture the stylized facts of E10 and E85 gasoline retail: in the foregoing, the two products are sold at different locations by different firms, whereas in reality E10 and E85 are typically marketed by refueling stations that sell both products; furthermore, this purely horizontal setting does not capture the vertical differentiation dimension that is an essential feature of E10 and E85 gasoline demand. Below we provide a suitably generalized model. Yet, this simple

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\[ \text{For example, considering the RIN obligations in 2013, Stock (2015) concluded that the net effect of RIN prices was a near-zero subsidy for E10 ($0.01/gal) and a large subsidy for E85 ($0.50/gal).} \]
model shows some of the reason why limited pass-through may arise in an imperfectly competitive setting, and why it is instructive to look at the subsidy pass-through on the products’ equilibrium price difference.

2.2 Pass-through of energy policy effects

Conceptually, the pass-through rate measures how consumer price is affected by a small change in a per-unit tax or subsidy. In the context of the RFS, framing the pass-through of the policy-implied tax/subsidy effects requires some attention to the mechanisms by which RIN prices affect costs of producers and retailers. In Knittel, Meiselman, and Stock (2017) RIN pass-through rate is measured as the partial effect of RIN obligation spread on retail price spread for E10 and E85. Lade and Bushnell (2019) measures how retail price of E85 changes in response to the change in E85 RIN subsidy. Li and Stock (2019) note that the changes in wholesale spread of E10 and E85 are mainly driven by fluctuations in RIN prices and estimate how the E85 retail price responses to the changes in the wholesale spread. As explained in more details below, in this study we define the pass-through rate as the impact of the E85 subsidy, induced by the RFS, on the spread between E10 and E85 retail prices.

To illustrate how the RFS tax/subsidy implications filter to retail prices in the context of the model we develop, we presume a competitive refining/blending industry that operates under constant returns to scale. Specifically, we consider a simplified structure where fossil gasoline and corn ethanol, which are blended into E10 and E85, can be obtained at constant per-unit costs. Such “producer prices” are denoted $p_g$ and $p_e$, respectively. [All prices are expressed in natural units, e.g., $/gallon].

To translate such prices into the costs faced by retailers, we start by noting that the RFS requires obligated parties (e.g., refineries) to retire a bundle of RINs (associated with the requirements of the RFS nested mandates) for every gallon of fossil gasoline sold. Let the cost of this bundle be denoted by $B$, and let $R$ denote the RIN price associated with ethanol (i.e., the price of D6 RINs).

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5 This assumption is attractive for its simplicity, but it is also consistent with the pass-through evidence presented by Pouliot, Smith, and Stock (2017) who estimate RIN pass-through at the rack and cannot reject complete RIN pass-through to wholesale fuel prices. Knittel, Meiselman, and Stock (2017) also find complete pass-through of RIN prices to wholesale gasoline prices.

6 Using the percentage standards for the 2017 year, $B$ is determined by the obligated party’s need to “retire” for each gallon of fossil fuel sold, 0.0167 D4 RINs to meet the biodiesel mandate, 0.0238 D4 or D5 RINs to meet the total advanced biofuel mandate, and 0.107 D4, D5 or D6 RINs to meet the total renewable fuel mandate.
Throughout the paper, we assume E10 includes 10% ethanol and E85 uses 74% ethanol (as maintained by Knittel, Meiselman, and Stock 2017). Then, wholesale prices of blended fuels satisfy:

\[ p_{E10}^w = 0.10(p_e - R) + 0.90(p_s + B) \]  
\[ p_{E85}^w = 0.74(p_e - R) + 0.26(p_s + B) \]

The retailing industry takes the wholesale prices \( p_{E10}^w \) and \( p_{E85}^w \) as given, such that their retailing costs can be represented as \( c_{E10} = p_{E10}^w + \mu \) and \( c_{E85} = p_{E85}^w + \mu \), where \( \mu \) is the sum of motor fuel taxes and per-unit marketing/retailing costs.

In the absence of the RFS policy (i.e., \( R = 0 \) and \( B = 0 \)), the cost of the two fuel blends to retailers are fully determined by the producer prices \( p_s \) and \( p_e \) (plus the aforementioned term \( \mu \)). The RFS, however, introduces product-specific tax/subsidies equal to \((0.1 - 0.9)R\) for E10 fuel and \((0.74 - 0.26)B\) for E85 fuel (as in Knittel, Meiselman, and Stock 2017). A more insightful analysis of how policy measures are passed through to retail prices can be obtained by looking at the cost advantage for the E85 fuel, defined as \( c_{E10} - c_{E85} \). From the foregoing, it is clear that this cost advantage is partly determined by the producer prices \( p_s \) and \( p_e \) (which we will hold constant in our analysis), and by the net subsidy to the E85 fuel (relative to E10). Specifically:

\[ c_{E10} - c_{E85} = 0.64(p_s - p_e) + s \]

where \( s \) denotes the per-gallon subsidy implied by the policy:

\[ s = 0.64(R + B) \]

The central question we want to address in this paper concerns how the RFS policy provides signals to consumers, vis-à-vis their choice of fuel type. A “more stringent” RFS policy would entail higher RIN prices, increasing both the D6 RIN price \( R \) and the cost of the RIN bundle obligations \( B \), which translate directly into an increase in the relative subsidy \( s \) enjoyed by E85. As noted, with a competitive retailing sector the retail prices satisfy \( p_{E10} = c_{E10} \) and \( p_{E85} = c_{E85} \). Thus, from (7), the “pass-through” rate of the policy subsidy would be \( \partial(c_{E10} - p_{E85})/\partial s = 1 \). That is, the policy subsidy \( s \) enjoyed by E85 would be completely reflected in the retail price spread, i.e., completely passed through to consumers. The model that we develop permits us to investigate the extent to which
such a complete pass-through fails under the assumed imperfect competition setting. This way of characterizing pass-through is similar to the approach used by Knittel, Meiselman, and Stock (2017). Their (empirical) motivation for looking at the price spread between E10 and E85 was different from ours, but the fact remains that looking at the price spread between E10 and E85 provides a clean and informative summary on the nature of the pass-through effects.

3. The Model

We study the duopoly setting where two stations are located at either end of the unit segment (these locations are labeled L0 and L1, respectively). A useful model for comparison is that where both stations only sell E10 fuel, which corresponds to the basic Hotelling duopoly model. Our main model is that with incomplete penetration of E85 stations: the station at L0 offers both E10 and E85, whereas the gas station at L1 only sells the conventional E10. Finally, we also consider the case of complete penetration of E85, where both firms sell both types of fuels. The two stations maximize their separate profits, and we derive the Nash equilibrium of the non-cooperative game. To proceed, however, we first need to specify consumers’ preferences.

3.1 Preferences

A unit mass of consumers are uniformly distributed on $[0,1]$. Each consumer has a car, either a normal car or an FFV. The proportion of cars that are FFV is $\alpha$. Consumers can fill the tank at either station to drive a distance of $M$ miles. Her utility from driving one mile is denoted as $\bar{u}$. If $x \in [0,1]$ denotes a consumer’s own location, she incurs a cost (disutility) of $tx$ when refueling at L0, and $\bar{t}(1-x)$ when refueling at L1, where the parameter $\bar{t} > 0$ captures the intensity of consumers’ cost due to their heterogeneous location attribute. This cost is meant to capture the disutility associated with the time and travel cost associated with a refueling stop, and it is independent of the type of fuel purchased. The prices for the two fuels of interest are denoted by $p^j$, where the superscript $\ell \in [0,1]$ denotes the location of the station and the subscript $j \in \{A,B\}$ denotes the type of fuel.7

Note that, for notational simplicity, the subscript A will refer to E10 fuel, and the subscript B will refer

7 These prices are quoted in natural units (e.g., $/gallon). Because of the lower energy content of E85 fuels, some authors prefer to express prices (and quantities) at equal energy content. For example, Pouliot and Babcock (2014) measure the quantity of E10 in E85-equivalent units, with prices appropriately scaled. As will become apparent in what follows, in our context it is more instructive to deal with quantity and prices for both fuels in their natural units, and to separately keep track of the lower energy content of E85.
to E85 fuel (as a mnemonic, B = biofuel). For a consumer located at \( x \), if she chooses to refuel with E10 at L0, the payoff associated with this choice would be

\[
U^0_A = \bar{u}M - p^0_A \cdot \left( \frac{M}{\phi_A} \right) - \bar{t}x \cdot \left( \frac{M}{k\phi_A} \right)
\]  

(9)

where \( \phi_j \) is the efficiency of fuel \( j \) (miles per gallon), and \( k \) denotes the size of the tank (gallons).

Thus, \( M/\phi_A \) measures the number of gallons needed for \( M \) miles, and \( M/k\phi_A \) is the number of service stops needed for \( M \) miles.

If the consumer owns an FFV and chooses to refuel with E85 at L0, her payoff from driving \( M \) miles would be

\[
U^0_B = \bar{u}M - p^0_B \cdot \left( \frac{M}{\phi_B} \right) - \bar{t}x \cdot \left( \frac{M}{k\phi_B} \right)
\]  

(10)

Note that drivers who refuel with E85 are penalized from more frequent refueling (because \( \phi_B < \phi_A \), then \( M/k\phi_B > M/k\phi_A \)), and how much they are penalized depends on their location, \( x \).

Some normalizations permit us to simplify these payoffs without loss of generality. Specifically, let \( t \equiv \bar{t}/k \), normalize \( M/\phi_A = 1 \), re-define \( u \equiv \bar{u}M \), and let \( \lambda \equiv \phi_A/\phi_B \). Then the payoffs in (9) and (10) can be re-written as:

\[
U^0_A = u - p^0_A - tx \\
U^0_B = u - \lambda p^0_B - \lambda tx
\]  

(11)

Here, \( t \) is a re-scaled Hotelling travel cost parameter, and the coefficient \( \lambda \) captures the energy efficiency of E10 relative to E85 (i.e., the energy content in one gallon of E10 is equivalent to that of \( \lambda \) gallons of E85). Also, \( \lambda = 1.25 \) is a known constant in our model.\(^8\)

This formulation maintains a systematic vertical ranking between E10 and E85: if the two fuels were priced equally in energy equivalent terms (i.e., \( p^0_A = \lambda p^0_B \)) then E85 would be dominated by E10 for all consumers (because \( \lambda > 1 \)). But we augment this basic structure by introducing a vertical differentiation parameter to capture the fact that consumers may have heterogeneous attitudes

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\(^8\) Given the assumed 74% average ethanol content of E85, and the U.S. Energy Information Administration (EIA) energy content of gasoline and ethanol (see, e.g., Moschini, Lapan, and Kim 2017), then \( \lambda = 1.25 \).
towards E85. Specifically, they may perceive some extra benefit from using E85 because they consider E85 a “green” fuel with lower environmental impact, or they may associate a lower payoff to E85 because of lack of awareness of E85 (Pouliot, Liao, and Babcock 2018) or because of the lower driving range permitted by one tank of E85 (Collantes 2010). To account for these effects, we replace the term $u$ by $(u + \theta)$ in the payoff associated with E85, where the parameter $\theta \in [\underline{\theta}, \overline{\theta}]$, with $\underline{\theta} < 0$ and $\overline{\theta} > 0$, captures drivers’ heterogeneous attitude towards E85. In solving the model we will assume that $\theta$ is uniformly distributed on the support $[\underline{\theta}, \overline{\theta}]$. In the paper, we refer to $\theta$ as drivers’ type and $x$ as their location.

This representation of consumers’ utility nests two dimensions of product differentiation. The parameter $\theta$ measures the degree of consumer heterogeneity with respect to vertical differentiation, whereas the location $x$ characterizes their horizontal differentiation. As both $\overline{\theta}$ and $\underline{\theta}$ approach zero, the heterogeneous component of vertical differentiation disappears. The parameter $t$ measures the intensity of preferences vis-à-vis horizontal differentiation. As $t \to 0$, horizontal differentiation disappears.

3.2 The model with one E85 station at location L0

This is our main model. Both gas stations provide E10, whereas only the gas station at L0 provides E85. For owners of normal cars, the payoffs associated with the two possible choices are:

$$
\begin{align*}
U^0_A &= u - p^0_A - tx & \text{if refuel with E10 at L0} \\
U^1_A &= u - p^1_A - t(1 - x) & \text{if refuel with E10 at L1}
\end{align*}
$$

Drivers of FFVs face a richer set of alternatives, however: the choice of station, and whether to refuel with E10 or E85. Hence, the payoffs associated with the choices available to an FFV driver are:

$$
\begin{align*}
U^0_A &= u - p^0_A - tx & \text{if refuel with E10 at L0} \\
U^1_A &= u - p^1_A - t(1 - x) & \text{if refuel with E10 at L1} \\
U^0_B &= u + \theta - \lambda p^0_B - \lambda tx & \text{if refuel with E85 at L0}
\end{align*}
$$

For normal car drivers, their choice of E10 at L0 or E10 at L1 depends on their location $x$ and relative prices of E10 at two locations. FFV drivers can choose E10 at L0, E10 at L1, or E85 at L0 based on their type $\theta$ and location $x$, as well as relative prices of each fuel, $p^0_A$, $p^1_A$, and $p^0_B$. To get the aggregate demands of each fuel, now we inquire into each driver’s decision on location and type to refuel.
For given fuel prices, normal car drivers’ payoffs from refueling at location L0 and L1 are shown as the orange line and the blue line respectively in Figure 1. The indifferent E10 consumer, identified by the condition $U_A^0 = U_A^1$, has location

$$\bar{x} = \frac{1}{2} \left[ \frac{p_A^1 - p_A^0}{t} + 1 \right]$$  \hspace{1cm} (14)

So, normal car drivers located at the left of $\bar{x}$ refuel with E10 at L0, whereas they choose to refuel at L1 if located at the right of $\bar{x}$.

Figure 1. FFV drivers’ choice of fuel at given prices $p_A^0$, $p_A^1$, and $p_B^0$

Figure 1 illustrates FFV drivers’ payoffs from each refueling option. If they choose to refuel with E10, the orange line and the blue line represent their payoff just as for normal car drivers. If they choose to refuel with E85, the payoff from refueling falls into the area between two parallel black lines (associated with the upper and lower bounds of the $\theta$ parameter) because of the heterogeneous preferences over E85. In Figure 1, $[u - \lambda p_B - \lambda tx + \theta]$ represents the payoff from E85 for a consumer with the highest preference for ethanol, whereas $[u - \lambda p_B - \lambda tx + \bar{\theta}]$ represents the
payoff from E85 for a consumer with the lowest preference for ethanol; \([u - p^0_B - tx]\) is the payoff from E10 at L0, and \([u - p^1_A - t(1 - x)]\) is the payoff from E10 at L1. FFV drivers choose the type of fuel that maximizes their payoff.

For drivers who are located at the left of \(\bar{x}\) (defined by equation (14)), the option of E10 at L1 is dominated by E10 at L0. The fuel choice is determined by comparing payoffs from the left two refueling options at L0. The indifferent consumer, identified by the condition \(U^0_B = U^0_A\), has a heterogeneity parameter that also depends on her location:

\[
\tilde{\theta}(x) \equiv (\lambda - 1)tx + \lambda p^0_B - p^0_A
\]  

(15)

Hence, a driver would choose to refuel with E85 at L0 if her type satisfies \(\theta > \tilde{\theta}(x)\), and she would choose E10 at L0 otherwise.

For drivers located at the right of \(\bar{x}\), the choice of E10 at L0 is dominated by E10 at L1. The coordinates of the indifferent consumer identified by the condition \(U^0_B = U^1_A\), for \(x \geq \bar{x}\), are:

\[
\tilde{\theta}(x) \equiv (\lambda + 1)tx - t + \lambda p^0_B - p^1_A
\]  

(16)

An FFV driver chooses to refuel with E85 at L0 if \(\theta > \tilde{\theta}(x)\), and use E10 at L1 otherwise.

Note that the indifferent consumer type is an increasing function of \(x\) in both equations (15) and (16), which implies that only FFV drivers with high enough preferences would choose E85 if they are located farther from the E85 station at L0. Evaluating equation (16) at \(\theta = \bar{\theta}\) and inverting it yields the farthest location consistent with a possible choice of E85 at L0:

\[
\bar{x}^1 = p^1_A - \frac{\lambda p^0_B + \bar{\theta} + t}{(\lambda + 1)t}
\]  

(17)

This point is shown in Figure 1 as the location of the intersection of \(U^0_B\) and \(U^1_A\) at \(\theta = \bar{\theta}\).

FFV drivers’ choices are depicted in Figure 2, where the \(x\) axis denotes FFV drivers’ location and the \(y\) axis denotes the type \(\theta\). In the rectangle \([0,1] \times [\bar{\theta}, \bar{\theta}]\), FFV drivers at the top left would choose to refuel with E85 from L0—these are FFV drivers who are close to L0 and have high preferences for E85; FFV drivers at the bottom left would choose to refuel with E10 from L0—these are FFV drivers who are close to L0 and have low preferences for E85; FFV drivers on the right portion of the
rectangle would choose E10 at L1—these are FFV drivers who are close to L1. The threshold \( \tilde{\theta}^0 \) (type of consumer at \( x = 0 \) who is indifferent between E10 at L0 and E85 at L0) in Figure 2 is obtained from evaluating equation (15) at \( x = 0 \), while \( \tilde{\theta} \) (type the consumer at \( x = \tilde{x} \) who is indifferent between E10 at L0 and E85 at L0 and E10 at L1) is derived from evaluating the same equation at \( x = \tilde{x} \).

\[
\begin{align*}
\tilde{\theta}^0 &= \frac{2\hat{\theta} - \hat{\theta} - \hat{\theta}^0}{2(\hat{\theta} - \hat{\theta})} + \left( \frac{\tilde{x}^1 - \tilde{x}}{2(\hat{\theta} - \hat{\theta})} \right) \\
\tilde{\theta} &= \left( 1 - \alpha \right)(1 - \tilde{x}) + \alpha \left[ \left( \frac{\tilde{x}^1 - \tilde{x}}{2(\hat{\theta} - \hat{\theta})} \right) \hat{\theta} + \hat{\theta} - 2\hat{\theta} \right] + 1 - \tilde{x}^1
\end{align*}
\]

Figure 2. FFV drivers’ demands in the one E85 station model, baseline scenario (“case 2”)

Let \( d_A^0 \), \( d_A^1 \), and \( d_B^0 \) denote the market demands for E10 at L0, E10 at L1, and E85 at L0 respectively. These demand functions can be obtained by integrating individual demands over the distributions of individual characteristics. Given the assumed uniform distribution of \( x \) and \( \theta \), then, from Figure 2, we can express \( d_A^0 \), \( d_A^1 \), and \( d_B^0 \) as functions of the threshold levels in the \((x, \theta)\) space:

\[
\begin{align*}
d_A^0 &= (1 - \alpha)\tilde{x} + \alpha\tilde{x} \frac{\tilde{\theta} + \tilde{\theta}^0 - 2\hat{\theta}}{2(\hat{\theta} - \hat{\theta})} \\
d_B^0 &= \lambda\alpha \left[ \tilde{x} \frac{2\hat{\theta} - \hat{\theta} - \hat{\theta}^0}{2(\hat{\theta} - \hat{\theta})} + \left( \frac{\tilde{x}^1 - \tilde{x}}{2(\hat{\theta} - \hat{\theta})} \right) \frac{\hat{\theta} - \hat{\theta}}{2(\hat{\theta} - \hat{\theta})} \right] \\
d_A^1 &= (1 - \alpha)(1 - \tilde{x}) + \alpha \left[ \left( \frac{\tilde{x}^1 - \tilde{x}}{2(\hat{\theta} - \hat{\theta})} \right) \frac{\hat{\theta} + \hat{\theta} - 2\hat{\theta}}{2(\hat{\theta} - \hat{\theta})} + 1 - \tilde{x}^1 \right]
\end{align*}
\]
In equation system (18), $d_A^0$ and $d_A^1$ are sums of E10 demands from both normal car drivers and FFV drivers. In $d_A^0$, $(1 - \alpha)\bar{x}$ is the demand of normal car drivers for E10 at L0: $(1 - \alpha)$ is the fraction of normal car drivers in the market, and $\bar{x}$ measures the fraction of normal car drivers who refuel with E10 at L0 (normal car drivers who are located at the left of \(\bar{x}\)). The second element of $d_A^0$ involves the term $0.5\bar{x}(\tilde{\theta} + \bar{\theta} - 2\bar{\theta})/(\bar{\theta} - \theta)$, which is the fraction of FFV drivers who choose to refuel with E10 at L0 (indicated by the area of the bottom left trapezoid in Figure 2). The demand for E10 at L1, $d_A^1$, is constructed in the same way. For $d_B^0$, $\lambda$ captures the E85 demand of a single FFV driver (recall that consumers need $\lambda$ gallons of E85 to drive the same number of miles as one gallon of E10). The expression in the square brackets represents the fraction of FFV drivers who choose E85 at L0 (a sum of the area of a trapezoid and the area of a triangle in Figure 2). Because we have normalized the mass of drivers in the market to one, and the market is covered, then $d_A^0 + d_A^1 + d_B^0/\lambda = 1$.

Recalling that the threshold levels in the $(x, \theta)$ space are themselves functions of the fuel prices $p_A^0$, $p_A^1$, and $p_B^0$, equation (18) implicitly defines the demand functions facing the retailing stations. Actually, with different combinations of prices, the demands of FFV drivers for each fuel may differ from what is shown in Figure 2. There are five scenarios in total (in addition to the extreme cases where no FFV driver chooses E85, or all FFV drivers refuel with E85). What is illustrated in Figure 2 is the case that arises under the baseline parameter values (discussed below) and it implies that FFV drivers do not refuel with E85 if they are located far enough from the E85 station and/or they have low enough preferences for E85. The other four scenarios are shown in Figure 3. When $p_B^0$ is relatively high, only FFV drivers with higher preferences for E85 and who are close to L0 would choose E85, i.e., for some consumers it might be that $\tilde{\theta} > \bar{\theta}$ (recall that $\tilde{\theta}$ is from evaluating equation (15) at $x = \bar{x}$); this is “case 1” in Figure 4. “Case 2” is the baseline scenario illustrated in Figure 2 and already discussed in the foregoing. With relatively low $p_B^0$, it may be the case that $\tilde{\theta} < \bar{\theta}$ (recall that $\tilde{\theta}$ is from evaluating equation (15) at $x = 0$), so that even FFV drivers with low preferences for E85 choose to refuel with E85; such a situation arises for “case 3”, “case 4,” and “case 5” in Figure 3. Case 5 differs from case 4 in that all FFV drivers on the left of $\bar{x}$ choose to refuel with E85. $\bar{x}^0$ and $\bar{x}^1$ in Figure 3 are obtained from evaluating equation (15) and (16), respectively, at
\( \theta = \theta \); \( \bar{\theta}^0 \) and \( \bar{\theta}^1 \) are obtained from evaluating these two equations, respectively, at \( \theta = \bar{\theta} \). A summary of all threshold levels is reported in Table A1 in Appendix A, which also provides more details on how the associated demand structure evolves with different combinations of fuel prices.

Figure 3. FFV drivers’ demands in the one E85 station model, other scenarios

3.3 The model with both E10 and E85 at both stations

To capture the effects of market penetration of E85 stations, we next consider the situation where both gas stations offer both E10 and E85. For normal car drivers, payoffs from using E10 at two locations are still as in equation (12). As for FFV drivers, their payoffs for the various choice possibilities are as follows:
\[
\begin{align*}
U^0_A &= u - p^0_A - tx & \text{if refuel E10 at location 0} \\
U^1_A &= u - p^1_A - t(1 - x) & \text{if refuel E10 at location 1} \\
U^0_B &= u - \lambda p^0_B - \lambda tx + \theta & \text{if refuel E85 at location 0} \\
U^1_B &= u - \lambda p^1_B - \lambda t(1 - x) + \theta & \text{if refuel E85 at location 1}
\end{align*}
\] (19)

We denote the locations of indifferent consumers for E10 and E85 as \(\tilde{x}_A\) and \(\tilde{x}_B\), respectively. From the conditions \(U^0_A = U^1_A\) and \(U^0_B = U^1_B\), we have:

\[
\begin{align*}
\tilde{x}_A &= \frac{1}{2} + \frac{1}{2t} \left( p^1_A - p^0_A \right) \\
\tilde{x}_B &= \frac{1}{2} + \frac{1}{2t} \left( p^1_B - p^0_B \right)
\end{align*}
\] (20)

In this symmetric model, without loss of generality, assume \(\tilde{x}_A \geq \tilde{x}_B\), which implies \(p^1_A - p^0_A \geq p^1_B - p^0_B\). For drivers who are located at the left of \(\tilde{x}_A\), fuel option of E10 at L1 is dominated by the option of E10 at L0; for drivers who are located at the left of \(\tilde{x}_B\), the fuel option of E85 at L1 is dominated by the option of E85 at L0. The FFV driver who is indifferent between E10 and E85 at L0 is identified by equation (15), and the FFV driver who is indifferent between the two fuels at L1 is identified by the condition \(U^1_A = U^1_B\), yielding

\[
\tilde{\theta}(x) \equiv (\lambda - 1)t(1 - x) + \lambda p^1_B - p^1_A
\] (21)

The demands of FFV drivers for each fuel are illustrated in Figure 4. As before, \(\tilde{\theta}^0\) is still from evaluating equation (15) at \(x = 0\), and \(\tilde{\theta}_B\) is by evaluating the equation at \(x = \tilde{x}_B\). Similarly, \(\tilde{\theta}^1\) is obtained from evaluating equation (21) at \(x = 1\), and \(\tilde{\theta}_A\) is by evaluating the equation at \(x = \tilde{x}_A\). FFV drivers’ fuel choices, under all combinations of \(\theta\) and \(x\), are shown in Figure 4.

Demands for fuels in the market are denoted as \(d^0_A\), \(d^1_A\), \(d^0_B\), and \(d^1_B\). As before, these demands are obtained by integrating individual demands over the distribution of individual characteristics on \([0,1] \times [\tilde{\theta}, \tilde{\theta}]\). Summing up the demands of all FFV drivers and normal car drivers, we can get
\[ d_A^0 = (1 - \alpha) \tilde{x}_A + \alpha \left( \tilde{x}_B \frac{\tilde{\theta}_B + \tilde{\theta}_A^0 - 2\tilde{\theta}}{2(\tilde{\theta} - \tilde{\theta}_0)} + (\tilde{x}_A - \tilde{x}_B) \frac{\tilde{\theta}_B + \tilde{\theta}_A - 2\tilde{\theta}}{2(\tilde{\theta} - \tilde{\theta}_0)} \right) \]

\[ d_A^1 = (1 - \alpha)(1 - \tilde{x}_A) + \alpha (1 - \tilde{x}_A) \frac{\tilde{\theta}_A + \tilde{\theta}_A^1 - 2\tilde{\theta}}{2(\tilde{\theta} - \tilde{\theta})} \]

\[ d_B^0 = \lambda \alpha \left[ \tilde{x}_B \frac{2\tilde{\theta} - \tilde{\theta}_B - \tilde{\theta}_0}{2(\tilde{\theta} - \tilde{\theta})} \right] \]

\[ d_B^1 = \lambda \alpha \left[ (\tilde{x}_A - \tilde{x}_B) \frac{2\tilde{\theta} - \tilde{\theta}_B - \tilde{\theta}_A}{2(\tilde{\theta} - \tilde{\theta})} + (1 - \tilde{x}_A) \frac{2\tilde{\theta} - \tilde{\theta}_A - \tilde{\theta}_A^1}{2(\tilde{\theta} - \tilde{\theta})} \right] \]

\[ \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix} + \begin{pmatrix} e \\ f \\ g \\ h \end{pmatrix} = \begin{pmatrix} i \\ j \\ k \\ l \end{pmatrix} \]

\[ \begin{pmatrix} a \\ b \\ c \end{pmatrix} = \begin{pmatrix} e \\ f \\ g \end{pmatrix} \]

\[ \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} e \\ f \end{pmatrix} \]

\[ \begin{pmatrix} a \end{pmatrix} \]

\[ \begin{pmatrix} a \end{pmatrix} \]

\[ (22) \]

Figure 4. FFV drivers’ demands in the two E85 stations model, baseline scenario

Again recalling that the threshold levels in the \((x, \theta)\) space are themselves function of the fuel prices, equation (22) implicitly defines the demand functions facing the retailing stations.

Of course, in this symmetric model, in equilibrium the fuel prices will satisfy \(p_A^1 = p_A^0\) and \(p_B^1 = p_B^0\) (as we assume the costs of the same fuels are the same for two stations). When both stations provide E85, again we find that multiple demand configurations can arise, depending on fuel prices. What we discuss in the text is the case that arises under the baseline parameter values (see below).
It implies that, with full penetration of E85 stations, any FFV driver may choose to refuel with E85 if she has a high enough type $\theta$ (regardless of her location $x$). There are a total of three cases. In addition to that illustrated in Figure 4, there is the scenario under high E85 price, such that $\tilde{\theta}^B > \tilde{\theta}$ and $\tilde{\theta}^A > \tilde{\theta}$ (only FFV drivers close to either station with high preferences for E85 would choose to refuel with E85) and the scenario under low E85 price such that $\tilde{\theta}^0 < \tilde{\theta}$ and $\tilde{\theta}^1 < \tilde{\theta}$ (most FFV drivers would select E85). When retail price of E85 is too high or too low relatively, there might be no consumption of E85 or all FFV drivers may choose to refuel with E85. A full discussion of all these cases can be found in Appendix A.

3.4 Nash equilibrium

Nash equilibrium requires that each station’s choice of prices be a payoff-maximizing “best response” to the choices of the other station, and this must hold simultaneously for both stations. To compute the Nash equilibrium, we first derive each gas station’s profit under each case. The working assumption is that of constant marginal cost $c_A$ and $c_B$ for E10 and E85, respectively, where the unit cost $c_B$ for E85 embeds the subsidy $s$. We further assume that fuel costs are the same for all stations.

For the benchmark model without E85 fuel (no E85 stations at either location), given the demand functions in equation (2) in section 2.1, the profits of the two stations are:

$$\pi^0 = \frac{1}{2t}(p_A^0 - c_A)[p_A^1 - p_A^0 + t]$$

$$\pi^1 = \frac{1}{2t}(p_A^1 - c_A)[p_A^0 - p_A^1 + t]$$

This is the textbook parameterization of the basic Hotelling’s model, yielding the Nash equilibrium solution (see, e.g., Tirole 1988):

$$p_A^0 = p_A^1 = t + c_A \quad , \quad d_A^0 = d_A^1 = \frac{1}{2} \quad , \quad \pi^0 = \pi^1 = \frac{t}{2}$$

The equilibrium values of these and other variables of interest are reported in Table 1 in section 5.1.

For the model with only one E85 station, the profits of the two gas stations are:

$$\pi^0 = (p_A^0 - c_A)d_A^0 + (p_B^0 - c_B)d_B^0$$

$$\pi^1 = (p_A^1 - c_A)d_A^1$$
where the demand functions are derived in section 3.2.

For the model with both stations offering both fuels, the profits of gas stations at locations L0 and L1 are

\[ \pi^0 = \left( p^0_A - c_A \right) d^0_A + \left( p^0_B - c_B \right) d^0_B \]
\[ \pi^1 = \left( p^1_A - c_A \right) d^1_A + \left( p^1_B - c_B \right) d^1_B \]

where the demand functions are as derived in section 3.3. In the duopoly setting, the gas station at L0 chooses \( p^0_A \) and \( p^0_B \), and its competitor chooses \( p^1_A \) and \( p^1_B \). In this symmetric market, we are looking for the symmetric equilibrium where \( p^0_A = p^1_A \) and \( p^0_B = p^1_B \), so \( \bar{x}_A = \bar{x}_B = 1/2 \). A complete list for the equilibrium values of several variables of interest is reported in Table 1 below.

Analytic solutions for the Nash equilibrium are not possible in models with E85, even the symmetric one. To proceed, we have computed the Nash equilibrium numerically, as follows. From the payoff functions defined in the foregoing we derive analytic first order conditions (FOCs) that define the best response functions for each station. In the model with one E85 station, we have two best response functions for the gas station at L0 and one for the gas station at L1. In the model with two E85 stations, we have two best response functions for each gas station. The best response functions are solved simultaneously in Matlab using \texttt{vpasolve}. Multiple systems of solutions from the FOCs are possible, hence we relied on local second order conditions (SOCs) for a maximum to narrow the possible candidates. Eventually, only one system of solutions survives the SOCs, which is the Nash equilibrium outcome. To perform this numerical process, of course, we first need the values of all parameters, which is what we do in the next section.

4. Parameter calibration

Two of the models discussed in the foregoing are not amenable to an analytic solution of the Nash equilibrium. To solve this model numerically, the first step is to calibrate the parameters of the model. The parameter \( \lambda \) captures the energy efficiency of E10 compared to E85, which, as discussed earlier, is a known constant \( \lambda = 1.25 \). In addition, the model has eight other parameters:

(i). \( s \), the per-unit subsidy of E85;
(ii). \( c_A \), the marginal cost of E10;
(iii). \( c_B \), the marginal cost of E85;
(iv). \( \alpha \), the fraction of FFVs;
(v). $u$, consumers’ reservation utility from driving one gallon of E10;
(vi). $t$, Hotelling’s “travel cost” parameter;
(vii). $\overline{\theta}$, the upper bound of drivers’ preference parameter for E85;
(viii). $\overline{\theta}$, the lower bound of drivers’ preference parameter for E85.

Prices ($p_A^0$, $p_A^1$, $p_B^0$, and $p_B^1$), and demands ($d_A^0$, $d_A^1$, $d_B^0$, and $d_B^1$), are all endogenous variables. To calibrate these parameters, we use relevant features of the model along with market data pertaining to the year 2017.

The subsidy $s$ captures the policy-induced subsidy for E85, relative to E10. Following the discussion in section 2.2, the subsidy is constructed by equation (8). In equation (8), $R = 0.72$ is the price of D6 RINs and $B = 0.0836$ is the cost of compliance for a gallon of obligated conventional gasoline.  

So, $s = 0.5143$.

c, and $c_B$ correspond to the terms $c_{E10}$ and $c_{E85}$ of section 2.2. We note here that the producer price $p_g$ is not observed. What we observe is the RIN-laden average gasoline wholesale price, denoted as $\tilde{p}_g$, which in 2017 was $1.689/$gal.  

In the postulated competitive refining/blending industry that operates under constant returns to scale, we should have $\tilde{p}_g = p_g + B$, where the bundle of obligations term $B$ was introduced in section 2.2. The average ethanol wholesale price, denoted $p_e$ in section 2.2 as, was $1.45/$gal in 2017. The average gasoline motor fuel tax, denoted as $\mu$ in section 2.2, is $0.449/$gal. Together with the values of $R$ and $B$, we calibrate the cost of E10

---

9 The prices of D4, D5, and D6 RINs (RIN year 2017 and transfer year 2017) are $p_{D4} = 1.03$, $p_{D5} = 0.91$, and $p_{D6} = 0.72$, respectively, from EPA, [https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information](https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information). Hence, from section 2, $B = 0.0167p_{D4} + 0.0071p_{D5} + 0.0832p_{D6} = 0.0836$.

10 The gasoline wholesale price is from EIA, [https://www.eia.gov/dnav/pet/pet_pri_refoth_dcus//nus_a.htm](https://www.eia.gov/dnav/pet/pet_pri_refoth_dcus//nus_a.htm). It is the “Motor Gasoline” price under “Sales for Resale” category.

11 The ethanol wholesale price is the ethanol rack price in Omaha, Nebraska.

12 The average gasoline motor fuel tax is from Moschini, Lapan, and Kim (2017). We do not consider the per-unit marketing/retailing costs. First, the marketing/retailing costs are too small to have a significant effect on the model results. Moreover, we will show next that any cost would be absorbed by the value of $t$ in our calibration procedure.
fuel to be \( c_A = 2.0421 \) and the cost of E85 fuel to be \( c_B = 1.4283 \) (recall that fuels are measured in volume terms, and they possess different energy content).

For the FFV fraction \( \alpha \), in 2017 there were 20.34 million FFVs and 215.09 million gasoline vehicles (cars and light trucks categories).\(^{13}\) Hence, we estimate \( \alpha = 0.0864 \). As it has been shown in the indifference consumers and equations (14)-(21) in section 3, the reservation utility \( u \) has no effect on driver’s choice of fuel so we do not specify an exact value for \( u \). In the duopoly models, we assume \( u \) is large enough so that all drivers would choose to refuel. For the parameter \( t \), in the basic Hotelling’s model this parameter decides the E10 equilibrium price margin: as discussed in section 3.4, the equilibrium E10 price in the basic Hotelling model is equal to \( t + c \), hence the retail price margin is \( t \). The retail price of E10 in 2017 was $2.3625/gal.\(^{14}\) Given the cost of E85 discussed earlier, the margin for E10 is $0.3204, so we set \( t = 0.32 \).

Concerning the bounds \((\theta, \bar{\theta})\) of the distribution of consumers’ preferences for the high-ethanol attribute of E85, we have assumed \( \theta < 0 \) and \( \bar{\theta} > 0 \). That is, FFV drivers with high preferences for E85 are willing to pay a premium, whereas FFV drivers with low preferences for E85 would only purchase it under some price discount. To calibrate these bound parameters, we rely on WTP estimates, as well as specific features of our model. Pouliot, Liao, and Babcock (2018) estimate the WTP for E85 in the United States using survey data. The survey targeted at FFV drivers and their estimates of WTP show that about 25% of motorists would prefer E85 when E85 and E10 are equally priced at energy-equivalent unit. The result would suggest that \( \bar{\theta}/(\bar{\theta} - \theta) = 0.25 \), implying \( \theta = -3\bar{\theta} \).

Next, recall that we would like our highly stylized model to capture a realistic scenario with the baseline parameters. Specifically, we would like to ensure that, in the baseline, \( x^1 < 1 \) and \( \bar{\theta}^0 > \theta \) (recall Figure 2). Numerical exploration of the model indicates that the value of \( \bar{\theta} \) has little effect on \( x^1 \) and \( \bar{\theta}^0 \), but \( x^1 \) and \( \bar{\theta}^0 \) vary significantly with \( \bar{\theta} \). To ensure that \( x^1 < 1 \), \( \bar{\theta} \) needs to be lower than 0.27. Hence, we pick \( \bar{\theta} = 0.25 \), which satisfies this constraint and still allows for “green” drivers to have a nontrivial WTP for E85 (this value implies that the highest WTP for FFV drivers is $0.25/gal under our model normalization; to fuel a car with capacity of 16 gal, this is equivalent to $4/tank).”

\(^{13}\) EIA Annual Energy Outlook, 2017.

\(^{14}\) Quarterly nationwide average retail prices of E10 are from the Clean Cities Alternative Fuel Price Report. The annual average price is just the average of each quarter.
Given the value of $\theta$, from the relation $\theta = -3\theta$ derived earlier, we have $\theta = -0.75$ (which also implies that the desired condition $\theta^0 > \theta$ is satisfied). In any event, we conduct the sensitivity analysis of model results under different $\theta$ and $\theta$ (Appendix D). In sum, the baseline parameter values used for our benchmark analysis are: $s = 0.5143$, $c_A = 2.0421$, $c_B = 1.4283$, $\alpha = 0.0864$, $t = 0.32$, $\bar{\theta} = 0.25$, and $\underline{\theta} = -0.75$. In the next section, we show the results of different models under baseline values of all parameters. We also evaluate how results are affected by changes in the subsidy of E85.

5. Results

We first present the Nash equilibrium results for duopoly models under the alternative conditions of no E85 fuel, incomplete penetration of E85 stations (only the station at L0 sells E85), and complete penetration of E85 stations (all stations sell both fuels). Next, in the comparative statics section, we evaluate how results are affected by changes in the subsidy level of E85.

5.1 Baseline results

Results for the three duopoly models are reported in Table 1. For the models with no E85, we report both the analytic solutions and the values of these solutions at the baseline parameters. This permits a straightforward comparison with the main model—where E85 is only sold in one station—for which we can only find numerical solutions. For the model with E85 at both stations, we report the numerical solutions where the analytic solutions are not applicable. For each case, we report equilibrium prices and quantities, profits for the two stations. We report the pass-through rate, defined as $\partial(p_A - p_B)/\partial s$ in section 2.2, which measures the rate at which the subsidy brought about by RINs is passed on to the retail spread between E85 and E10 prices. Because both stations provide E10, we report $\partial(p_A - p_B)/\partial s$ as the average of $\partial(p^0_A - p^0_B)/\partial s$ and $\partial(p^1_A - p^1_B)/\partial s$. The effects of the subsidy $s$ on individual prices are discussed in section 5.2. The process of computing all pass-through rates is detailed in Appendix B.
### Table 1. Nash Equilibrium Outcomes for Duopoly Models

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<th>Two E85 stations</th>
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<td>Baseline values</td>
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<tr>
<td>$p^1_B$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\frac{\partial(p_A - p_B)}{\partial s}$</td>
<td>-</td>
<td>-</td>
<td>0.7188</td>
</tr>
<tr>
<td>$d^0_A$</td>
<td>$\frac{1}{2}$</td>
<td>0.5000</td>
<td>0.4807</td>
</tr>
<tr>
<td>$d^1_A$</td>
<td>$\frac{1}{2}$</td>
<td>0.5000</td>
<td>0.4959</td>
</tr>
<tr>
<td>$d^0_B$</td>
<td>-</td>
<td>-</td>
<td>0.0292</td>
</tr>
<tr>
<td>$d^1_B$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\pi_0$</td>
<td>$\frac{t}{2}$</td>
<td>0.1600</td>
<td>0.1643</td>
</tr>
<tr>
<td>$\pi_1$</td>
<td>$\frac{t}{2}$</td>
<td>0.1600</td>
<td>0.1579</td>
</tr>
</tbody>
</table>

From Table 1, we see the effects of competition as the possibility of E85 substituting for E10 is introduced. Adding an E85 pump at L0 causes E10 price at the same location to increase slightly while E10 price at the other location decreases. Demand for E10 at both locations decreases (recall that, with the assumed covered market condition with a given mass of consumers, the availability of E85 substitutes for some E10 at both locations). In the model with only one E85 location, E85 consumption is 0.0292 at baseline parameter values, which means that about 27% ($= \frac{d^0_B}{\alpha s}$) of FFV drivers choose E85. Adding another E85 location increases E85 consumption by 61.6%. Having an E85 pump increases the L0 gas station’s profit by 2.69% but decreases the other gas station’s profits by 1.31%.
The pass-through rate of the E85 subsidy due to RIN prices, at the baseline parameters, is 0.7188 (i.e., approximately 70%). Hence, competition with incomplete penetration of E85 stations is characterized by incomplete pass-through. This result formalizes the role of retail market power in affecting pass-through of RIN prices to retail prices. The gas station at L0 has a product that the other station does not have, it is effectively a monopoly for E85. The exercises of this market power, by raising E85 prices, is constrained by the fact that E10 is also sold by the same station (in addition to being sold by a competitor station). Still, at the equilibrium solution the markup, over cost, of the E85 price is higher than for E10.

It is interesting to note that the market power that is relevant for the pass-through effect just discussed differs from the source of market power that arises from the structure of the basic Hotelling model. In the model with E85 available at both locations, the pass-through rate is still incomplete but close to one (0.9665), which implies that it is the market power from exclusivity of selling E85 that mostly determines the incompleteness of the pass-through of the E85 subsidy, rather than the market power stemming from horizontal differentiation. The incompleteness of pass-through rate is very much related to the difference in the markups of E10 and E85. In the model with pure E10, the markup over cost is \( t = 0.32 \); in the model with pure E85, the markup over cost is \( \lambda t = 0.4 \)—that is, it is more profitable to sell E85 than E10 to an FFV driver. In the model with both fuels at both locations, this effect provides an incentive for stations to decrease the price of E85 while increasing the price of E10. The equilibrium markup of each fuel depends on the relative demand elasticities. The results show that, in equilibrium, the markup of E85 is 0.3713 \( (\lambda(p_B - c_B)) \) while the markup of E10 is 0.3208 \( (p_A - c_A) \).

Essentially, the availability of E85, together with consumer heterogeneity, brings about differentiation along a vertical attribute. This is valuable to a firm only insofar as it has some exclusivity. When all stations sell E85, alongside E10, this exclusivity vanishes and what remains is the horizontal differentiation of consumers, which is what endows firms with some limited market power in the Hotelling model. With full penetration of E85 stations, the value of the E85 subsidy is mostly captured by consumers.

Despite the fact that full penetration of E85 stations brings limited additional profit to the fuel-retailing firms, this situation should not be interpreted as a lack of incentives for retail stations to adopt E85 pumps. It is quite clear that, with incomplete penetration, the station that sells E85 enjoys higher returns than in the case when no station carries E85 (0.1644 > 0.16), and the firm who does
not sells E85 in the case of incomplete penetration can increase its profit by also adopting an E85 pump (0.1614 > 0.1579). Although this model is not quite suited to investigate the conditions for optimal entry of E85 stations, the structure of the model is such that the “excess entry” result discussed by Mankiw and Whinston (1986) is expected to apply.

5.2 Comparative statics

Of all parameters, the subsidy is of the most interest. Assessing the effect subsidy provides us key implications on evaluating the effectiveness of the RIN system. For the model with E85, for which we only have numerical solutions, in this section we present some numerical comparative statics results. Here, we focus specifically on understanding how varying the subsidy may affect the pass-through rate in equilibrium outcomes for the duopoly model with one E85 station (incomplete penetration of E85). Corresponding results for the duopoly model with two E85 stations (full penetration of E85) are reported in the Appendix C. Comparative statics results for parameters other than the subsidy level are reported in Appendix D.

To evaluate the equilibrium results under alternative values of the subsidy, all other parameters (except the cost of E85, which is directly affected by the subsidy as in equation (7)) are held at their baseline values. The results, reported in tabular form in the Appendix, are summarized in Figure 5. The vertical black dashed line in Figure 5 represents the baseline subsidy value of $s = 0.5143$. The dotted points along the separate lines mean that pass-through rates in the model are not a continuous function of the subsidy. The discontinuity is a result of the fact that alternative demand system configurations can be attained under different values of the subsidy. These alternative “cases,” illustrated earlier in Figure 2 and Figure 3, are specifically labeled in Figure 5. In Appendix A, we provide the actual values of the subsidy at the kink points in Figure 5.
Figure 5. Pass-through rate and the E85 subsidy in the duopoly model with one E85 station

From Figure 5, we see that when the subsidy $s$ is small ($s < 0.1089$, as shown in Appendix A), no E85 is sold in the market, and the pass-through rate (to the implicit choke-off prices) is equal to 1. In this case, even if the gas station passes all the subsidy to FFV drivers, the latter would still choose to refuel with E10 as the price of E85 is not low enough to compensate for its low energy content (even for the FFV driver with highest preference for E85). At $s = 0.1089$, the gas station at $L_0$ is just indifferent between selling E10 or E85, and the FFV driver with highest preference for E85 is just indifferent between choosing E10 or E85 at $L_0$. Then the pass-through rates jump to $2/3$ (for $0.1089 < s < 0.1569$), which is exactly the pass-through of subsidy/tax on an obligated product in equation (3). This corresponds to case 1 in Figure 3, for which $\theta > \overline{\theta}$. In this case, the equilibrium results show that offering E85 in the market has no effect on the equilibrium prices of E10—E10 prices at both locations are $t + c$. So, when the subsidy is low such that E85 does not directly compete with E10 at another location, the introduction of E85 in the market will not affect the equilibrium price of E10. For higher values of the subsidy, specifically over the domain $0.1569 < s < 0.5265$, the pass-through rate decreases from 0.9402 to 0.7179 as the subsidy increases. For still higher values of the subsidy, over the domain $0.5265 < s < 1.4735$, the pass-through rate
stays around 0.5, and then decreases toward zero as $s > 1.4735$. Note that case 5 of Figure 3 is not depicted in Figure 5 because case 5 only materializes when $s > 2.1343$ (we observe a small jump from case 4 to case 5, and the pass-through rate then monotonically decreases to zero in case 5).

Comparative statics for the pass-through rate in the duopoly model with two E85 locations are presented in Appendix C. Similar to the duopoly model with one E85 station, we find that the pass-through rate in the model with two E85 stations is not a continuous function of the subsidy. Furthermore, the complete penetration of E85 stations has notable effects on the pass-through rate. Instead of generally decreasing with $s$ as in the one E85 station situation (recall Figure 5), with two E85 stations the pass-through rate increases toward one.

In Figure 6, we provide some additional details by reporting the equilibrium prices, shares of FFV drivers who choose each fuel, and pass-through to individual fuels at values of the subsidy from 0 to 1.8. The orange line represents the equilibrium results of E10 at L0; the red line represents the equilibrium results of E85 at L0; and, the blue line represents the equilibrium results of E10 at L1. The vertical dashed line standing near 0.5 indicates the baseline value of $s$.

The top panel of Figure 6 depicts the equilibrium prices of each fuel. It shows that under the assumption of constant E10 cost, the retail prices of E10 barely change. As shown by the equilibrium results at representative values of the subsidy reported in Table C1 in Appendix C, E10 price at L0 is higher than that at L1. The decrease in E85 prices as $s$ increases is significant, which is in line with the pass-through rate in the duopoly model with one E85 station. The middle panel of Figure 6 reports the share of FFV drivers who choose each fuel rather than the demands of each fuel. With larger subsidy, the share of FFV drivers who choose to refuel with E85 goes from 0 to 0.9, and the share of FFV drivers who choose to refuel with E10 at L0 decreases from 0.5 to 0. The share of FFV drivers who choose to refuel with E10 at L1 also decreases but slower. The bottom panel of Figure 6 reports the pass-through of the subsidy to each retail price, defined as $\partial p_A^0/\partial s$, $\partial p_A^1/\partial s$ and $\partial p_A^0/\partial s$, respectively. Note that the pass-through rate reported in Table 1, $\partial(p_A - p_B)/\partial s$, is equivalent to $0.5\left(\partial p_A^0/\partial s + \partial p_A^1/\partial s\right) - \partial p_B^0/\partial s$. The equilibrium results of the duopoly model with two E85 locations are relegated to Appendix C. Numerical equilibrium results at some representative values of $s$ in both models are also reported in Appendix C.
Figure 6. Simulated equilibrium results in the duopoly model with one E85 station
The advantage of a stylized model, such as ours, is that we can evaluate the partial effect of each parameter on the model result. In additional to the subsidy, we run the model with alternative values of some key parameters—the fraction of FFVs ($\alpha$), Hotelling’s “travel cost” parameter ($t$), high type preference ($\theta$), and low type preference ($\overline{\theta}$). We analyze the impact of each parameter one at a time, holding all other parameters at their baseline values. We find that equilibrium prices and the pass-through rate barely change with $\alpha$ and $\theta$. The effects of these two parameters on E85 demand are proportional: larger $\alpha$ relates to more FFV drivers and larger $\theta$ in absolute value corresponds to smaller proportion of high type FFV drivers. As $t$ increases, all equilibrium prices increase as expected (recall that $t$ is reflected in the price margin in the Hotelling’s model), along with the pass-through rate (the increase is moderate as shown in Table D4 in Appendix D). The parameter $\overline{\theta}$ has little effect on equilibrium E10 prices, whereas an increase of this preference parameter results in higher E85 price and lower pass-through rate.

6. More on market power: monopoly

In Hotelling’s framework, firms have some relief from the predicament of price competition. Firms enjoy some local market power because of the spatial heterogeneity of consumers, vis-à-vis the location of the retailing firms. The intensity of this effect is captured by the parameter $t$. The possibility of selling E85 provides an additional venue for a station to extract rent from consumers’ vertical differentiation, provided the station has some exclusivity in its access to E85. In our modeling framework, such a situation is captured by E85 being available at only one of the two stations. With full penetration of E85, the pass-through rate is almost complete and the profits from selling an additional fuel are quite limited.

There are reasons to believe that the characterization of market power provided by Hotelling’s model may be insufficient in our setting. Firms may be able to enjoy more market power if they collude. Indeed, the possibility of tacit collusion is particularly real in settings, such as fuel retailing, where firms interact repeatedly (Tirole 1988). Furthermore, in reality, neighboring stations/brands may be owned by the same firm. As shown by Hastings (2004), the loss of independent, unbranded competitor would increase local fuel price. In such cases, market outcomes close to monopolistic may be quite plausible.

15 Tables of results with alternative values of these parameters are reported in Appendix D, specifically Table D1-Table D4.
To investigate the effects that collusive behavior may have on the market outcomes of interest, in this section we solve the monopoly problem that would arise if the two stations in our model perfectly coordinated their choices (for both E10 and E85) with the objective of maximizing joint profit. The demand structures in the monopoly models with one or two E85 stations are the same as those under their duopoly counterparts. Thus, there are five cases in the monopoly with one E85 station, and three cases in the monopoly with two E85 stations. However, the values of subsidy at the kink points are different (see Appendix A). At the baseline values of all parameters, the demand structure that applies to monopoly with one E85 station is the same as in Figure 2, and in the model with two E85 stations is the same as Figure 4.

In the case of monopoly, we can find analytic solutions for the settings where there is no E85 station, and where both stations sell both fuels. When only one of the two stations sells E85, however, we again need to resort to a numerical solution. A monopoly, given the characterization of consumers’ preferences used in the model, would want to charge the highest possible price, conditional on consumers’ participation that ensures a covered market. This condition, in term of prices, requires $p^0_A + p^1_A \leq 2u - t$ (it can be verified that a covered market is indeed a profit-maximizing feature of the parameter space we investigate). Profit maximization solutions for the monopoly case when there is no E85 are $p^0_A = p^1_A = u - t/2$ (at these prices the consumer most distant to a station, located at $x = 0.5$, is just willing to refuel). Unlike the duopoly model, we need the value of reservation utility $u$ to get the numerical solutions in the monopoly models. To make the result comparable with the duopoly model, we choose the value of $u$ such that in the case with no E85, equilibrium price of E10 is same with that of the duopoly model. So, when there is no E85, $p^0_A = p^1_A = 2.3621$, implying $u = 2.5221$. Equilibrium values of other variables of interest are reported in Table 2.
Table 2. Nash equilibrium outcomes for Monopoly model

<table>
<thead>
<tr>
<th></th>
<th>No E85 stations</th>
<th>One E85 station</th>
<th>Two E85 stations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Analytic solution</td>
<td>Baseline values</td>
<td>Numerical solution</td>
</tr>
<tr>
<td>( p_A^0 )</td>
<td>( u - \frac{t}{2} )</td>
<td>2.3621</td>
<td>( u - \frac{t}{2} )</td>
</tr>
<tr>
<td>( p_A^1 )</td>
<td>( u - \frac{t}{2} )</td>
<td>2.3621</td>
<td>( u - \frac{t}{2} )</td>
</tr>
<tr>
<td>( p_B^0 )</td>
<td>-</td>
<td>-</td>
<td>( \frac{2u-t+\bar{\theta}+\lambda c_B-c_A}{2\lambda} - \frac{t(\lambda-1)}{8\lambda} )</td>
</tr>
<tr>
<td>( p_B^1 )</td>
<td>-</td>
<td>-</td>
<td>( \frac{2u-t+\bar{\theta}+\lambda c_B-c_A}{2\lambda} - \frac{t(\lambda-1)}{8\lambda} )</td>
</tr>
<tr>
<td>( \frac{\partial (p_A - p_B)}{\partial \bar{s}} )</td>
<td>-</td>
<td>-</td>
<td>0.6051</td>
</tr>
<tr>
<td>( d_A^0 )</td>
<td>0.5</td>
<td>0.5000</td>
<td>0.4895</td>
</tr>
<tr>
<td>( d_A^1 )</td>
<td>0.5</td>
<td>0.5000</td>
<td>0.4948</td>
</tr>
<tr>
<td>( d_B^0 )</td>
<td>-</td>
<td>-</td>
<td>0.0196</td>
</tr>
<tr>
<td>( d_B^1 )</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \pi )</td>
<td>( u - \frac{t}{2} - c )</td>
<td>0.32</td>
<td>0.3234</td>
</tr>
</tbody>
</table>

Because of our model setup, the equilibrium price level is largely determined by the parameter \( u \) (which has no effect on the competitive duopoly equilibrium analyzed in the previous section).

Adding an E85 pump only at location L0 decreases the E10 price at the same location and increases the E10 price at the other location, which contrasts with the results we found for duopoly. The price effects of introducing E85, however, are minimal, as the monopoly charges the maximum price consistent with retaining a covered market. The monopoly’s total profits, reported in Table 2, show that adding E85 pumps to one or both stations increases profits. The additional profit afforded by E85, however, is minimal, a reflection of the small size of the E85 market at the baseline. E85 consumption slightly increases with implementation of E85 at another location. Comparing of profit
outcomes under duopoly and monopoly also provides some insights concerning the incentive for adoption of E85 pumps. At baseline parameter values, under duopoly we find that the station at L1 can increase its profit by 0.0035 by also adding an E85 pump. Under monopoly, the comparable additional profit is 0.0017. Hence, full penetration of E85 stations is less likely when collusive behavior at the retailing level applies.

Of more direct interest to us is the pass-through of the E85 subsidy, which turns out to be incomplete. When only one station sells E85, the pass-through rate is 60.51%, clearly lower than what is attained under duopoly. Perhaps most interestingly, full penetration of E85 stations lowers, rather than increasing, the equilibrium pass-through rate. Table 2 shows that the pass-through rate of the E85 subsidy is just 50% when both stations sell both fuels, regardless of other parameters, as long as the baseline demand configuration applies.\textsuperscript{16} To get a full idea of how pass-through rate evolves with the subsidy under incomplete penetration, we provide the following Figure 7.

\textbf{Figure 7. Pass-through rate and the E85 subsidy in the monopoly model with one E85 station}

\textsuperscript{16} In the model with two E85 stations, from the analytic solution for $p_B$ in Table 2, the pass-through of subsidy is $\frac{1}{2}$ to the E85 price and zero to the E10 price, hence the pass-through rate is $\frac{1}{2}$. 

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In Figure 7, we depict the equilibrium pass-through rate for the subsidy ranging from $s = 0$ to $s = 1.8$ (taking $c_A$ as given). The dotted lines connecting the pass-through rates show that they are not continuous functions of the subsidy $s$. The vertical black dashed line indicates the baseline value $s = 0.5143$. Figure 7 shows that when $0.1089 < s < 0.1569$ the pass-through rate is $2/3$ as in equation (3). Indeed, for this domain the pass-through rate is $2/3$ in all models that we have considered—the duopoly model with one E85 station in Figure 5, the duopoly model with two E85 stations in Figure in the Appendix, and the monopoly model with two E85 stations in Figure in the Appendix. This means that, for these relatively low subsidy levels, market structure (duopoly or monopoly) and the number of E85 stations (one or two) have no effect on the pass-through rate nor on E10 prices, as there is no direct competition between E85 and E10 at different locations. Over the domain $0.1569 < s < 0.6518$, the pass-through rate increases with the subsidy level (from around 0.5 to a little higher than 0.6). For $s > 0.6518$, the pass-through rate stays around 0.5, jumping down at $s = 1.6141$ and decreasing toward zero for large subsidy levels. In the monopoly model with two E85 stations, details for which are reported in the Appendix C, the pass-through rate exhibits a similar behavior as with the one E85 station case of Figure 7.

The foregoing results, together with Figure 5, establish that when market power arises from exclusivity of selling E85 (duopoly model with one E85 station) or general collusive/monopoly power, then the pass-through rate decreases toward zero as the subsidy level increases. Conversely, if market power arises just horizontal differentiation (duopoly model with two E85 stations), then the pass-through rate increases toward one as the subsidy level increases.

7. Conclusion

The RFS implemented by the United States over the last decade represents an ambitious policy aimed at promoting the substitution of fossil fuel with renewable fuel. To fulfill the mandates envisioned by the RFS, it is becoming necessary for the market to absorb an increasing amount of biofuel as high-ethanol blends, such as E85. The mechanism that should bring this about is rooted in RIN prices, which simultaneously constitute an implicit subsidy for biofuels and a tax on fossil fuels. The effectiveness of this mechanism, however, depends critically on the E85 subsidy, due to RIN prices, to pass through to consumers. Indeed, as noted by previous research, owners of FFVs “… will have little incentive to use E85 unless it is priced significantly lower than gasoline” (Collantes 2010). The findings of an emerging empirical literature, discussed earlier, suggest obstacles to the pass-through of RIN prices to retail E85 prices. It seems that the pass-through of the E85 subsidy,
mediated by RIN prices, may be incomplete and the pass-through rate relates to the possible existence of market power.

In this paper, we build a structural model of how market power may arise in E85 retailing, and use this model to gain insights into the nature of imperfect competition in this market, and the role of the E85 subsidy in determining the market outcomes of interest. Our model is rooted in Hotelling’s spatial competition framework, which provides a natural representation of gas stations’ market power due to location differentiation. This basic model is extended to account for important features of the market for E85, specifically the imperfect substitution between E85 and E10 (which itself depends on consumer heterogeneity), and the limited availability of E85 stations. We specifically evaluate three duopoly models and, to gain further insights into the role of market power, three monopoly models. Analytic solutions for the Nash equilibrium are possible only for the basic Hotelling’s models (and the extended model with full penetration of E85 stations under monopoly). For all other models we resort to numerical solutions (upon calibration of key models parameters, consistent with real-world data).

Results from the model suggest that pass-through of the E85 subsidy to retail prices is indeed generally incomplete. In our baseline model, which maintains the incomplete penetration of E85 refueling stations, the equilibrium pass-through rate is about 70%. With full penetration of E85 pumps (i.e., all stations offer both E10 and E85), the pass-through of the E85 subsidy to retail prices is near complete (even though gas stations retain some market power from their location differentiation).

In the collusive outcome whereby gas stations act as a monopoly (as may arise from tacit collusion due to repeated interaction), the pass-through rate is significantly lower; furthermore, in this case, full penetration of E85 pumps decreases the equilibrium pass-through rate (rather than increasing it, as in the duopoly model). Noticeably, when E85 only substitutes for E10 demand at the same location but not E10 demand at the other location, the pass-through rate is 2/3 regardless of whether it is monopoly or duopoly, partial or full penetration of E85. When the subsidy is large enough (i.e., greater than some threshold levels, which take different values in different models), the pass-through rate goes to one in the duopoly model with two E85 stations, whereas in the other three models (duopoly with one E85 station, monopoly with one E85 station, and monopoly with two E85 stations) the pass-through rate goes to zero. The result highlights the different implications for market power that arise from horizontal differentiation as opposed to from stations’ exclusivity (or monopoly power) in selling E85 fuel.
The model we build enables us to examine the effect of the subsidy on equilibrium fuel prices and demands. We show, as expected, E85 consumption increases with the subsidy. When the subsidy increases from 0.1 (when $s < 0.1$, there is no E85 consumption in the market) to 1, the percentage of FFV drivers who refuel with E85 goes up from 0% to 58%. However, as the FFV fleet size is quite small ($\alpha = 0.0864$), even at the subsidy level of $1.00$, only 5% of all drivers would choose to refuel with E85. We show that the introduction of E85 has little effect on E10 prices and the effect is different in duopoly and in monopoly. In duopoly, price of E10 at the same location with E85 is slightly higher than that at the other location, whereas in monopoly it reverses. This result may serve as an indicator of monopoly power. Both in duopoly and monopoly, introduction of one E85 station reduces E10 demand at the same location more than E10 demand at the other station.
References


Supplementary Appendix for
“Pass-through of the policy-induced E85 subsidy: Insights from Hotelling’s model”

Jinjing Luo and GianCarlo Moschini
Iowa State University

NOT for Publication – to be made available ONLINE

This version: July 30, 2019

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Appendix C -- Effects of the subsidy on equilibrium (all models)
Appendix D -- Effects of other parameters on equilibrium (duopoly model with one E85 station)
Appendix A. Demand configurations in the market with one E85 station and two E85 stations

In this appendix, we discuss in detail the different cases in each model—duopoly model with one E85 station, duopoly model with two E85 stations, monopoly model with one E85 station, and monopoly model with two E85 stations. As mentioned in the main text, in addition to the scenario of no E85 consumption and all FFV drivers refueling with E85, there are five possible demand configurations (“cases”) in the market with one E85 station, and three possible cases in the market with two E85 stations, regardless of whether we have duopoly or monopoly. An alternative scenario for case 3 in the duopoly model with one E85 station, case 3a as shown in Figure A3a below, arises under different parameter conditions (we call it case “3a” because, taking other parameters as given, either case 3 or case 3a will materialize with the increase in the subsidy). In part A1, we discuss the different cases that pertain to the market with one E85 station; in part A2, we discuss the different cases for the market with two E85 stations. Specifically, we describe the conditions under which each case arises, provide a diagrammatic illustration, and construct the corresponding demand systems. Although the markets under duopoly or monopoly share the same possible case configurations, the parametric conditions required for each case are different. The critical values of the subsidy $s$ at which we have transition between cases are also reported in each section. Before getting into these details, however, in Table A1 we first summarize the threshold levels of drivers’ characteristics (type and location) that are used to define the various cases and to derive the corresponding demand systems.
Table A1. Summary of threshold levels (drivers’ type and location) for FFV drivers

<table>
<thead>
<tr>
<th>FFV driver</th>
<th>Defined by</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{x}$</td>
<td>$U_A^0 = U_A^1$</td>
<td>$\frac{1}{2} + \frac{1}{2t}(p_A^1 - p_A^0)$</td>
</tr>
<tr>
<td>$\bar{x}^0$</td>
<td>$U_A^0 = U_B^0 \mid_{\theta = \bar{\theta}}$</td>
<td>$p_A^0 - \lambda p_B^0 + \bar{\theta}$</td>
</tr>
<tr>
<td>$\bar{x}^1$</td>
<td>$U_A^0 = U_B^1 \mid_{\theta = \bar{\theta}}$</td>
<td>$p_A^1 - \lambda p_B^0 + \bar{\theta} + \frac{t}{(\lambda + 1)}$</td>
</tr>
<tr>
<td>$\tilde{x}^0$</td>
<td>$U_A^0 = U_B^0 \mid_{\theta = \tilde{\theta}}$</td>
<td>$p_A^0 - \lambda p_B^0 + \tilde{\theta}$</td>
</tr>
<tr>
<td>$\tilde{x}^1$</td>
<td>$U_A^0 = U_B^1 \mid_{\theta = \tilde{\theta}}$</td>
<td>$p_A^1 - \lambda p_B^0 + \tilde{\theta} + \frac{t}{(\lambda + 1)}$</td>
</tr>
<tr>
<td>$\bar{\theta}^0$</td>
<td>$U_A^0 = U_B^0 \mid_{x = 0}$</td>
<td>$\lambda p_B^0 - p_A^0$</td>
</tr>
<tr>
<td>$\bar{\alpha}$</td>
<td>$U_A^0 = U_B^0 \mid_{x = \bar{x}}$</td>
<td>$\frac{1}{2} + \frac{1}{2t}(p_B^1 - p_B^0)$</td>
</tr>
<tr>
<td>$\bar{\theta}^A$</td>
<td>$U_A^1 = U_B^1 \mid_{x = \bar{x}}$</td>
<td>$1 - \frac{1}{2}(p_A^1 + t) - \frac{\lambda + 1}{2} p_A^0 + \lambda p_B^0$</td>
</tr>
<tr>
<td>$\bar{\theta}^B$</td>
<td>$U_A^0 = U_B^0 \mid_{x = \bar{x}}$</td>
<td>$1 - \frac{1}{2}(p_B^1 + t) - \frac{\lambda + 1}{2} p_A^0 + \lambda p_B^0$</td>
</tr>
<tr>
<td>$\tilde{\theta}^1$</td>
<td>$U_A^0 = U_B^1 \mid_{x = 1}$</td>
<td>$\lambda p_B^0 - p_A^1 + \lambda t$</td>
</tr>
<tr>
<td>$\tilde{\theta}^1$</td>
<td>$U_A^1 = U_B^1 \mid_{x = 1}$</td>
<td>$\lambda p_B^0 - p_A^1$</td>
</tr>
</tbody>
</table>

A1. Possible demand configurations in the market with one E85 station

In this market, normal car drivers can refuel with E10 at either L0 or L1 depending on their location and the relative retail prices of E10 at two gas stations. FFV drivers can either refuel with E10 at both locations, or E85 at L0. Their choice of fuel type and gas station relates to their type $\theta$, location $x$, and location $\bar{x}$. 
and the retail prices of all fuels. The key differences among all cases relate to whether \( \tilde{\theta}^0 \in (\theta, \bar{\theta}) \), 
\( \tilde{\theta} \in (\theta, \bar{\theta}) \), and \( \tilde{\theta}^1 \in (\theta, \bar{\theta}) \). Here, \( \tilde{\theta}^0 \) is the type of the consumer at \( x = 0 \) who is indifferent
between choosing E10 and E85 at L0; \( \tilde{\theta} \) is the type of the consumer at \( x = \bar{x} \) who is indifferent
between choosing E10 and E85 at L0; \( \tilde{\theta}^1 \) is the type of the consumer at \( x = 1 \) who is indifferent
between choosing E10 at L1 and E85 at L0. See Table A1 for the relevant expressions.

When \( p_{B}^0 \) is relatively high compared to \( p_{A}^0 \) and \( p_{A}^1 \), no FFV drivers in the market refuels with E85.

As the price \( p_{B}^0 \) goes down, at first only high type FFV drivers with low convenience cost of refueling
choose to refuel with E85. This is Case 1, which is illustrated in Figure A1. The parametric conditions
for case 1 are \( \theta < \tilde{\theta}^0 < \bar{\theta} \) and \( \tilde{\theta} > \bar{\theta} \). These conditions imply no direct competition between E85 at
L0 and E10 at L1, and that E85 only substitutes E10 demand at the same location.

Figure A1. FFV drivers’ demands in the one E85 station model (“case 1”)

As noted in the text, we assume that FFV drivers are independently and uniformly distributed in the
\((\theta, x)\) space. In Case 1, only FFV drivers at the top left corner of Figure 1 choose to refuel with E85.
Other than this corner area, FFV drivers located at the left of \( \bar{x} \) would choose to refuel with E10 at
L0; FFV at the right of $\bar{x}$ choose to refuel with E10 at L1. The demand for E85 is the aggregate demand over all FFV drivers. The demands for E10 at L0 and L1 are the aggregate demands of relevant FFV drivers and normal car drivers respectively. The demand system is shown as following.

$$d^0_A = (1 - \alpha)\bar{x} + \alpha \left[ (\bar{x} - \bar{x}^0) + \bar{x}^0 \frac{\bar{\theta} - \bar{\theta}^0 - 2\theta}{2(\bar{\theta} - \theta)} \right]$$

$$d^0_B = \lambda\alpha\bar{x}^0 \frac{\bar{\theta} - \bar{\theta}^0}{2(\bar{\theta} - \theta)}$$

$$d^1_A = (1 - \alpha)(1 - \bar{x})$$

When the price $p^0_B$ further decreases, FFV drivers with lower preferences of E85 and further location may choose E85. This is Case 2, the case in the main text. This case differs from Case 1 because FFV drivers on the left of $\bar{x}$ may also refuel with E85 at L0 if they have high preferences for E85. The parametric conditions for case 2 are $\bar{\theta}^0 > \theta$, $\bar{\theta} < \bar{\theta}$, and $\bar{\theta}^0 > \bar{\theta}$. Case 2 is illustrated in Figure A2, which is exactly the same with Figure 2 in the text. The demand system is discussed in detail in the main text (section 3.3).

![Figure A2. FFV drivers' demands in the one E85 station model (“case 2”)](image)
When \( p^0_B \) is substantial lower than \( p^1_A \), \( \overline{x}^1 \) exceeds 1, which leads to case 3 shown in Figure A3. The parametric conditions for case 3 are \( \overline{\theta}^0 > \overline{\theta} \) and \( \overline{\theta}^1 < \overline{\theta} \). We do not need the constraint on \( \overline{\theta} \) because \( \overline{\theta}^0 < \overline{\theta} < \overline{\theta}^1 \) by definition. The demand system for this case is,

\[
d^0_A = (1 - \alpha) \bar{x} + \alpha \bar{x} \left( \bar{\theta} + \bar{\theta}^0 - 2 \bar{\theta} \right) / 2(\bar{\theta} - \bar{\theta})
\]

\[
d^0_B = \lambda \alpha \left[ \bar{x} \frac{2\bar{\theta} - \bar{\theta} - \bar{\theta}^0}{2(\bar{\theta} - \bar{\theta})} + (1 - \bar{x}) \frac{2\bar{\theta} - \bar{\theta} - \bar{\theta}^1}{2(\bar{\theta} - \bar{\theta})} \right]
\]

\[
d^1_A = (1 - \alpha)(1 - \bar{x}) + \alpha \left[ (1 - \bar{x}) \frac{\bar{\theta} + \bar{\theta}^1 - 2\bar{\theta}^1}{2(\bar{\theta} - \bar{\theta})} \right]
\]

Figure A3. FFV drivers’ demands in the one E85 station model (“case 3”)

When \( p^0_A \) is low enough compared to \( p^1_A \), \( \bar{\theta}^0 \) may reach \( \bar{\theta} \) before \( \overline{x}^1 \) reaches 1, which means that all FFV drivers near L0 refuel with E85. The parametric conditions are \( \bar{\theta}^0 < \bar{\theta} \), \( \bar{\theta}^0 < \bar{\theta} < \bar{\theta}^1 \), and \( \bar{\theta}^1 > \bar{\theta} \). This is shown as case 3a in Figure A3a. We label this case “3a” to emphasize its relationship with case 3—as the subsidy level changes, either case 3 or case 3a can arise (at the baseline values of other parameters, only case 3 can materialize). However, we will show in Table D1 in Appendix D that
when \( \theta \) and \( \bar{\theta} \) move away from their baseline values, case 3a may replace case 3. The demand system for case 3a is

\[
d_A^0 = (1 - \alpha) \bar{x} + \alpha (\bar{x} - x^0) \frac{\bar{\theta} - \theta}{2(\bar{\theta} - \theta)} \\
d_B^0 = \lambda \alpha \left[ x^0 + (\bar{x} - x^0) \frac{2\bar{\theta} - \bar{\theta} - \theta}{2(\bar{\theta} - \theta)} + (x^1 - \bar{x}) \frac{\bar{\theta} - \bar{\theta}}{2(\bar{\theta} - \theta)} \right] \\
d_A^1 = (1 - \alpha)(1 - \bar{x}) + \alpha \left[ 1 - x^1 + (x^1 - \bar{x}) \frac{\bar{\theta} + \bar{\theta} - 2\bar{\theta}}{2(\bar{\theta} - \theta)} \right]
\]

Figure A3a. FFV drivers’ demands in the one E85 station model ("case 3a")

When \( p_B^0 \) further decreases, more FFV drivers choose to refuel with E85. This leads to Case 4, which has both \( x^1 > 1 \) and \( \bar{\theta}^0 < \bar{\theta} \), and the parametric conditions are \( \bar{\theta}^0 < \theta, \bar{\theta} > \theta \), and \( \bar{\theta}^1 < \bar{\theta} \). In Case 4, FFV drivers at L1 refuel with E85 if they have high \( \theta \) preferences. This case is illustrated in Figure A4. The demand system for this case is:
\[
\begin{align*}
    d^0_{\Lambda} &= (1 - \alpha) \bar{x} + \alpha \left(\bar{x} - x^0\right) \frac{\bar{\theta} - \theta}{2(\bar{\theta} - \theta)} \\
    d^0_{\beta} &= \lambda \alpha \left[ x^0 + \left(\bar{x} - x^0\right) \frac{2\bar{\theta} - \bar{\theta} - \theta}{2(\bar{\theta} - \theta)} + \left(1 - \bar{x}\right) \frac{2\bar{\theta} - \bar{\theta} - \theta^1}{2(\bar{\theta} - \theta)}\right] \\
    d^1_{\Lambda} &= (1 - \alpha)(1 - \bar{x}) + \alpha \left(1 - \bar{x}\right) \frac{\theta^1 + \bar{\theta} - 2\theta}{2(\bar{\theta} - \theta)}
\end{align*}
\]

Figure A4. FFV drivers’ demands in the one E85 station model (“case 4”)

With even lower price of E85, only FFV drivers who locate far away from L0 and have low enough preferences for E85 refuel with E10. This is Case 5, illustrated in Figure A5. The difference between case 5 and case 4 is that now all FFV drivers on the left of \( \bar{x} \) choose to refuel with E85, even with the lowest type \( \theta \). Accordingly, the parametric conditions that pertain to this case are \( \bar{\theta} < \theta \) and \( \theta < \theta^1 < \bar{\theta} \). The demand system for this case is:

\[
\begin{align*}
    d^0_{\Lambda} &= (1 - \alpha) \bar{x} \\
    d^0_{\beta} &= \lambda \alpha \left[ x^1 + \left(1 - x^1\right) \frac{2\bar{\theta} - \bar{\theta} - \theta^1}{2(\bar{\theta} - \theta)}\right] \\
    d^1_{\Lambda} &= (1 - \alpha)(1 - \bar{x}) + \alpha \left(1 - \bar{x}\right) \frac{\theta^1 - \theta}{2(\bar{\theta} - \theta)}
\end{align*}
\]
Eventually, when the retail price of E85 is low enough, relative to those of E10 at two locations, all FFV drivers in the market choose to refuel with E85. Under different combinations of parameters, either there is no E85 consumption in the market, or the demand for each fuel meets one of the above scenarios, or all FFV drivers in the market choose E85. In our model, all retail prices are endogenous determined. With the increase in subsidy $s$ and decrease in E85 retail price, we would expect market equilibria to move from no E85 consumption, to case 1, to case 2, to either case 3 or case 3a, to case 4, to case 5, and then to the case where every FFV driver chooses E85. The critical values of the subsidy $s$ that correspond to the transition between cases are reported in Table A2 (separately for the duopoly and monopoly market structures).
Table A2. Critical values of the subsidy level in the market with one E85 station

<table>
<thead>
<tr>
<th>Case</th>
<th>Condition</th>
<th>Duopoly s</th>
<th>Monopoly s</th>
</tr>
</thead>
<tbody>
<tr>
<td>No E85</td>
<td>$\tilde{\theta}^0 \geq \bar{\theta}$</td>
<td>0.1089</td>
<td>0.1089</td>
</tr>
<tr>
<td>Case 1</td>
<td>$\theta &lt; \tilde{\theta}^0 &lt; \bar{\theta}$, $\tilde{\theta} &gt; \bar{\theta}$</td>
<td>0.1569</td>
<td>0.1569</td>
</tr>
<tr>
<td>Case 2</td>
<td>$\tilde{\theta}^0 &gt; \theta$, $\tilde{\theta} &lt; \bar{\theta}$, $\tilde{\theta}^1 &gt; \bar{\theta}$</td>
<td>0.5265</td>
<td>0.6518</td>
</tr>
<tr>
<td>Case 3</td>
<td>$\tilde{\theta}^0 &gt; \theta$, $\tilde{\theta}^1 &gt; \bar{\theta}$</td>
<td>1.4735</td>
<td>1.6141</td>
</tr>
<tr>
<td>Case 4</td>
<td>$\tilde{\theta}^0 &gt; \theta$, $\tilde{\theta}^1 &lt; \bar{\theta}$</td>
<td>2.1343</td>
<td>2.4968</td>
</tr>
<tr>
<td>Case 5</td>
<td>$\tilde{\theta} &lt; \bar{\theta}$, $\theta &lt; \tilde{\theta}^1 &lt; \bar{\theta}$</td>
<td>&gt;10</td>
<td>&gt;10</td>
</tr>
<tr>
<td>All E85</td>
<td>$\tilde{\theta}^1 &lt; \bar{\theta}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A2. Possible demand configurations in the market with two E85 stations

When there are two E85 stations, no matter whether in duopoly or monopoly, the demand configurations are different. When the prices of E85 are relative high compared to E10 prices, we have case 1 for the market of two E85 stations, which is illustrated in Figure A6. Unlike the foregoing case 1 in part A1, FFV drivers with high preferences for E85 close to both stations refuel with E85. In Figure A6, $\bar{x}^0$ is the location of the FFV driver with type $\bar{\theta}$ who is indifferent between choosing E10 or E85 at $L_0$ as in Figure A1. The threshold $\tilde{\theta}^1_1$ is newly introduced for the market with two E85 stations, and it indicates the type of FFV driver located at $x = 1$ who is indifferent between E10 and E85 at $L_1$. As noted in the main text, we assume $\bar{x}_A \geq \bar{x}_B$, implying $p^1_A - p^0_A \geq p^1_B - p^0_B$. The parametric conditions for case 1 are $\theta < \tilde{\theta}^0 < \bar{\theta}$ and $\tilde{\theta}_B > \bar{\theta}$. We do not need the restriction on $\tilde{\theta}_1^1$ and $\tilde{\theta}_A$ because in equilibrium $\tilde{\theta}^1_1 = \tilde{\theta}^0$ and $\tilde{\theta}_A = \tilde{\theta}_B$. The demand system for this case is
\[d^0_A = (1 - \alpha) \tilde{x}_A + \alpha \left( \tilde{x}_A - \tilde{x}^0 \right) + \tilde{x}^0 \frac{\bar{\theta} + \bar{\theta}^0 - 2\theta}{2(\bar{\theta} - \theta)}\]

\[d^0_B = \lambda \alpha \tilde{x}^0 \frac{\bar{\theta} - \bar{\theta}^0}{2(\bar{\theta} - \theta)}\]

\[d^1_A = (1 - \alpha)(1 - \tilde{x}_A) + \alpha \left( \tilde{x}_A^1 - \tilde{x}_A \right) + \left( 1 - \tilde{x}_A^1 \right) \frac{\bar{\theta} + \bar{\theta}^1 - 2\theta}{2(\bar{\theta} - \theta)}\]

\[d^1_B = \lambda \alpha \left( 1 - \tilde{x}_A^1 \right) \frac{\bar{\theta} - \bar{\theta}^1}{2(\bar{\theta} - \theta)}\]

Figure A6. FFV drivers’ demands in the two E85 stations model (“case 1”)

When prices of E85 fall, FFV drivers with low \(\theta\) preferences choose to refuel with E85, such that \(\bar{\theta}^0 > \theta\) and \(\bar{\theta}_B < \bar{\theta}\). This is Case 2, the case discussed in the main text (section 3.3) that arises with the baseline parameter values. This case is illustrated in Figure A7, which is exactly the same as Figure 4 in the main text (section 3.3). Section 3.3 also presents the demand system for this case.
When the prices of E85 continuously go down, the market moves to case 3, where $\theta^0 < \theta$ and $\theta < \tilde{\theta}_B < \bar{\theta}$. The scenario is depicted in Figure A8, and is associated with the following demand system:

$$
\begin{align*}
    d_A^0 &= (1 - \alpha) \tilde{x}_A + \alpha \left[ (\tilde{x}_A - \bar{x}_B) \tilde{\theta}_A + \tilde{\theta}_B - \frac{2\theta}{2(\theta - \bar{\theta})} \right] \left( \tilde{x}_B - \bar{x}_0 \right) \frac{\tilde{\theta}_B - \theta}{2(\theta - \bar{\theta})} \\
    d_B^0 &= \lambda \alpha \left[ \bar{x}_0 + (\bar{x}_B - \bar{x}_0) \frac{2\theta - \tilde{\theta}_B - \theta}{2(\theta - \bar{\theta})} \right] \\
    d_A^1 &= (1 - \alpha) (1 - \tilde{x}_A) + \alpha \left[ (\bar{x}_1 - \bar{x}_A) \frac{\tilde{\theta}_A - \theta}{2(\theta - \bar{\theta})} \right] \\
    d_B^1 &= \lambda \alpha \left[ (1 - \bar{x}_1) + (\bar{x}_1 - \bar{x}_A) \frac{2\theta - \tilde{\theta}_A - \theta}{2(\theta - \bar{\theta})} \right] + \left( \tilde{x}_A - \bar{x}_B \right) \frac{2\theta - \tilde{\theta}_A - \tilde{\theta}_B}{2(\theta - \bar{\theta})}
\end{align*}
$$

Figure A7. FFV drivers’ demands in the two E85 stations model (“case 2”)
When prices of E85 are very low compared to E10, all FFV drivers in the market choose to refuel with E85. Because we only sort for symmetric equilibria, we assume the prices differences between the same type of fuel at different locations are negligible compared to the price differences between E10 and E85 in all three cases above. We do not consider the scenario in which E85 price is high in one station but relatively low in another station such that the parametric requirements on $\tilde{\theta}_A$ and $\tilde{\theta}_1^0$ are different from those on $\tilde{\theta}_B$ and $\tilde{\theta}_0^0$ (for example, $\tilde{\theta}_B > \bar{\theta}$ whereas $\tilde{\theta}_A < \bar{\theta}$). The scenario that actually materializes in the market depends on fuel prices, which further depends on parameters. At the baseline values of all other parameters, as we increase the subsidy $s$ from 0, the market moves from no E85 consumption, to case 1, to case 2, to case 3, and then to the situation where all FFV drivers refuel with E85. The critical values of $s$ that correspond to these transitions are listed in Table A3.

**Figure A8. FFV drivers’ demands in the two E85 stations model (“case 3”)**
Table A3. Critical values of the subsidy level in the market with two E85 stations

<table>
<thead>
<tr>
<th>Case</th>
<th>Condition</th>
<th>Duopoly $s$</th>
<th>Monopoly $s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No E85</td>
<td>$\tilde{\theta}^0 &gt; \overline{\theta}$</td>
<td>0.1089</td>
<td>0.1089</td>
</tr>
<tr>
<td>Case 1</td>
<td>$\theta &lt; \tilde{\theta}^0 &lt; \overline{\theta}, \tilde{\theta}_B &gt; \overline{\theta}$</td>
<td>0.1569</td>
<td>0.1569</td>
</tr>
<tr>
<td>Case 2</td>
<td>$\tilde{\theta}^0 &gt; \theta, \tilde{\theta}_B &lt; \overline{\theta}$</td>
<td>0.9581</td>
<td>1.693</td>
</tr>
<tr>
<td>Case 3</td>
<td>$\tilde{\theta}^0 &lt; \theta, \theta &lt; \tilde{\theta}_B &lt; \overline{\theta}$</td>
<td>1.0049</td>
<td>&gt;10</td>
</tr>
<tr>
<td>All E85</td>
<td>$\tilde{\theta}_B &lt; \overline{\theta}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix B. Pass-through of the subsidy to equilibrium prices

In the duopoly model with one E85 station, the profits of gas stations at L0 and L1 are,

\[ \pi^0 = (p_A^0 - c_A)d_A^0 + (p_B^0 - c_B)d_B^0 \]
\[ \pi^1 = (p_A^1 - c_A)d_A^1 \]

The gas station at L0 maximizes its profit with respect to \( p_A^0 \) and \( p_B^0 \), while the gas station at L1 maximizes its profit with respect to \( p_A^1 \). Their best response functions can be derived from,

\[
\frac{\partial \pi^0}{\partial p_A^0}(p_A^0, p_B^0, p_A^1 | s) = 0 \\
\frac{\partial \pi^0}{\partial p_B^0}(p_A^0, p_B^0, p_A^1 | s) = 0 \\
\frac{\partial \pi^1}{\partial p_A^1}(p_A^0, p_B^0, p_A^1 | s) = 0
\]

Recall that the subsidy level \( s \) affects the equilibrium prices through \( c_B \), the cost of E85. Equilibrium prices are functions of the subsidy \( s \), \( p_A^0(s) \), \( p_A^1(s) \), and \( p_B^0(s) \). Because we do not have closed-form solutions for these equilibrium prices, they are simulated using Matlab at different values of the subsidy while holding other parameters at their baseline. The pass-through rates of \( s \) to equilibrium prices, \( p_A^0 \), \( p_B^0 \), and \( p_A^1 \), are determined by comparative statics.

\[
\begin{align*}
\frac{\partial^2 \pi^0}{\partial p_A^0 \partial p_A^0} + \frac{\partial^2 \pi^0}{\partial p_B^0 \partial p_A^0} + \frac{\partial^2 \pi^0}{\partial p_B^0 \partial p_A^0} + \frac{\partial^2 \pi^0}{\partial p_A^0 \partial c_B} + \frac{\partial^2 \pi^0}{\partial p_A^0 \partial c_B} & = 0 \\
\frac{\partial^2 \pi^0}{\partial p_A^0 \partial p_A^0} + \frac{\partial^2 \pi^0}{\partial p_B^0 \partial p_A^0} + \frac{\partial^2 \pi^0}{\partial p_B^0 \partial p_A^0} + \frac{\partial^2 \pi^0}{\partial p_B^0 \partial c_B} + \frac{\partial^2 \pi^0}{\partial p_B^0 \partial c_B} & = 0 \\
\frac{\partial^2 \pi^1}{\partial p_A^1 \partial p_A^1} + \frac{\partial^2 \pi^1}{\partial p_B^1 \partial p_A^1} + \frac{\partial^2 \pi^1}{\partial p_B^1 \partial p_A^1} + \frac{\partial^2 \pi^1}{\partial p_B^1 \partial c_B} + \frac{\partial^2 \pi^1}{\partial p_B^1 \partial c_B} & = 0
\end{align*}
\]

In this system of equations, the variables to be solved for are \( \frac{\partial p_A^0}{\partial s} \), \( \frac{\partial p_B^0}{\partial s} \), and \( \frac{\partial p_A^1}{\partial s} \). The coefficients are all the second-order derivatives evaluated at equilibrium prices, whose values are further determined by the subsidy \( s \). This system of equations is solved in Matlab using `vpasolve`. 
The pass-through rate of interest, defined as $\partial (p_A - p_B) / \partial s$, is 0.5$\left( \partial p_A^0 / \partial s + \partial p_A^1 / \partial s \right) - \partial p_B^0 / \partial s$.

Pass-through rates for the other models—duopoly with two E85 station, monopoly with one E85 station, and monopoly with two E85 stations—are derived in the say way: first, best response functions are constructed under profit-maximizing conditions; then, pass-through rates are calculated by comparative statics assuming exogenous parameters other than the cost of E85. In models with two E85 stations, $\partial (p_A - p_B) / \partial s$ is directly $\partial (p_A^0 - p_B^0) / \partial s$ because in equilibrium $\partial p_A^0 / \partial s = \partial p_A^1 / \partial s$ and $\partial p_B^0 / \partial s = \partial p_B^1 / \partial s$. 
Appendix C. Effects of the subsidy on equilibrium (all models)

In this appendix, we complete the analysis of comparative statics effects of the subsidy on equilibrium in all models. We first provide Figure C1 which shows how pass-through rates evolve with the subsidy level in all models. We then supplement Figure 6 of section 5.2 by Table C1 with equilibrium results at representative values of the subsidy. We also provide effects of the subsidy on equilibrium in the other models—duopoly with two E85 stations, monopoly with one E85 station, and monopoly with two E85 stations. For each model, we provide diagrams (Figure C2, Figure C3, and Figure C4) illustrating the effects on prices, demands, and pass-through rates, along with tables (Table C2, Table C3, and Table C4) of equilibrium solutions at various representative values of the subsidy.

Panels (1) and (3) in Figure C1 correspond to Figure 5 and Figure 7 in the main text, respectively. The two panels on the right in Figure C1 are their counterparts for the models with two E85 stations. It is clear that case 1 results in the same pass-through rate in all models. When \( s > 0.1569 \) (kink point of case 1 and case 2 in all models), the pass-through rate in panel (2) of Figure C1 jumps to 0.87 and then increases toward 1. Another discontinuity instance in panel (2) of Figure C1 arises at \( s = 0.9581 \), when the demand configuration changes from case 2 to case 3 (Figure A7 and A8, respectively). The pass-through rate increases and jumps back to one at \( s = 1.0049 \). In panel (4) of Figure C1, for the monopoly model with two E85 stations, the pass-through rate jumps down to about 0.5 for \( s > 0.1569 \) and falls further toward zero for \( s > 1.6930 \). By comparing all panels in Figure C1, we observe that, except for panel (2) that corresponds to the duopoly model with two E85 stations, pass-through rates in all other models decrease toward zero as the subsidy level increases.
Figure C1. Pass-through rates and the E85 subsidy in all models

In the tables below, the first row indicates the “case” experienced by the market under the value of the subsidy level shown in the second row. Case “No E85” means that there is no E85 consumption with the parameters associated with this scenario (see Appendix A for a discussion of all the cases). For all figures, we have consider a wider range for the subsidy $s$, from zero to 1.8. In the tables, however, we report the results for subsidy levels of 0, 0.1, 0.15, 0.2, 0.4, 0.5143 (the baseline), 0.6, 0.8, and 1.
Table C1. Effect of the E85 subsidy in the duopoly model with one E85 station

<table>
<thead>
<tr>
<th>Case</th>
<th>No E85</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>0</td>
<td>0.1</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>$p_A^0$</td>
<td>2.3621</td>
<td>2.3621</td>
<td>2.3621</td>
<td>2.3622</td>
</tr>
<tr>
<td>$p_A^1$</td>
<td>2.3621</td>
<td>2.3621</td>
<td>2.3621</td>
<td>2.3622</td>
</tr>
<tr>
<td>$p_B^0$</td>
<td>2.1986</td>
<td>2.0986</td>
<td>2.0623</td>
<td>2.0189</td>
</tr>
<tr>
<td>$d_A^0$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4994</td>
<td>0.4970</td>
</tr>
<tr>
<td>$d_A^1$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4999</td>
</tr>
<tr>
<td>$d_B^0$</td>
<td>0</td>
<td>0</td>
<td>0.0008</td>
<td>0.0039</td>
</tr>
<tr>
<td>$\partial p_A^0 / \partial S$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0029</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
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<td>0.16</td>
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<td>0.16</td>
<td>0.16</td>
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Table C2. Effect of the E85 subsidy in the duopoly model with two E85 stations

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<th>Case</th>
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<td></td>
<td></td>
</tr>
<tr>
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<td>2.3621</td>
<td>2.3621</td>
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<td>2.3632</td>
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Figure C2. Simulated equilibrium results of the duopoly model with two E85 stations
Table C3. Effect of the E85 subsidy in the monopoly model with one E85 station

<table>
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<td>$p_A^0$</td>
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<td>2.3621</td>
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<td>1</td>
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<td>0.5317</td>
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Figure C3. Simulated equilibrium results of the monopoly model with one E85 station
Table C4. Effect of the E85 subsidy in the monopoly model with two E85 stations

<table>
<thead>
<tr>
<th>Case</th>
<th>s</th>
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<th>0.15</th>
<th>0.2</th>
<th>0.4</th>
<th>0.5143</th>
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<td>2.3621</td>
<td>2.3621</td>
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<td>0.6667</td>
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<td>0.5</td>
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<tr>
<td>\hat{\pi}</td>
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<td>0.3276</td>
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<td>0.3458</td>
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Figure C4. Simulated equilibrium results of the monopoly model with two E85 stations
Appendix D. Effects of other parameters on equilibrium (duopoly model with one E85 station)

In a stylized model, our results depend on the calibrated parameters—the subsidy $s$, marginal costs of each fuel, FFV fraction size $\alpha$, consumers’ reservation utility $u$, Hotelling’s travel cost $t$, the preference upper bound $\theta$, and lower bound $\bar{\theta}$. In this appendix, we evaluate how other parameters (beyond the E85 subsidy) affect equilibrium, and thus investigate the sensitivity of our model results. Specifically, we run the model at various representative values of FFV fraction size, Hotelling’s travel cost, high type preference, and low type preference.

As stated in section 4, the calibration of preference bounds $\theta$ and $\bar{\theta}$ relies on some model feature and previous literature, specifically Pouliot, Liao, and Babcock (2018)’s estimates of WTP for E85. To get an idea of what the equilibrium would be at higher or lower consumer preferences for E85, we simulate our results under different values of $\theta$ and $\bar{\theta}$ in the duopoly model with one E85 station.

In Table D1, we let $\theta$ change from $-1.5$ to $-0.1$ (with other parameters held at their baseline values). The value $\theta = -1.5$, which is more than half of the fuel price in absolute value, means that the driver strongly dislike E85. At $\theta = -0.1$, only a small fraction of FFV drivers has negative preferences for E85. In Table D2, we let $\bar{\theta}$ vary from 0.01 to 2 (with other parameters held at their baseline values). In the first row of Table D1 and D2, “2” means case 2, “3” means case 3, and “3a” means case 3a, and these are all cases in the model with one E85 station (see Appendix A1). As shown in these tables, we find that $\theta$ has little effect on the equilibrium, although it may affect which case (demand configuration) arises. On the other hand, $\bar{\theta}$ does have significant effects on equilibrium. With an increase in $\bar{\theta}$, the equilibrium prices of E10 barely change but equilibrium price of E85 goes up significantly, which is consistent with the decrease in the pass-through rate. Similar to the lower bound parameter, changing the upper bound parameter also affects which case may materialize, and which demand system matters.

Table D3 reports the equilibrium results at different fractions of FFVs. As $\alpha$ increases from 0.01 to one, equilibrium prices and the pass-through rate of the subsidy to the price spread barely change, whereas E85 demand goes up proportionally, along with a decrease in both E10 demands. The equilibrium results under the travel cost are reported in Table D4, where we allow its representative values to vary from 0.01 to one. All prices go up with $t$ as expected (recall in the basic Hotelling model, this parameter decides the price margin), so does the price difference between E10 and E85.
Consistently, the pass-through rate goes up—with higher $t$, the market is more differentiated, which indicates less competition between two gas stations, which is further associated with more competition between E10 and E85 at the same location. The E85 demand, interestingly, first goes up and then goes down, with a peak at the baseline value of $t$.

Table D1. Effect of low type preference in the duopoly model with one E85 station

<table>
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<tr>
<th>Case ( \theta )</th>
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<th>0.25</th>
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<td>2.3624</td>
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<td>2.3612</td>
<td>2.3609</td>
<td>2.3606</td>
<td>2.3600</td>
</tr>
<tr>
<td>( p_B^0 )</td>
<td>1.7772</td>
<td>1.7772</td>
<td>1.7772</td>
<td>1.7771</td>
</tr>
<tr>
<td>( d_A^0 )</td>
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<tr>
<td>( d_A^1 )</td>
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<td>0.4959</td>
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</tr>
<tr>
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<td>0.0234</td>
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<tr>
<td>( \hat{p}_A^0 )</td>
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<td>-0.0005</td>
<td>-0.0006</td>
<td>-0.0008</td>
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<tr>
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<tr>
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Table D2. Effect of high type preference in the duopoly model with one E85 station

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<tr>
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Table D3. Effect of the fraction of FFVs in the duopoly model with one E85 station

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Table D4. Effect of travel cost in the duopoly model with one E85 station

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<tr>
<td>( p_A^0 )</td>
<td>2.0522</td>
<td>2.1432</td>
<td>2.1934</td>
<td>2.3627</td>
</tr>
<tr>
<td>( p_A^1 )</td>
<td>2.0522</td>
<td>2.1424</td>
<td>2.1923</td>
<td>2.3606</td>
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<tr>
<td>( p_B^0 )</td>
<td>1.6355</td>
<td>1.6763</td>
<td>1.6988</td>
<td>1.7772</td>
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<tr>
<td>( d_A^0 )</td>
<td>0.4853</td>
<td>0.4839</td>
<td>0.4831</td>
<td>0.4807</td>
</tr>
<tr>
<td>( d_A^1 )</td>
<td>0.4928</td>
<td>0.4937</td>
<td>0.4942</td>
<td>0.4959</td>
</tr>
<tr>
<td>( d_B^0 )</td>
<td>0.0274</td>
<td>0.0281</td>
<td>0.0284</td>
<td>0.0292</td>
</tr>
<tr>
<td>( \frac{\partial p_A^0}{\partial s} )</td>
<td>0.0004</td>
<td>0.0037</td>
<td>0.0055</td>
<td>-0.0006</td>
</tr>
<tr>
<td>( \frac{\partial p_B^0}{\partial s} )</td>
<td>-0.4999</td>
<td>-0.4985</td>
<td>-0.4978</td>
<td>-0.7247</td>
</tr>
<tr>
<td>( \frac{\partial p_A^1}{\partial s} )</td>
<td>0.0002</td>
<td>0.0018</td>
<td>0.0027</td>
<td>-0.0112</td>
</tr>
<tr>
<td>( \frac{\partial (p_A - p_B)}{\partial s} )</td>
<td>0.5001</td>
<td>0.5013</td>
<td>0.5019</td>
<td>0.7188</td>
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<tr>
<td>( \pi_0 )</td>
<td>0.0106</td>
<td>0.0559</td>
<td>0.0808</td>
<td>0.1643</td>
</tr>
<tr>
<td>( \pi_1 )</td>
<td>0.0050</td>
<td>0.0495</td>
<td>0.0742</td>
<td>0.1579</td>
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