Online Appendix for "Economic and Environmental Implications of Ride-Hailing and Vehicle Age Limits for Car Sales Markets"

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A1. Derivations of the Consumer Demand Functions in §3.3

In this section, we present the derivations of the consumer demand functions characterized in §3.3. First, we identify the non-dominated consumer strategies. Note that in every period $t > 0$, a consumer can choose from the following mobility options: (i) buy a new car (N), (ii) keep a used car for a second period of use if a new one was purchased in the previous period (K), (iii) buy a used car from the secondary market (U), (iv) use the ride-hailing service (R), or (v) remain inactive without car usage (I). We next derive the single-period net utility for a consumer with valuation θ, from each of these consumer choices in the current period. Note that these single-period net utilities also depend on the consumer choice in the previous period. For example, consider a consumer who bought a new car (N) in the previous period, and chooses to buy a new car again (N) in the current period: In the current period, the consumer sells off the used car (bought in the previous period) on the secondary market and receives a payment p_u; the consumer also pays the new car price p and obtains the utility from usage $\lambda\theta$. Therefore, the single-period net utility for this consumer will be $\lambda\theta - p + p_u$. For a consumer who bought a new car (N) in the previous period, and chooses to keep the used car (K) in the current period, the single-period net utility in the current period will be $\lambda\delta\theta$. Similarly, for a consumer who bought a new car (N) in the previous period, the single-period net utilities in the current period from using ride-hailing service (R) and remaining inactive without car usage (I), respectively, will be $\lambda\beta(\delta_R(\delta)\theta - f) + p_u$ and p_u (as the consumer first sells off the used car bought in the previous period on the secondary market at p_u in both cases). Following a similar analysis, for a consumer who bought a used car (U) in the previous period, the single-period net utilities in the current period from buying a new car (N), buying a used car (U), using ride-hailing service (R), and remaining inactive without car usage (I), will be $\lambda\theta - p$, $\lambda\delta\theta - p_u$, $\lambda\beta\left(\delta_R(\delta)\theta - f\right)$, and 0, respectively (and keeping a used car (K) is not relevant for the consumer here since no new car was purchased in the previous period). Similarly, it is easy to see that a consumer that kept a used car (K), used ride-hailing (R), or remained inactive (I) in the previous period, will have the same single-period utilities in the current period as a consumer who bought a used car (U) in the previous period as shown above.

Based on these single-period net consumer utilities, we can then identify the non-dominated strategies for consumers. Note that given the two-period useful life of cars, we only need to focus on the two-period consumer strategies at the focal point; an example of such a two-period consumer strategy can be: buy a used car in one period and use ride-hailing in the next period, and then repeat this two-period strategy, over the infinite horizon of our model. To this end, we examine all the possible two-period consumer strategies and eliminate the dominated ones. For example, buying a used car in one period and then using ride-hailing in the next period is dominated: A consumer with valuation θ obtains a utility of $\lambda\delta\theta - p_u$ in the period of buying a used car, and a utility of $\lambda\beta(\delta_R(\delta)\theta - f)$ in the period of using ride-hailing. If $\lambda\delta\theta - p_u > \lambda\beta(\delta_R(\delta)\theta - f)$, then the consumer will gain a higher utility from always buying a used car in every period; otherwise (if $\lambda\delta\theta - p_u \leq \lambda\beta(\delta_R(\delta)\theta - f)$), the consumer will be better off always using ride-hailing in every period. Following a similar argument, we rule out the dominated strategies and identify all the non-dominated strategies to be NN, UU, RR and II, as described in §3.3.

We next construct the expected per-period net utilities from all the non-dominated strategies for a consumer with valuation θ. (i) In every period, a NN consumer sells off the used unit from the new purchase in the previous period and receives the used car price payment p_u, pays p for the new car, and obtains a utility $\lambda\theta$ (which accounts for both the consumer valuation of car usage and the actual per-period usage). Therefore, the expected per-period net utility from the NN strategy is $V_{NN}(\theta) = \lambda\theta - p + p_u$. (ii) A UU consumer pays p_u for the used car, and obtains utility $\lambda\delta\theta$ (which accounts for the consumer valuation of car usage, the actual per-period usage, and the product durability) in every period. Therefore, $V_{UU}(\theta) = \lambda\delta\theta - p_u$. (iii) The utility of using the ride-hailing service is $\delta_R(\delta)\theta - f$, which accounts for the probabilities of getting new or used cars for the consumer rides (with $\delta_R(\delta)$) and the ride-hailing price (f); moreover, the actual usage of the RR consumers is $\lambda\beta$, which accounts for the probabilities of both incurring the mobility needs and being matched with an available driver when needed. Therefore, $V_{RR}(\theta) = \lambda\beta(\delta_R(\delta)\theta - f)$. (iv) It is trivial to see that $V_{II}(\theta) = 0$. These results are summarized in §3.3.

All consumers maximize their utility, by self-selecting into one of the non-dominated strategies identified above, which then divides the market into four segments accordingly. As discussed in the paper, we assume that $\delta > \beta\delta_R(\delta)$, and then have that consumers who choose NN have higher valuations than those who choose UU, who in turn have higher valuations than those who choose RR, and finally, those who choose to remain inactive have the lowest valuations. If we denote the θ that solves $V_{NN}(\theta) = V_{UU}(\theta)$, $V_{UU}(\theta) = V_{RR}(\theta)$, and $V_{RR}(\theta) = V_{II}(\theta)$ by θ_1, θ_2 and θ_3, respectively, we have that consumers with $\theta \in (\theta_1, 1]$ choose NN, consumers with $\theta \in (\theta_2, \theta_1]$ choose UU, consumers with $\theta \in (\theta_3, \theta_2]$ choose RR, and the rest remain inactive, where $0 \leq \theta_3 \leq \theta_2 \leq \theta_1 \leq 1$, $\theta_1 = \frac{p-2p_u}{\lambda-\delta\lambda}$, $\theta_2 = \frac{2\beta f\lambda - 2p_u}{\lambda((\beta-2)\delta+\beta)}$, and $\theta_3 = \frac{2f}{\delta+1}$. Based on these results, we calculate the new car ownership among consumers to be $D_{NN} = 1 - \theta_1 = \frac{p-2p_u}{(\delta-1)\lambda} + 1$, the used car ownership to be $D_{UU} = \theta_1 - \theta_2 = \frac{2(p_u - \beta f \lambda)}{\lambda((\beta-2)\delta+\beta)} + \frac{p-2p_u}{\lambda-\delta\lambda}$, and the ride-hailing demand to be $D_{RR} = \theta_2 - \theta_3 = \frac{4\delta f\lambda - 2(\delta+1)p_u}{(\delta+1)\lambda((\beta-2)\delta+\beta)}$.

We next derive the used car price p_u in the secondary market, which is endogenously determined by the market-clearing condition that balances the total supply and demand of used cars. Specifically, the total demand of used cars comes from the UU consumers, which amounts to D_{UU}; and the total supply of used cars comes from the NN consumers, which amounts to D_{NN}. Meanwhile, the ride-hailing price f is endogenously determined by the market clearing-condition that balances the total supply and demand of consumer rides. Specifically, the total supply can be calculated by αS_S and the total demand is $\lambda\beta D_{RR}$. We solve the market-clearing conditions $D_{NN} = D_{UU}$ and $\lambda\beta D_{RR} = \alpha S_S$, which yields $p_u = \frac{\alpha M\left(\alpha(\delta+1)\rho((\beta-2)\delta+\beta)((\delta-1)\lambda+2p)+\beta\left(\delta^2-1\right)\lambda p\right)+4\beta\delta\lambda(-\delta\lambda+\lambda-2p)}{2\alpha^2(\delta+1)M\rho(2\beta(\delta+1)-3\delta-1)-4\beta(3\delta+1)\lambda}$ and $f = \frac{(\delta+1)(2\beta(\delta-1)\lambda+\alpha Mp(-2\beta(\delta+1)+3\delta+1)+4\beta p)}{4\beta(3\delta+1)\lambda-2\alpha^2(\delta+1)M\rho(2\beta(\delta+1)-3\delta-1)}$. We can then substitute them into the OEM profit, which gives $\Pi_N = \frac{(c-p)(\alpha(\delta+1)M\rho(\lambda(2\alpha(\beta-1)(\delta+1)-\beta(\delta-1)\lambda)+2p(\alpha-\beta\lambda))+\beta\lambda(p(M(-2\alpha(\delta+1)+3\delta\lambda+\lambda)+4)-4(\delta+1)\lambda))}{4\beta(3\delta+1)\lambda^2-2\alpha^2(\delta+1)\lambda M\rho(2\beta(\delta+1)-3\delta-1)}$.

A2. Proofs

Proof of Lemma 1. We solve the constrained profit maximization problem for the OEM: $\max_p \Pi_N$, subject to $p, D_{NN}, S_S \geq 0$. Note that the non-negativity constraints already ensure $p_u, f \geq 0$ as well. To solve this problem, we associate Lagrange multipliers (μ_1, μ_2, μ_3) with all the constraints to form the Lagrangian $L_N = \Pi_N + (\mu_1)(p) + (\mu_2)(D_{NN}) + (\mu_3)(S_S)$. We then apply the Karush-Kuhn-Tucker (KKT) conditions to identify all the candidate solutions, after which we compare all the resulting profits from each of the candidate solutions, along with the parameter conditions under which they are valid (i.e., indeed meeting all the constraints), to rule out the dominated ones. As such, we summarize the final optimal solution below.

Let $\bar{c}_1(\alpha,\beta,\rho,M) = \frac{36\alpha^2 M\rho(5-8\alpha\rho)+3\beta(\alpha\rho(M(12\alpha(12\alpha\rho-\rho-7)+5)-64)+40)}{2(12\alpha\rho-5)\left(24\alpha^2 M\rho+\beta(M(5-12\alpha(\rho+1))+16)\right)}$, and $\bar{c}_2(\alpha,\beta,\rho,M) = \frac{3\left(3\alpha^2(\beta-1)M\rho-2\beta\right)\left(\beta(M(12\alpha(\rho+1)-5)-16)-24\alpha^2 M\rho\right)-3\sqrt{\beta M(1-2\alpha\rho)^2\left(2\beta+3\alpha^2 M\rho\right)\left(3\alpha^2(6\beta-5)M\rho-10\beta\right)\left(\beta(M(12\alpha(\rho+1)-5)-16)-24\alpha^2 M\rho\right)}}{2\left(6\alpha^2 M\rho+\beta(4-3\alpha M)\right)\left(24\alpha^2 M\rho+\beta(M(5-12\alpha(\rho+1))+16)\right)}$,

then $\bar{c}_1(\alpha,\beta,\rho,M) < \bar{c}_2(\alpha,\beta,\rho,M)$ and:

(R0i) When $c \leq \bar{c}_1(\alpha,\beta,\rho,M)$: $p^* = \frac{3\alpha\rho}{24\alpha\rho-10}$, $f^* = \frac{3}{48\alpha\rho-20}$, $D^*_{NN} = \frac{3-6\alpha\rho}{5-12\alpha\rho}$, $D^*_{UU} = \frac{3-6\alpha\rho}{5-12\alpha\rho}$, $D^*_{RR} = 0$;

(R0ii) when $\bar{c}_1(\alpha,\beta,\rho,M) < c < \bar{c}_2(\alpha,\beta,\rho,M)$: $p^* = \frac{12\alpha^2(4c+3)M\rho+\beta(c(-24\alpha M(\rho+1)+10M+32)-3\alpha(12\alpha+1)M\rho+24)}{96\alpha^2 M\rho+\beta(-48\alpha M(\rho+1)+20M+64)}$, $f^* = \frac{3(\beta-8\beta c+\alpha(6\beta-5)cM)}{12\alpha^2(6\beta-5)M\rho-40\beta} + \frac{48\beta-3M(12\alpha(\beta-1)+\beta)}{192\alpha^2 M\rho+8\beta(M(5-12\alpha(\rho+1))+16)}$,

$D^*_{NN} = \frac{1}{4}\left(\frac{2\alpha}{\beta-2\alpha} + \frac{1-8c}{5-6\beta} - \frac{12\beta(\beta-8\beta c+\alpha(6\beta-5)cM)}{(6\beta-5)\left(3\alpha^2(6\beta-5)M\rho-10\beta\right)} + \frac{\beta(16\beta-M(12\alpha(\beta-1)+\beta))}{(2\alpha-\beta)\left(24\alpha^2 M\rho+\beta(M(5-12\alpha(\rho+1))+16)\right)} + 2\right)$,

$D^*_{UU} = \frac{1}{4}\left(\frac{2\alpha}{\beta-2\alpha} + \frac{1-8c}{5-6\beta} - \frac{12\beta(\beta-8\beta c+\alpha(6\beta-5)cM)}{(6\beta-5)\left(3\alpha^2(6\beta-5)M\rho-10\beta\right)} + \frac{\beta(16\beta-M(12\alpha(\beta-1)+\beta))}{(2\alpha-\beta)\left(24\alpha^2 M\rho+\beta(M(5-12\alpha(\rho+1))+16)\right)} + 2\right)$,

$D^*_{RR} = \frac{\alpha M\left(3\alpha\rho+\frac{(10-24\alpha\rho)\left(12\alpha^2(4c+3)M\rho+\beta(c(-24\alpha M(\rho+1)+10M+32)-3\alpha(12\alpha+1)M\rho+24)\right)}{96\alpha^2 M\rho+\beta(-48\alpha M(\rho+1)+20M+64)}\right)}{3\alpha^2(6\beta-5)M\rho-10\beta}$;

(R0iii) when $\bar{c}_2(\alpha,\beta,\rho,M) \leq c < \frac{3\alpha\rho}{2}$: $p^* = \frac{1}{4}(3\alpha\rho+2c)$, $f^* = \frac{3(\beta+\alpha cM)}{8\beta+12\alpha^2 M\rho} + \frac{3}{8}$, $D^*_{NN} = 0$, $D^*_{UU} = 0$, $D^*_{RR} = \frac{\alpha M(3\alpha\rho-2c)}{4\beta+6\alpha^2 M\rho}$;

(R0iv) otherwise (when $c \geq \frac{3\alpha\rho}{2}$): $p^* = 0$, $f^* = 0$. .

As such, $D^*_{RR} = 0$ when $c \leq \bar{c}_1(\alpha,\beta,\rho,M)$. Moreover, assuming $c < \bar{c}_2(\alpha,\beta,\rho,M)$ as mentioned in the problem formulation (in §3.4) allows us to focus on the more interesting case where some consumers purchase new cars in the market.

Moreover, we also derive $\frac{\partial \overline{c}_1(\alpha,\beta,\rho,M)}{\partial \rho} = -\frac{15\alpha}{(5-12\alpha\rho)^2} - \frac{3(12\alpha-5)\alpha\beta M(M(12\alpha(\beta-1)+\beta)-16\beta)}{2\left(24\alpha^2 M\rho+\beta(M(5-12\alpha(\rho+1))+16)\right)^2}$; with $\rho,\alpha,\beta \in [0,1]$, we can then confirm that $\frac{\partial \overline{c}_1(\alpha,\beta,\rho,M)}{\partial \rho} < 0$. Similarly, we can show that $\frac{\partial \overline{c}_1(\alpha,\beta,\rho,M)}{\partial M} = \frac{12(12\alpha-5)\beta^2(2\alpha\rho-1)}{\left(\beta(M(12\alpha(\rho+1)-5)-16)-24\alpha^2 M\rho\right)^2} > 0$.

In the following discussion, we focus on Case(R0ii) where both ride-hailing and new car sales exist in the consumer market in equilibrium (i.e., $D^*_{NN}, D^*_{RR} > 0$). In particular in this case, $\Pi^*_N = \frac{(3\alpha M\rho(\beta+4\alpha(3\beta+4c-3)-8\beta c)+2\beta(c((5-12\alpha)M+16)-12))^2}{32\left(3\alpha^2(6\beta-5)M\rho-10\beta\right)\left(\beta(M(12\alpha(\rho+1)-5)-16)-24\alpha^2 M\rho\right)}$,

$$\Pi^*_P = \frac{\left[\begin{array}{c} 3\alpha\beta M(\rho-1)(128\beta^2(2c+1)+\alpha(6\beta-5)M^2(3\alpha\rho(\beta-4\alpha(-3\beta+4c+3)+8\beta c)+2(12\alpha-5)\beta c)+4\beta M(24\alpha^2\rho \\ (-3\beta+4c+2)+\alpha(6\beta(\rho-4)-48\beta c(\rho+2)+40c+30)+5\beta(4c-1)))(12\alpha^2 M\rho(5(4c+3)-24\alpha(2c+1)\rho) \\ +\beta(2c(12\alpha\rho-5)(M(12\alpha(\rho+1)-5)-16)+3\alpha\rho(M(12\alpha(12\alpha\rho-\rho-7)+5)-64)+120)) \end{array}\right]}{32(10\beta+3\alpha^2(5-6\beta)M\rho)^2(\beta(M(12\alpha(\rho+1)-5)-16)-24\alpha^2 M\rho)^2},$$

$TP^* = \frac{3\alpha M\rho(\beta+4\alpha(3\beta+4c-3)-8\beta c)+2\beta(c((5-12\alpha)M+16)-12)}{24\alpha^2(6\beta-5)M\rho-80\beta}$, and

$$TU^* = \frac{\left[\begin{array}{c} (\eta+1)(c(\beta\lambda(\alpha(\delta-1)M+4)-2\alpha^2(\beta-1)(\delta+1)M\rho)(2\alpha^2(\delta+1)M\rho+\beta\lambda(M(-2\alpha(\delta+1)(\rho+1)+3\delta\lambda+\lambda) \\ +4))+(\delta+1)\lambda(2\alpha^3(\delta+1)M^2\rho^2(2\alpha(\beta^2+((\beta-1)\beta-1)\delta+\beta-1)+\beta\lambda(-\beta(3\delta+5)+5\delta+3))-4\beta^2\lambda^2 \\ (M(-5\alpha\delta-3\alpha+6\delta\lambda+2\lambda)+4)+\alpha\beta\lambda M\rho(\lambda(4\beta(5\delta+3)+\alpha M(\beta(\delta(7\delta+18)+7)-4(\delta+1)(3\delta+1))) \\ -2\alpha(4\beta(\delta-1)+8(\delta+1)+\alpha(\delta+1)M(\beta(3\delta+5)-5\delta-3))))) \end{array}\right]}{2(\alpha^2(\delta+1)M\rho(2\beta(\delta+1)-3\delta-1)-2\beta(3\delta+1)\lambda)(4\alpha^2(\delta+1)M\rho+2\beta\lambda(M(-2\alpha(\delta+1)(\rho+1)+3\delta\lambda+\lambda)+4))}.$$

Proof of Proposition 1. To facilitate the comparison, we first model the "pure-sales" benchmark case, where ride-hailing programs are absent from the market and consumers can only buy (new or used) cars to meet their mobility needs. We solve this case by following a similar analysis approach as in the main model with ride-hailing, to first identify the non-dominated consumer strategies, which include NN, UU, and II (with the same descriptions as in the main model with ride-hailing). We can then characterize the market, which is segmented into the consumers who follow the NN, UU and II strategies, respectively, with $V^{PS}_{NN}(\theta) = \lambda\theta - p^{PS} + p^{PS}_u$, $V^{PS}_{UU}(\theta) = \lambda\delta\theta - p^{PS}_u$, and $V^{PS}_{II}(\theta) = 0$ (where the superscript "PS" is used to indicate values associated with this case). Since $V^{PS}_{NN}(\theta) - V^{PS}_{UU}(\theta)$ and $V^{PS}_{UU}(\theta) - V^{PS}_{II}(\theta)$ are both increasing functions in θ, consumers who optimally choose NN, UU, and II have descending valuation θ. Therefore, there exist θ^{PS}_2 and θ^{PS}_1, with $0 \le \theta^{PS}_2 \le \theta^{PS}_1 \le 1$, such that consumers of types $\theta \in (\theta^{PS}_1, 1], (\theta^{PS}_2, \theta^{PS}_1], [0, \theta^{PS}_2]$ choose the NN, UU, and II strategies, respectively. In particular, θ^{PS}_1 and θ^{PS}_2 can be solved from the utilities of the indifferent consumers, with $V^{PS}_{NN}(\theta^{PS}_1) = V^{PS}_{UU}(\theta^{PS}_1)$ and $V^{PS}_{UU}(\theta^{PS}_2) = V^{PS}_{II}(\theta^{PS}_2)$, respectively. As such, the demand can be calculated by $D^{PS}_{NN} = 1 - \theta^{PS}_1$ and $D^{PS}_{UU} = \theta^{PS}_1 - \theta^{PS}_2$. Meanwhile, the new car price p^{PS} is set by the OEM, and the used car price p^{PS}_u is endogenously determined by the market-clearing condition in the secondary market that balances the total supply (from the NN consumers) and demand (from the UU consumers) of used cars, i.e., $D^{PS}_{NN} = D^{PS}_{UU}$, which yields $p^{PS}_u = \frac{8p-1}{20}$. We can then write the profit function for the OEM as $\Pi^{PS}_N = (p^{PS} - c)D^{PS}_{NN}$. The OEM solves the profit maximization problem $\max_{p^{PS}} \Pi^{PS}_N$, subject to $p^{PS}, D^{PS}_{NN} \ge 0$. As in the main model, we focus on the more interesting case with $c < \frac{3}{4}$ to ensure that some consumers in the market buy new cars (i.e., $D^{PS*}_{NN} > 0$). The market outcome in this case can be characterized below: $p^{PS*} = \frac{3+4c}{8}$, $D^{PS*}_{NN} = \frac{3-4c}{10}$, and $D^{PS*}_{UU} = \frac{3-4c}{10}$; accordingly, $\Pi^{PS*}_N = \frac{1}{80}(3-4c)^2$, $TP^{PS*} = \frac{1}{10}(3-4c)$, and $TU^{PS*} = \frac{1}{20}(3-4c)(\eta+1)$. We can then compare the results of this pure-sales benchmark case to those of the case with ride-hailing in the market (as presented in the Proof of Lemma 1 above).

For the new car price, recall that $p^* = \frac{12\alpha^2(4c+3)M\rho+\beta(c(-24\alpha M(\rho+1)+10M+32)-3\alpha(12\alpha+1)M\rho+24)}{96\alpha^2 M\rho+\beta(-48\alpha M(\rho+1)+20M+64)}$ in the presence of ride-hailing, direct comparison shows that it is always lower than p^{PS*} in the pure-sales benchmark case. Note that all comparisons in this analysis are conducted with the assumption $\delta > \beta\delta_R(\delta)$ as mentioned in §3.3. For the new car ownership, recall that $D_{NN}^{PS*} = \frac{3-4c}{10}$ in the pure-sales benchmark case and $D_{NN}^* = \frac{1}{4}\left(\frac{2\alpha}{\beta-2\alpha} + \frac{1-8c}{5-6\beta} - \frac{12\beta(\beta-8\beta c+\alpha(6\beta-5)cM)}{(6\beta-5)\left(3\alpha^2(6\beta-5)M\rho-10\beta\right)} + \frac{\beta(16\beta-M(12\alpha(\beta-1)+\beta))}{(2\alpha-\beta)\left(24\alpha^2 M\rho+\beta(M(5-12\alpha(\rho+1))+16)\right)} + 2\right)$ in the presence of ride-hailing; let $\Delta D_{NN}^{PS} \doteq D_{NN}^* - D_{NN}^{PS*}$, i.e., ΔD_{NN}^{PS} is the difference in the new car ownership between the cases with and without the presence of ride-hailing in the market. We can first show that ΔD_{NN}^{PS} is a decreasing function in c. Solving $\Delta D_{NN}^{PS} = 0$ yields the solution $c = \bar{c}_{N0}(\alpha,\beta,\rho,M) = \frac{3\alpha^2 M\rho(2\alpha(12\alpha-25)\rho+25)+\beta(\alpha\rho(3\alpha(M(48\alpha\rho-12\alpha-25)+16)-100)+50)}{2\alpha(12\alpha\rho-5)\left(24\alpha^2 M\rho+\beta(M(5-12\alpha(\rho+1))+16)\right)} \in (\bar{c}_1(\cdot),\bar{c}_2(\cdot))$ (recall that we focus on the case with $c \in (\bar{c}_1(\cdot),\bar{c}_2(\cdot))$ such that ride-hailing and new car sales both exist in the market). Therefore, $D_{NN}^* > D_{NN}^{PS*}$ when $c < \bar{c}_{N0}(\cdot)$, and $D_{NN}^* < D_{NN}^{PS*}$ when $c > \bar{c}_{N0}(\cdot)$, as in the proposition.

Proof of Proposition 2. To compare the total new car sales, we calculate the difference in the total new car sales between the cases with and without the presence of ride-hailing $\Delta TP^{PS} \doteq TP^* - TP^{PS*}$, based on the optimal solutions characterized above. We can then first show that ΔTP^{PS} is a decreasing function in c, and solving $\Delta TP^{PS} = 0$ yields the solution $c = \bar{c}_{TP0}(\alpha,\beta,\rho,M) = \frac{3\alpha\rho}{24\alpha\rho-10} \in (\bar{c}_1(\cdot),\bar{c}_2(\cdot))$. Therefore, $TP^* > TP^{PS*}$ when $c < \bar{c}_{TP0}(\cdot)$, and $TP^* < TP^{PS*}$ when $c > \bar{c}_{TP0}(\cdot)$. Moreover, direct comparison between the thresholds shows that $\bar{c}_{TP0}(\cdot) > \bar{c}_{N0}(\cdot)$. To also compare the total environmental impact of car usage, we again compare the cases with and without the presence of ride-hailing by calculating $\Delta TU^{PS} \doteq TU^* - TU^{PS*}$. We can then first show that ΔTU^{PS} is a decreasing function in c, and solving $\Delta TU^{PS} = 0$ yields the solution $c = \bar{c}_{TU0}(\alpha,\beta,\rho,M,\eta) = \frac{18\alpha^2 M\rho\left(104\alpha^2\rho-50\alpha(\rho+1)+25\right)+3\beta(\alpha(\rho(\alpha(M(12\alpha(-60\alpha\rho+29\rho+29)-175)+416)-200)-200)+100)}{2\alpha(12\alpha\rho-5)\left(24\alpha^2 M\rho+\beta(M(5-12\alpha(\rho+1))+16)\right)}$. Therefore, $TU^* > TU^{PS*}$ when $c < \bar{c}_{TU0}(\cdot)$, and $TU^* < TU^{PS*}$ when $c > \bar{c}_{TU0}(\cdot)$. Moreover, direct comparison between the two thresholds shows that $\bar{c}_{TU0}(\cdot) > \bar{c}_{TP0}(\cdot)$.

Proof of Proposition 3. First, we solve the model in the presence of a vehicle age limit, by following a similar solution approach as in the main model above in the absence of the age limit. We can first show that the non-dominated consumer strategies include NN, UU, RR, and II, with $V'_{NN}(\theta)$ and $V'_{UU}(\theta)$ being the same as in the main model, and $V'_{RR}(\theta) = \lambda\beta(\theta - f')$. As mentioned in the paper, we assume $\delta > \beta$ in this analysis, such that consumers who choose the NN, UU, RR, and II always have descending valuations with or without the vehicle age limit. Accordingly, there exist $\theta'_3, \theta'_2, \theta'_1$ with $0 \le \theta'_3 \le \theta'_2 \le \theta'_1 \le 1$, such that consumers with $\theta \in (\theta'_1, 1]$, $\theta \in (\theta'_2, \theta'_1]$, $\theta \in (\theta'_3, \theta'_2]$, and $\theta \in [0, \theta'_3]$ will respectively choose the NN, UU, RR, and II strategies. We solve for θ'_1 from the consumers that are indifferent between choosing the NN and UU strategies i.e., $V_{NN}(\theta'_1) = V_{UU}(\theta'_1)$, to have $\theta'_1 = \frac{p'-2p'_u}{\lambda-\delta\lambda}$; and similarly for θ'_2 and θ'_3. Then we calculate the new car ownership among consumers to be $D'_{NN} = 1 - \theta'_1 = \frac{p' - 2p'_u}{(\delta-1)\lambda} + 1$; and similarly for the used car ownership $D'_{UU} = \theta'_1 - \theta'_2$ and the ride-hailing demand $D'_{RR} = \theta'_2 - \theta'_3$. Meanwhile for the ride-hailing platform, as the average per-period payoff for drivers joining the platform to provide service is given by $V'_S = \rho\alpha f' - (p' - p'_u)$, the total number of drivers providing ride-hailing service is thus given by $S'_S = M\int_0^{V'_S} 1 d\Theta = M(\rho\alpha f' - (p' - p'_u))$. In this case, the used car price p'_u in the secondary market is solved from the market-clearing condition that balances the total supply (from both the NN consumers as well as the ride-hailing drivers when they replace their used cars by new ones) and demand of used cars (from the UU consumers), i.e., $D'_{NN} + S'_S = D'_{UU}$. The OEM profit in this case is given by $\Pi'_N = (D'_{NN} + S'_S)(p' - c)$, as the total new car sales to both consumers and drivers become $TP' = D'_{NN} + S'_S$. The OEM solves $\max_{p'} \Pi'_N$, subject to $p', D'_{NN}, S'_S \geq 0$.

The results are structurally similar to those in the main model; we also focus on the more interesting case where the ride-hailing and new car sales both exist in the consumer market in equilibrium (i.e., $D'^*_{NN}, D'^*_{RR} > 0$), which can be shown to take place when $\overline{c}'_1(\alpha,\beta,\rho,M) < c < \overline{c}'_2(\alpha,\beta,\rho,M)$ with $\overline{c}'_1(\alpha,\beta,\rho,M) = \frac{2\alpha^2 M\rho(11-16\alpha\rho)+\beta(-16\alpha\rho+\alpha M(8\alpha\rho(8\alpha\rho-\rho-5)+2\rho+1)+M+11)}{2(8\alpha\rho-3)\left(4\alpha^2 M\rho+\beta(-2\alpha M(\rho+1)+M+2)\right)}$ and $\overline{c}'_2(\alpha,\beta,\rho,M) =$

$$\frac{\left[\begin{array}{r}\sqrt{\beta M(4\alpha M\rho(2\alpha(8\beta-5)-\beta)-\beta(4\alpha M+M+20))\,(8\alpha^2 M\rho+\beta(4\alpha M(\rho+1)+M+4))\,(\beta(M(2\alpha(\rho+1)-1)-2)-4\alpha^2 M\rho)}\\ \sqrt{2}(1-2\alpha\rho)+(4\alpha M\rho(\alpha(8\beta-6)-\beta)-\beta(4\alpha M+M+12))(\beta(M(2\alpha(\rho+1)-1)-2)-4\alpha^2 M\rho)\end{array}\right]}{4(4\alpha M\rho(2\alpha+\beta)-\beta(4\alpha M+M-4))(4\alpha^2 M\rho+\beta(-2\alpha M(\rho+1)+M+2))}.$$

Moreover, we can also show that $\overline{c}_1(\cdot) \leq \overline{c}'_1(\cdot) < \overline{c}'_2(\cdot) \leq \overline{c}_2(\cdot)$.

At optimality in this case with the vehicle age limit, $p'^* = \frac{2\alpha^2(4c+3)M\rho+\beta(2c(-2\alpha M(\rho+1)+M+2)+\alpha M(1-8\alpha\rho)+3)}{4\left(4\alpha^2 M\rho+\beta(-2\alpha M(\rho+1)+M+2)\right)}$,

$f'^* = \frac{2\beta(\alpha(8c+1)M-c(M+8)+1)-\alpha(12c+1)M}{4\alpha M\rho(2\alpha(8\beta-5)-\beta)-\beta(4\alpha M+M+20)} + \frac{\beta+M(\alpha-\alpha\beta)}{4\alpha^2 M\rho+\beta(-2\alpha M(\rho+1)+M+2)}$,

$$D'^*_{NN} = \frac{\left[\begin{array}{l}16\alpha^4(3-4c)M^2\rho^2-2\alpha^2\beta M\rho(M(8\alpha+4(\alpha(8\alpha+7)\rho-8\alpha c+c)-17)+8(4c-3))+\beta^2(M(-4\alpha((8\alpha+7)\rho+2)\\ \quad +4(8\alpha-1)c+2cM(4\alpha(\rho-1)-1)(2\alpha(\rho+1)-1)+\alpha M(4\alpha(\rho(8\alpha(3\rho+1)-2\rho-15)-1)+2\rho+3)+M+17)-16c+12)\end{array}\right]}{(4\alpha M\rho(2\alpha(8\beta-5)-\beta)-\beta(4\alpha M+M+20))(\beta(M(2\alpha(\rho+1)-1)-2)-4\alpha^2 M\rho)},$$

$D'^*_{UU} = \frac{4\alpha M\rho(\alpha(4\beta+4c-3)-2\beta c)-2\beta(\alpha(4c+1)M-2c(M+2)+3)}{4\alpha M\rho(2\alpha(8\beta-5)-\beta)-\beta(4\alpha M+M+20)}$, $D'^*_{RR} = \frac{2\alpha M\left(4\alpha\rho+\frac{(3-8\alpha\rho)\left(2\alpha^2(4c+3)M\rho+\beta(2c(-2\alpha M(\rho+1)+M+2)+\alpha M(1-8\alpha\rho)+3)\right)}{4\alpha^2 M\rho+\beta(-2\alpha M(\rho+1)+M+2)}+1\right)}{4\alpha M\rho(2\alpha(8\beta-5)-\beta)-\beta(4\alpha M+M+20)}$.

Accordingly, we can also calculate the OEM profit (Π'^*_N), ride-hailing platform profit (Π'^*_P), total new car sales (TP'^*), and total usage impact of cars (TU'^*) (expressions omitted here for brevity).

Based on these results, we can compare the ride-hailing platform profit. To this end, let $\Delta\Pi_P \doteq \Pi'^*_P - \Pi^*_P$, i.e., $\Delta\Pi_P$ is the difference in the platform profit between the cases with and without the vehicle age limit. We can first show that $\Delta\Pi_P$ is a convex quadratic function in c. Solving $\Delta\Pi_P = 0$ yields the two solutions $\overline{c}_{\Pi_{P1}}(\alpha,\beta,\rho,M) \leq \overline{c}_{\Pi_{P2}}(\alpha,\beta,\rho,M)$ (expressions omitted for brevity). We can also show that only $\overline{c}_{\Pi_{P2}}(\cdot) \in (\overline{c}'_1(\cdot), \overline{c}'_2(\cdot))$ (as we focus on the case with $c \in (\overline{c}'_1(\cdot), \overline{c}'_2(\cdot))$ such that ride-hailing and new car sales both exist in the consumer market), but $\overline{c}_{\Pi_{P1}}(\cdot) < \overline{c}'_1(\cdot)$. Therefore, $\Delta\Pi_P$ increases in c and $\Delta\Pi_P = 0$ at $\overline{c}_{\Pi_P}(\cdot) = \overline{c}'_{\Pi_{P2}}(\cdot)$; i.e., the platform profit is higher under the vehicle age limit if and only if $c > \overline{c}_{\Pi_P}(\cdot)$.

Proof of Proposition 4. For the total new car sales, we compare the value in the presence of the vehicle age limit $TP'^* = \frac{4\alpha M\rho(\alpha(4\beta+4c-3)-2\beta c)-2\beta(\alpha(4c+1)M-2c(M+2)+3)}{4\alpha M\rho(2\alpha(8\beta-5)-\beta)+\beta(-4\alpha M-M-20)}$ with that in the absence of the age limit as characterized above. To this end, we let $\Delta TP \doteq TP'^* - TP^*$, i.e., ΔTP is the difference in the total new car sales between the cases with and without the vehicle age limit. We can first show that ΔTP is a decreasing function in c. Solving $\Delta TP = 0$ yields the solution $c = \bar{c}_{TP}(\alpha, \beta, \rho, M) = \frac{12\alpha^2 M\rho(2\alpha(-4\alpha\rho+\rho-4)+3)+\beta(\alpha(\rho(-112\alpha+3M(4\alpha(4\alpha(\rho+3)-\rho-4)-1)+36)-64)+24)}{32\alpha^2 M\rho(6\alpha(-4\alpha\rho+\rho+1)-1)+2\beta(16\alpha(-28\alpha\rho+9\rho+9)+M(8\alpha(4\alpha\rho-\rho-1)(6\alpha(\rho+1)-1)+5)-44)}$. Therefore, $\Delta TP > 0$ and hence $TP'^{*} > TP^{*}$, if and only if $c < \bar{c}_{TP}(\cdot)$. The comparisons of the new car price, OEM profit, and total environmental impact of car usage with and without the age limit can be conducted similarly based on the respective expressions at optimality (details omitted for brevity).

We can also compare the new car ownership. Let $\Delta D_{NN} \doteq D'^{*}_{NN} - D^{*}_{NN}$, i.e., ΔD_{NN} is the difference in the new car ownership among consumers between the cases with and without the vehicle age limit. We can first show that ΔD_{NN} is a decreasing function in c. Solving $\Delta D_{NN} = 0$ yields the solution $c = \bar{c}_N(\alpha, \beta, \rho, M)$ (expression omitted for brevity); therefore, the new car ownership is higher under the age limit ($\Delta D_{NN} > 0$), if and only if the production cost is low ($c < \bar{c}_{\Delta D_{NN}}(\cdot)$).

A3. Benchmark Cases with No Secondary Market

In this section, we study two models in the absence of secondary market, and compare the results with those from our main model that accounts for the presence of secondary market. As such, we highlight the effects of the secondary market through its interactions with new car sales and ride-hailing service in the consumer market. Specifically, we show that, in contrast to our main model, the presence of the ride-hailing program will always lead to lower new car ownership among consumers and total new car sales by the OEM.

In the first model with no secondary market, we consider non-durable (rather than durable) products with $\delta = 0$; i.e., the product has an effective one-period useful life. In the second model, we consider durable products (with $\delta > 0$), but the secondary market of used car trade among consumers is not allowed. To discuss and highlight the effect of ride-hailing as in our main model, under each of the no-secondary market cases, we compare the corresponding pure-sales benchmark case and the case in the presence of the ride-hailing program in the market as in §4. Also recall that as in §4, we restrict our attention to the case without the age limit imposed by the platform.

Non-Durable Products. In this section, we study the case with non-durable products, i.e., $\delta = 0$. In this case, all cars are the same as they have an effective one-period useful life; i.e., in contrast with the main model with $\delta > 0$, there is no distinction between new and used cars. We refer to all cars as new cars for ease of exposition in this case. We describe the modeling details for the case in the presence of ride-hailing, with no vehicle age limit imposed by the platform; the corresponding pure-sales benchmark case can be analyzed in a similar way with elimination of the consumer option of using ride-hailing. In every period, a consumer can choose to buy a new car and receive a net per-period utility of $\lambda\theta - p^{NS1}$ (where the superscript "$NS1$" is used to indicate values associated with this case), use the ride-hailing service and receive a net per-period utility of $\lambda\beta(\theta - f^{NS1})$, or remain inactive without car usage. Based on these utilities, we can then show that there are three non-dominated consumer strategies in the market, which include (i) buy new cars (which will reach the end-of-life after one period of use) in every period (NN), (ii) use the ride-hailing service in every period (RR), or (iii) always remain inactive (II). It is also easy to show that the corresponding expected per-period net utilities for a consumer with valuation θ of the car usage will be $V_{NN}^{NS1}(\theta) = \lambda\theta - p^{NS1}$, $V_{RR}^{NS1}(\theta) = \lambda\beta(\theta - f^{NS1})$, and $V_{II}^{NS1}(\theta) = 0$, respectively. Based on these utilities, consumers who optimally choose NN, RR, II, have descending valuations θ. Therefore, there exist $0 \le \theta_2^{NS1} \le \theta_1^{NS1} \le 1$, such that consumers with $\theta \in (\theta_1^{NS1}, 1], (\theta_2^{NS1}, \theta_1^{NS1}], [0, \theta_2^{NS1}]$ optimally choose NN, RR, II, respectively; where θ_1^{NS1} can be solved from $V_{NN}^{NS1}(\theta_1^{NS1}) = V_{RR}^{NS1}(\theta_1^{NS1})$, and θ_2^{NS1} can be solved from $V_{RR}^{NS1}(\theta_2^{NS1}) = V_{II}^{NS1}(\theta_2^{NS1})$. In particular, we derive $\theta_1^{NS1} = \frac{\beta f^{NS1} - 2p^{NS1}}{\beta - 1}$ and $\theta_2^{NS1} = f^{NS1}$. Therefore, the new car ownership among consumers in the market can be calculated by $D_{NN}^{NS1} = 1 - \theta_1^{NS1} = \frac{\beta - \beta f^{NS1} + 2p^{NS1} - 1}{\beta - 1}$, and the demand for ride-hailing can be calculated by $D_{RR}^{NS1} = \theta_1^{NS1} - \theta_2^{NS1} = \frac{f^{NS1} - 2p^{NS1}}{\beta - 1}$.

For the ride-hailing drivers, their per-period payoff of joining the platform to provide service is $V_S^{NS1} = \rho\alpha f^{NS1} - p^{NS1}$. Accordingly, $S_S^{NS1} = M\int_0^{V_S^{NS1}} 1 d\Theta$ is the total number of drivers who join the platform to provide ride-hailing service. As such, f^{NS1} in equilibrium can be solved from the market-clearing condition that balances the total demand and supply of consumer rides, i.e., $\lambda\beta(D_{RR}^{NS1}) = \alpha(S_S^{NS1})$, which yields $f^{NS1} = \frac{2p^{NS1}(\alpha M(\beta-1) - \beta)}{2\alpha^2 M(\beta-1)\rho - \beta}$. Accordingly, the overall platform profit can be calculated by $\Pi_P^{NS1} = (1-\rho) f^{NS1}(\alpha S_S^{NS1})$.

For the OEM, the total new car sales are consisting of both the consumer demand for new car ownership in the market (that amounts to D_{NN}^{NS1}), as well as the sales to ride-hailing drivers (that amounts to S_S^{NS1} as each driver needs to make new car purchase in every period). Therefore, $TP^{NS1} = D_{NN}^{NS1} + S_S^{NS1}$. The OEM profit is then given by $\Pi_N^{NS1} = (p^{NS1} - c)\,(D_{NN}^{NS1} + S_S^{NS1})$, and the OEM solves $\max_{p^{NS1}} \Pi_N^{NS1}$, subject to $p^{NS1}, D_{NN}^{NS1}, S_S^{NS1} \ge 0$. We solve the problem in a similar way as in the main model, and we characterize the optimal solution below.

(NS1i) When $c < \bar{c}^{NS1}(\alpha,\beta,\rho,M) = \frac{\left(2\alpha^2(\beta-1)M\rho - \beta\right)(2\alpha M\rho(\beta-\alpha) + \beta((\alpha-1)M-1))}{\left(\beta + 2\alpha^2 M\rho - \alpha\beta M\right)\left(4\alpha^2 M\rho + \beta(-2\alpha M(\rho+1) + M + 2)\right)}$, then $p^{NS1*} = \frac{\beta + 2\alpha^2(2c+1)M\rho - 2\alpha\beta M\rho(\alpha+c) + \beta c(-2\alpha M + M + 2)}{8\alpha^2 M\rho + 2\beta(-2\alpha M(\rho+1) + M + 2)}$, $f^{NS1*} = \frac{c(\alpha(\beta-1)M - \beta)}{2\alpha^2(\beta-1)M\rho - \beta} + \frac{\beta + M(\alpha - \alpha\beta)}{4\alpha^2 M\rho + \beta(-2\alpha M(\rho+1) + M + 2)}$, $D_{NN}^{NS1*} = 1 + \frac{2\left(\beta + 2\alpha^2 M\rho - \alpha\beta M\right)\left(\beta + 2\alpha^2(2c+1)M\rho - 2\alpha\beta M\rho(\alpha+c) + \beta c(-2\alpha M + M + 2)\right)}{\left(2\alpha^2(\beta-1)M\rho - \beta\right)\left(8\alpha^2 M\rho + 2\beta(-2\alpha M(\rho+1) + M + 2)\right)}$, $D_{RR}^{NS1*} = \frac{2\alpha M(1 - 2\alpha\rho)\left(\beta + 2\alpha^2(2c+1)M\rho - 2\alpha\beta M\rho(\alpha+c) + \beta c(-2\alpha M + M + 2)\right)}{\left(2\alpha^2(\beta-1)M\rho - \beta\right)\left(8\alpha^2 M\rho + 2\beta(-2\alpha M(\rho+1) + M + 2)\right)}$, $TP^{NS1*} = \frac{\beta(c(-2\alpha M + M + 2) - 1) - 2\alpha M\rho(\beta c - \alpha(\beta + 2c - 1))}{4\alpha^2(\beta-1)M\rho - 2\beta}$. (NS1ii) Otherwise (when $c \ge \bar{c}^{NS1}(\cdot)$), then $p^{NS1*} = \frac{\beta - 2\alpha^2(\beta-1)M\rho}{2\left(\beta + 2\alpha^2 M\rho - \alpha\beta M\right)}$, $f^{NS1*} = \frac{\beta - \alpha\beta M + \alpha M}{\beta + 2\alpha^2 M\rho - \alpha\beta M}$, $D_{NN}^{NS1*} = 0$, $D_{RR}^{NS1*} = \frac{\beta - \alpha\beta M + \alpha M}{\beta + 2\alpha^2 M\rho - \alpha\beta M}$. In the following discussion, we focus on the more interesting Case(NS1i) with $c < \bar{c}^{NS1}(\cdot)$, where the new car sales and ride-hailing both exist in the market (i.e., $D_{NN}^{NS1*}, D_{RR}^{NS1*} > 0$). We then also solve the pure-sales benchmark case in the absence of the ride-hailing program, and we focus on settings where $D_{NN0}^{NS1*} > 0$, which takes place when $c < \frac{1}{2}$; we can show that $D_{NN0}^{NS1*} = TP_0^{NS1*} = \frac{1}{2} - c$ in this case.

To compare the new car ownership, we study the difference $\Delta D_{NN}^{PSNS1} = D_{NN}^{NS1*} - D_{NN0}^{NS1*} = \beta M\left(\frac{\alpha c(2\alpha\rho - 1)}{2\alpha^2(\beta-1)M\rho - \beta} + \frac{1 - 2\alpha\rho}{8\alpha^2 M\rho + 2\beta(-2\alpha M(\rho+1) + M + 2)}\right)$; we can show that ΔD_{NN}^{PSNS1} is a decreasing function in c, and $\Delta D_{NN}^{PSNS1} = 0$ at $c = \overline{c}_{N0}^{NS1}(\alpha, \beta, \rho, M) < 0$; therefore, $D_{NN}^{NS1*} < D_{NN0}^{NS1*}$ always holds. Similarly, we can also prove that $TP^{NS1*} < TP_0^{NS1*}$ always holds. Therefore, for non-durable products, both the new car ownership and total new car sales are always lower in the presence of ride-hailing.

Absence of Secondary Market. We now explore another scenario where we account for the durable nature of cars with $\delta > 0$, but the secondary market of used car trade is absent; this may happen, for example, when the secondary market is suppressed by the transaction frictions. In this case, while both new and used cars exist in the market, the trade of used cars is absent. We start by solving the case in the presence of ride-hailing in the market, with no vehicle age limit imposed by the platform; moreover, we focus on the case where the new car sales to consumers exist in the market at optimality. For consumers, there will be three non-dominated strategies, which include: (NH) buy a new car and keep it for two periods of use throughout the car's useful life, then repeat this again in the next periods (as we can show that the strategy of always buying a new car and then discarding it after one period of use at no trade value in the absence of the secondary market is now dominated); (RR) always use ride-hailing in every period; or (II) remain inactive with no car usage. They respectively generate the following expected per-period net utilities for a consumer with valuation θ: $V_{NH}^{NS2}(\theta) = \frac{1}{2}((\delta\theta + \theta)\lambda - p^{NS2})$ (we use the superscript "$NS2$" to indicate values associated with this case), $V_{RR}^{NS2}(\theta) = \beta\lambda(\delta_R(\delta)\theta - f^{NS2})$ (with $\delta_R(\delta) = \frac{1}{2} + \frac{1}{2}\delta$ to account for the probabilities of getting new or used cars for ride-hailing for consumers in the absence of the vehicle age limit, as in the main model), $V_{II}^{NS2}(\theta) = 0$. We can then characterize the market similarly as in the main model, to show that there exist $0 \le \theta_1^{NS2} \le \theta_2^{NS2} \le 1$ with $\theta_1^{NS2} = \frac{4p^{NS2} - 4\beta f^{NS2}}{3 - 3\beta}$ and $\theta_2^{NS2} = \frac{4f^{NS2}}{3}$, such that consumers with valuation $\theta \in (\theta_1^{NS2}, 1], (\theta_2^{NS2}, \theta_1^{NS2}], [0, \theta_2^{NS2}]$ optimally choose NH, RR, II, respectively. Accordingly, $D_{NH}^{NS2} = 1 - \theta_1^{NS2}$ and $D_{RR}^{NS2} = \theta_1^{NS2} - \theta_2^{NS2}$.

For the ride-hailing drivers, their per-period payoff of joining the platform to provide service is $V_S^{NS2} = \rho\alpha f^{NS2} - (1/2)p^{NS2}$; we can then derive the total number of drivers that join the platform to provide service to be $S_S^{NS2} = M\int_0^{V_S^{NS2}} 1 d\Theta$. The ride-hailing price f^{NS2} in equilibrium can be solved from the market-clearing condition that balances the demand and supply of the consumer rides, i.e., $\lambda\beta(D_{RR}^{NS2}) = \alpha(S_S^{NS2})$, which yields $f^{NS2} = \frac{p^{NS2}(3\alpha(\beta-1)M - 4\beta)}{6\alpha^2(\beta-1)M\rho - 4\beta}$. Accordingly, the overall platform profit can be calculated by $\Pi_P^{NS2} = (1-\rho)f^{NS2}(\alpha S_S^{NS2})$.

For the OEM, the new car sales to the drivers will be $(\frac{1}{2})S_S^{NS2}$, and those to the consumers for the new car ownership demand is $(\frac{1}{2})D_{NH}^{NS2}$ (as the NH consumers buy a new car every two periods); therefore, the total new car sales in this case is $TP^{NS2} = (1/2)S_S^{NS2} + (1/2)D_{NH}^{NS2} = \frac{3\alpha M\rho(\alpha(3\beta+4p-3)-2\beta p)+\beta(p((3-6\alpha)M+8)-6)}{18\alpha^2(\beta-1)M\rho-12\beta}$, and the OEM solves $\max_{p^{NS2}} \Pi_N = (p^{NS2} - c)(TP^{NS2})$, subject to $p^{NS2}, D_{NH}^{NS2}, S_S^{NS2} \ge 0$. We solve this problem and focus on the more interesting case where the new car sales and ride-hailing both exist in the market (i.e., $D_{NH}^{NS2*}, D_{RR}^{NS2*} > 0$); as such, we have $p^{NS2*} = \frac{\beta\left(c(-6\alpha M(\rho+1)+3M+8)-9\alpha^2 M\rho+6\right)+3\alpha^2(4c+3)M\rho}{24\alpha^2 M\rho+2\beta(M(3-6\alpha(\rho+1))+8)}$, $f^{NS2*} = \frac{1}{4}(3\alpha(\beta-1)M - 4\beta)\left(\frac{c}{3\alpha^2(\beta-1)M\rho-2\beta} - \frac{3}{12\alpha^2 M\rho+\beta(-6\alpha M(\rho+1)+3M+8)}\right)$,

$D_{NH}^{NS2*} = \frac{2\left(6\alpha^2 M\rho+\beta(4-3\alpha M)\right)\left(\beta\left(c(-6\alpha M(\rho+1)+3M+8)-9\alpha^2 M\rho+6\right)+3\alpha^2(4c+3)M\rho\right)}{\left(9\alpha^2(\beta-1)M\rho-6\beta\right)\left(24\alpha^2 M\rho+2\beta(M(3-6\alpha(\rho+1))+8)\right)} + 1$, and $TP^{NS2*} = \frac{3\alpha M\rho(\alpha(3\beta+4c-3)-2\beta c)+\beta(c((3-6\alpha)M+8)-6)}{36\alpha^2(\beta-1)M\rho-24\beta}$. We also solve the corresponding pure-sales case under this model in the absence of the secondary market to show that $D_{NH0}^{NS2*} = \frac{1}{6}(3-4c)$ and $TP_0^{NS2*} = \frac{1}{4} - \frac{c}{3}$.

To compare the new car ownership, we study the difference $\Delta D_{NN}^{PSNS2} = D_{NN}^{NS2*} - D_{NN0}^{NS2*} = \beta M\left(\frac{\alpha c(2\alpha\rho-1)}{6\alpha^2(\beta-1)M\rho-4\beta} + \frac{3-6\alpha\rho}{48\alpha^2 M\rho-4\beta(6\alpha M(\rho+1)-3M-8)}\right)$; we can show that ΔD_{NN}^{PSNS2} is a decreasing function in c, and $\Delta D_{NN}^{PSNS2} = 0$ at $c = \bar{c}_{N0}^{NS2}(\alpha,\beta,\rho,M) = \frac{9\alpha^2(\beta-1)M\rho-6\beta}{24\alpha^3 M\rho+2\alpha\beta(M(3-6\alpha(\rho+1))+8)} < 0$; therefore, $D_{NN}^{NS2*} < D_{NN0}^{NS2*}$ always holds. Similarly, we can also prove that $TP^{NS2*} < TP_0^{NS2*}$ always holds. Therefore, when the secondary market is absent, both the new car ownership and total new car sales are always lower in the presence of ride-hailing.

The results from these two models with no secondary market for the trade of used cars contrast those from the main model, as the latter show that both the new car ownership among consumers and total new car sales for the OEM can be higher in the presence of ride-hailing in the market. These insights highlight the importance of properly accounting for the nuanced effects of secondary market while evaluating the effects of ride-hailing.

A4. Details of the Extensions in §6

In this section, we explain the details of the extensions presented in §6 to generalize our insights.

A4.1. Numerical Calibration

In this section, we describe how we estimate the parameter values based on real-world data for the calibrated numerical study presented in §6.1.

First, we estimate α, which is the probability that an available ride-hailing driver is matched with consumers for rides. Industry studies show that $1-\alpha$, which is the probability that an available driver is unoccupied between rides and commonly referred to as deadheading in practice, is about 60% (MIT Technology Review 2018, LA Times 2023). Therefore, we estimate α to be $1-0.6=0.4$.

Second, we estimate δ, which is the durability of cars, i.e., the value of a used car compared to a new one after accounting for the physical and economic depreciation. Survey data shows that the average lifespan of cars on the road in the U.S. is about 12 years (Statista 2023); accordingly, a six-year car corresponds to a used car in our model with the two-period useful life of cars. Industry studies have estimated that a five-year car typically loses 40%-60% of its original value (Edmunds 2017, Nerdwallet 2017). Therefore, we estimate δ to be $1-0.6=0.4$ for our model.

Third, we estimate M, which is the size of the potential driver pool for ride-hailing. Industry report shows that there are approximately 2 million current Uber and Lyft drivers in the U.S. (Campbell 2023). Meanwhile, the taxi drivers can be another group of potential drivers for ride-hailing given the close similarity of the service they provide; and there are about 0.28 million of them currently (Data USA 2023). As such, we estimate the total number of potential ride-hailing drivers to be about 2.28 million. We further normalize this value to be compatible with our model where the size of the consumer market has been normalized to 1. To do so, we collect data on the U.S. population, which is estimated to be about 250 million that are aged between 16 and 75 years old (Statista 2022), and we use it as proxy for the market size of consumers that actively seek to meet their mobility needs. As such, $2.28/250 \approx 0.01$ will be the normalized value of M for our model.

Next, we also estimate λ, i.e., the probability that a consumer incurs need for car usage. Since mobility needs are incurred only as part of a person's daily life; thus, instead of using 24 hours/day, we use 7 hours/day that already qualifies a driver as full-time ride-hailing driver (TIME 2015), as the maximum amount of commute needs for a consumer. We also collect data on the average driving time in the U.S., which is estimated to be approximately 101 minutes (Gitnux Marketdata 2023). Combining the information, we estimate λ to be $101/(7 \times 60) \approx 0.25$ for our model.

We proceed to estimate β, i.e., the probability that a consumer in need of a ride can be matched with an available driver by the platform. The average waiting time for ride-hailing consumers is estimated to be approximately 4 minutes in major cities in the U.S. (Newsweek 2014, Kekach 2019). Meanwhile, the probability that a ride-hailing consumer can be matched with an available driver within 5 minutes is estimated to be 50% (Brown and LaValle 2021). We use the probability that a ride-hailing consumer can be matched with an available driver within the average waiting time as a proxy for β, which is estimated based on the above information to be approximately 0.4.

Finally, we estimate the practical values of c and ρ for benchmarks for our discussion. For ρ, which is the payment split to drivers: Uber advertises a 25% commission rate and Lyft advertises a 20% rate in the U.S. (Life Asset 2022, Hoyt and Gardner 2024), which correspond to $\rho = 75\%$ and 80%, respectively. In practice, the platforms may also charge other fees (e.g., the marketplace or booking fees) or give bonuses before allocating the revenue to drivers (Quartz 2020, The Verge 2021, The Hartford 2023), and hence the effective ρ may be further adjusted. Using the benchmark values, we investigate ρ in the range of 55% to 100% in the numerical study. To estimate the unit production cost c, we first use the optimal solution of the new car price (which is solved as in the main model) and calibrate it at the estimated parameter values we derive above with $\alpha = 0.4$, $\lambda = 0.25$, $\beta = 0.4$, $\delta = 0.4$, and $\rho = 0.75$, which then gives the approximate value of the optimal new car price to be $0.175 + 0.5c$ for our model. Meanwhile, industry reports show that the production cost can take up 75% of the new car price (Cech 2022, Matijssen 2023). We can therefore let $0.175 + 0.5c = c/(0.75)$, solving it gives $c \approx 0.2$ for our model. Accordingly, we investigate the production cost c in the range of 0.05 to 0.35 in our numerical study. All the results are presented in the main paper.

A4.2. Drivers' Personal Usage of Vehicles

In this section, we describe the model where we also account for the drivers' personal usage of vehicles. We focus on the case in the absence of the ride-hailing vehicle age limit for demonstration;

the case with the age limit can be solved similarly. In this case, the consumer utilities and consumer strategies remain the same as in the main model. Yet since the average driver's expected per-period payoff now becomes $V_S^p(\theta^P) = \zeta(\delta_R(\delta)\theta^P) + (1-\zeta)(\rho\alpha f^p) - \frac{1}{2}p^p$ (where the superscript "p" is used to indicate values associated with this case), where $\delta_R(\delta) = \frac{1}{2} + \frac{1}{2}\delta$ and the drivers' valuation of car usage for personal needs θ^P is uniformly distributed over $[0,1]$ as for consumers. Recall that a driver's outside options of using their time yield a maximum per-period utility of Θ, which is assumed to be uniformly distributed over $[0,1]$ among all drivers as described in the main model. Therefore, a driver will choose to join the platform to provide ride-hailing service if and only if they obtain lower utility from spending $1-\zeta$ fraction of the time (during which they are not driving the car for personal usage) for their outside option rather than serving as a ride-hailing driver; i.e., when $(1-\zeta)\Theta \le \zeta(\delta_R(\delta)\theta^P) + (1-\zeta)(\rho\alpha f^p) - \frac{1}{2}p^p$, which reduces to $\Theta \le \frac{(\delta+1)\zeta\theta^P}{2-2\zeta} + \alpha f^p \rho + \frac{p^p}{2(\zeta-1)}$. To also account for the heterogeneity of θ^P among drivers, the total number of drivers that join the platform to provide service in this case can then be calculated by $S_S^p = \int_0^1 \int_0^{\frac{(\delta+1)\zeta\theta^P}{2-2\zeta} + \alpha f^p \rho + \frac{p^p}{2(\zeta-1)}} 1 d\Theta d\theta^P = \alpha M f^p \rho - (M(\delta\zeta + \zeta - 2p^p))/(4(\zeta-1))$. Accordingly, we can solve the model both for the cases without and with the age limit, and then compare them to study the effects of ride-hailing on the car sales markets (by comparing the pure-sales benchmark case and the case with ride-hailing in the absence of the vehicle age limit), as well as the effect of the ride-hailing vehicle age limit (by comparing the cases in the presence of ride-hailing without and with the vehicle age limit), similarly to the main model. As the comparisons become intractable due to the added complexity of this extension, we study the problem numerically. The results are presented in Figures 5 and 6, both of which show structural similarity with our main findings from Propositions 1 - 4, with the implications of the drivers' personal usage as discussed in §6.2.

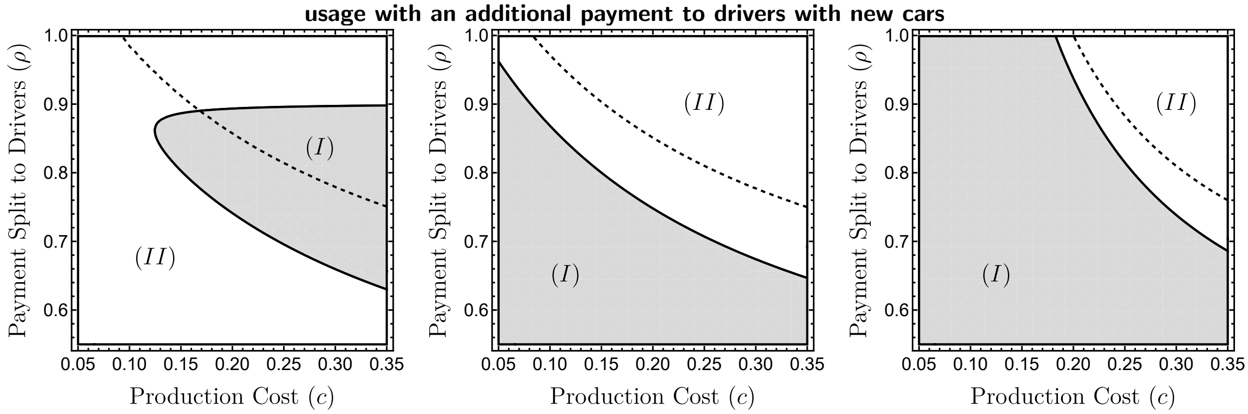
A4.3. Heterogeneous Payments to Drivers Based on Vehicle Age

In this section, we extend our analysis to consider that the ride-hailing platform offers heterogeneous payments to drivers, with an additional payment $z \in [0, 1-\rho]$ to drivers with new cars. In this case, the payment splits to drivers with new and used cars are $\rho + z$ and ρ, respectively. In the absence of a vehicle age limit, the average per-period payoff for ride-hailing drivers becomes $V_S^Z = \frac{1}{2}(\rho+z)\alpha f^Z + \frac{1}{2}(\rho)\alpha f^Z - \frac{1}{2}p^Z$ (where the superscript "Z" is used to indicate values associated with this case), the total number of drivers that join the platform to provide service is $S_S^Z = M\int_0^{V_S^Z} 1 d\Theta$, and the platform profit is $\Pi_P^Z = \frac{1}{2}(1-\rho-z)\alpha f^Z S_S^Z + \frac{1}{2}(1-\rho)\alpha f^Z S_S^Z$. Under a vehicle age limit, $V_S^{Z\prime} = (\rho+z)\alpha f^{Z\prime} - (p^{Z\prime} - p_u^{Z\prime})$ and $S_S^{Z\prime} = M\int_0^{V_S^{Z\prime}} 1 d\Theta$ for the drivers and $\Pi_P^{Z\prime} = (1-\rho-z)\alpha f^{Z\prime} S_S^{Z\prime}$ for the platform. Similarly to the main model, we can study the effects of ride-hailing on the car sales markets (by comparing the pure-sales benchmark case and the case with ride-hailing in the absence of the age limit), as well as the effects of a ride-hailing vehicle age limit (by comparing the cases in the presence of ride-hailing without and with the age limit). We first solve all the cases to characterize the optimal solutions. Yet as the comparisons become intractable due to the added complexity, we study the problem numerically. The results are presented in Figures 7 in §6.3 in the paper and Figure A1 below, both of which demonstrate structural similarity with our main findings from Propositions 1 - 4.

Qualitatively, as discussed in the paper, we also show that with the additional payment to drivers with new cars, ride-hailing leads to lower new car ownership among consumers and lower total new car sales (see Figures 7a and 7b). Moreover, the age limit now has an amplified effect in lowering both the OEM profit and total environmental impact of car usage (see Figures A1b and A1c).

In addition, Figure A1a shows that the effect of the additional payment on the platform profit is more nuanced. With the additional payment, the vehicle age limit can still lead to a higher platform profit when the production cost is sufficiently high. Furthermore, when the base payment split (ρ) is lower, this effect is amplified (the corresponding range expands). This is because the additional payment to drivers with new cars can ease the higher vehicle costs imposed by the age limit; as a result, the age limit can now increase the service quality and overall ride-hailing profit more significantly. However, when ρ is higher, the additional payment becomes too costly and makes the age limit less viable for the platform (and hence the corresponding range shrinks).

Figure A1 Effect of vehicle age limit on platform profit, OEM profit, and total environmental impact of car usage with an additional payment to drivers with new cars



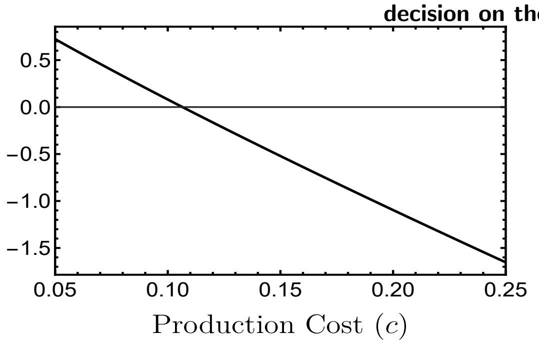
(a) Platform profit (b) OEM profit (c) Total usage env. impact

Note. The above figure is based on calibrated values, where $\lambda = 0.25$, $\delta = 0.4$, $\alpha = 0.4$, $M = 0.01$, $\beta = 0.4$, $\eta = 5$, and $z = 0.075$. In panel (a), the platform profit is higher under the vehicle age limit in Region (I), but lower in Region (II); the dashed line shows the analogous threshold from the main model. In panel (b), the OEM profit is higher under the age limit in Region (I), but lower in Region (II); the dashed line shows the analogous threshold from the main model. In panel (c), the total environmental impact of car usage is higher under the age limit in Region (I), but lower in Region (II); the dashed line shows the analogous threshold from the main model. Overall, we find that an additional payment to drivers with new cars leads to lower OEM profit and lower total usage impact.

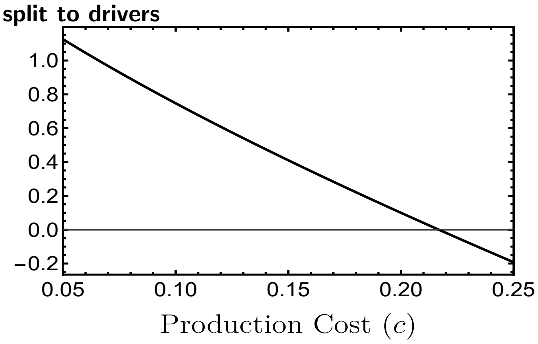
A4.4. Endogenous Payment Split to Drivers

In this section, we extend our analysis to also consider the optimal choice of payment split to drivers (ρ) by the ride-hailing platform. To so do, we numerically solve the optimal ρ that maximizes the platform's profit. The results are presented in §6.4. We also numerically verify that our key findings from Propositions 1 - 4 remain structurally the same in this extended model. Similar to Propositions 1 and 2, we show that ride-hailing can lead to higher new car ownership among consumers and higher total new car sales for the OEM when the production cost is sufficiently low (see Figure A2). In addition, similar to Propositions 3 and 4, the vehicle age limit imposed by the platform can lead to a higher platform profit when the production cost is sufficiently high (see Figure A3a). Moreover, the age limit can lead to a lower total environmental impact associated with car usage and hence allows ride-hailing to contribute to more sustainable transportation (see Figure A3b). Finally, we also find that when the platform imposes a vehicle age limit, it should increase the payment split to drivers to help alleviate the higher vehicle costs (see Figure A3c).

Figure A2 Effect of ride-hailing on new car ownership and total new car sales with the optimal platform decision on the payment split to drivers



(a) Increase in new car ownership due to ride-hailing ($D^*_{NN}(\rho^*) - D^{PS*}_{NN}$, in 10^{-4})



(b) Increase in total new car sales due to ride-hailing ($TP^*(\rho^*) - TP^{PS*}$, in 10^{-4})

Note. The above figure is based on calibrated values, where $\lambda = 0.25$, $\delta = 0.4$, $\alpha = 0.4$, $M = 0.01$, $\beta = 0.4$, and $\eta = 5$. Panel (a) shows the change in new car ownership due to the presence of ride-hailing ($D^*_{NN}(\rho^*) - D^{PS*}_{NN}$). Panel (b) shows the change in total new car sales due to the presence of ride-hailing ($TP^*(\rho^*) - TP^{PS*}$). In the plotted region, the total environmental impact of car usage is higher in the presence of ride-hailing.

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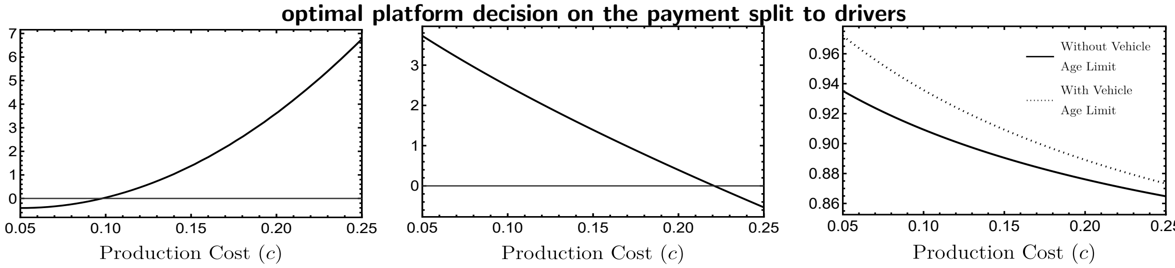
Figure A3 **Effect of vehicle age limit on platform profit, total environmental impact of car usage, and the optimal platform decision on the payment split to drivers**



(a) Increase in platform profit due to age limit ($\Pi'^*_P(\rho'^*) - \Pi^*_P(\rho^*)$, in 10^{-6})

(b) Increase in total usage env. impact due to age limit ($TU'^*(\rho'^*) - TU^*(\rho^*)$, in 10^{-4})

(c) Optimal payment splits to drivers with and without an age limit (ρ^* and ρ'^*)

Note. The above figure is based on calibrated values, where $\lambda = 0.25$, $\delta = 0.4$, $\alpha = 0.4$, $M = 0.01$, $\beta = 0.4$, and $\eta = 5$. Panel (a) shows the change in platform profit due to the presence of vehicle age limit ($\Pi'^*_P(\rho'^*) - \Pi^*_P(\rho^*)$). Panel (b) shows the change in total environmental impact of car usage due to the presence of vehicle age limit ($TU'^*(\rho'^*) - TU^*(\rho^*)$). Panel (c) shows the optimal payment splits to drivers with and without the vehicle age limit.

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