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E-Companion: Consequences of Resorting to Fines and Investments to Regulate Data Portability

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Appendix A: Micro-Modelling User Behavior

In this section we provide a micro-model of user behavior that leads to the inverse demand function posited in Section 3. Our goal is to validate the robustness of our assumptions by specifying the utility functions that lead to the assumptions we make on inverse demand. We follow standard analytical models where consumers choose whether to consume from each DC based on their utility, DC pricing (r^c and r^{nc}), and compliance (ρ) decisions. We focus on the users' utility maximization problem, deriving the inverse demand functions, and demonstrating the characteristics in Assumption 1 (impact of capability and output on inverse demand), Assumption 2 (impact of proportion of compliant DCs on non-compliant inverse demand) and Assumption 4(a) (capability increases compliant DC inverse demand more than non-compliant DC inverse demand). We do not investigate Assumptions 3 and 4(b), as they consider costs and the equilibrium results, respectively, which are not related to user behavior.

To demonstrate the behavior of users and how it results in the demand (output) and inverse demand (price) characteristics we describe, we provide an example of the model using utility functions derived from a Salop-based model of DC competition (Salop 1979) that is based on a set of users that are heterogeneously distributed. For the ease of exposition, we consider 3 DCs that compete for users with varying preferences for the DCs. Considering 3 DCs allows us to meaningfully analyze the impact of the proportion of compliant DCs in Assumption 2. Our analysis extends to any arbitrarily large number of DCs without a qualitative change in the results.

A.1. Setup

Consider 3 DCs located equidistant from each other on a Salop circle (Salop 1979) with circumference of 1 as shown in Figure EC.1: DC 1 located at $L_1 = 0$ (top of the circle, also equivalent to $L_1 = 1$), DC 2 at $L_2 = 1/3$, and DC 3 at $L_3 = 2/3$. Users are evenly distributed around the circle.

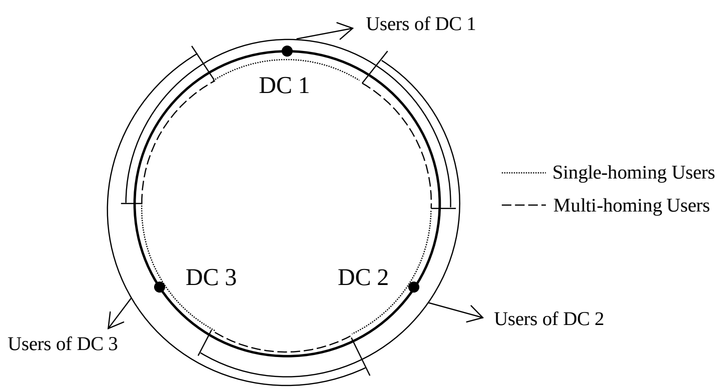


Figure EC.1 DCs and users on Salop circle

The utility that a user located at $y \in [0,1]$ receives from DC i depends on whether the DC is compliant or non-compliant. We consider a classic Salop-based utility model with network effects, increasing value in DC capability, and a positive utility from the feature of portability from compliant DCs. We allow the utility from both compliant and non-compliant DCs to increase in the proportion of compliant DCs. Based on the above arguments, we consider the benefit – defined as utility without considering the price, that a user located at y receives from DC i which can be either compliant (c) or non-compliant (nc) as

$$B_i^c(y) = [v + \vartheta + \mu^c \rho]\theta_i + \alpha x_i - t|L_i - y|, \qquad B_i^{nc}(y) = [v + \mu^{nc}\rho]\theta_i + \alpha x_i - t|L_i - y|, \tag{EC.1}$$

where $v \in \mathbb{R}_{>0}$ is the basic utility that users receive from the DCs, $\theta_i \in \mathbb{R}_{>0}$ is DC i's capability, $\vartheta \in \mathbb{R}_{>0}$ is the additional utility from the feature of portability due to users being able to download their data from compliant DCs, $\alpha \in \mathbb{R}_{\geq 0}$ is the magnitude of network effects, $x_i \in \mathbb{R}_{>0}$ is DC i's demand or *output*, $\rho \in [0,1]$ is the proportion of compliant DCs, and $\mu^c \in \mathbb{R}_{\geq 0}$ and $\mu^{nc} \in \mathbb{R}_{\geq 0}$ capture the additional utility that users receive due to having more sources to download and port their data from for the compliant and non-compliant DCs, respectively.

In the above benefit characterization, the argument $t|L_i - y|$ represents the distance of the user to a particular DC or its preference for a DC, as specified in the Salop model with a distance parameter t. The argument αx_i captures the same-side network effects, where as more users use a DC, that DC becomes more attractive to the users. This specification is commonly used in modeling both cross-sided and same-sided network effects (Dou and Wu 2021, Chellappa and Mukherjee 2021, Xie et al. 2021). The inclusion of network effects in the model is not needed for the derivation of assumptions of our general-form model, but shows the robustness of our assumptions and demonstrates how network effects can be parameterized.

Next, the arguments $\mu^c \rho \theta_i$ and $\mu^{nc} \rho \theta_i$ capture the value from portability to compliant and non-compliant DCs, respectively. This depends on the proportion of compliant DCs, ρ, which represents the number of sources that users can download and port their data from. As described above, we consider that $\mu^c \geq \mu^{nc}$, because compliant DCs may have exclusive access to additional porting tools that simplify or facilitate seamless porting of data, where porting can be done with a few clicks rather than having to manually download and upload the data. For example, Data Transfer Initiative, Universal Digital Profile, and Open Banking allow for such easy porting of data. If it is just as easy to port data from compliant DCs to non-compliant DCs as it is to port to compliant ones, then $\mu^c = \mu^{nc}$. Further, the inclusion of cross-DC network effects in the model through μ^c and μ^{nc} is not needed for the derivation of assumptions in our general-form model. Finally, as described earlier, the additional utility from portability also depends on the capability of the focal DC because capability implies reliability, uptime, accuracy, speed, and ease of use, all of which improve the value from portability.

Using the above benefit functions and considering that the utility a user receives is derived as the net of benefit and price of the DC, the utility functions are derived as

$$\begin{aligned} U_i^c(y) &= B_i^c(y) - r_i^c = [v + \vartheta + \mu^c \rho]\theta_i + \alpha x_i - t|L_i - y| - r_i^c \quad \text{and} \\ U_i^{nc}(y) &= B_i^{nc}(y) - r_i^{nc} = [v + \mu^{nc}\rho]\theta_i + \alpha x_i - t|L_i - y| - r_i^{nc}, \end{aligned} \tag{EC.2}$$

where r_i^{nc} and r_i^c are DC i's price or *inverse demand* where the DC is non-compliant and compliant, respectively. We also allow users to multi-home, where some users may use two DCs. Due to the possible substitution of the DCs' services, a user that uses two DCs may not receive the whole utility from both, for example, due to the limited user time or attention spent on the DCs. Particularly, the utility that a user that uses DCs i and j receives is given as

$$U_{i,j}^{k_i,k_j}(y) = \sigma[B_i^{k_i}(y) + B_j^{k_j}(y)] - r_i^{k_i} - r_j^{k_j},$$

where $k_i \in \{c, nc\}$ represent the compliance (c) or non-compliance (nc) of DC i, $B_i^{k_i}$ is defined in (EC.1), and $\sigma \in [1/2, 1]$ is the inverse substitution factor among the two DCs. Where σ is close to 1/2, there is a high substitution among the two DCs' services, resulting in a negligible benefit to a user that multi-homes compared to one that single-homes. On the other hand, where σ is close to 1, multi-homing users benefit from full services of each DC. We do not consider the case where $0 < \sigma < 1/2$, as this implies that single-homing provides a higher benefit compared to multi-homing and restricts users to single-homing.

A.2. Demand Characterization

We first derive the DCs' demands as function of prices, and then solve for prices to derive the inverse demand or *price* as a function of output or *demand*. As described above, we consider users to possibly multi-home if they receive positive utility from two DCs. In order to model a setting with competition between DCs, we assume a covered market. The demand between DCs i and j where $i, j \in \{1, 2, 3\}$, $L_i < L_j$, is characterized by three types of users: those with a strong preference for DC i single-home with DC i, those with a strong preference for DC j single-home with DC j exclusively, and those in the middle multi-home at both DCs i and j (Figure EC.1). To characterize the demand, we find the user that is indifferent between single-homing with DC i or multi-homing with DCs i and j, and indifferent between single-homing with DC j or multi-homing with DCs i and j. The user that is indifferent between single-homing with DC i and multi-homing with DCs i and j is characterized by finding the location of the user, which we refer to as $\tilde{y}_{i,j}^i$, for which $U_i^{k_i}(\tilde{y}_{i,j}^i) = U_{i,j}^{k_i,k_j}(\tilde{y}_{i,j}^i)$. Similarly, the user that is indifferent between single-homing with DC j and multi-homing with DCs i and j is characterized by finding the user $\tilde{y}_{i,j}^j$ for which $U_j^{k_j}(\tilde{y}_{i,j}^j) = U_{i,j}^{k_i,k_j}(\tilde{y}_{i,j}^j)$. The demand characterization is then provided as follows: users in the range $[L_i, \tilde{y}_{i,j}^i]$ single-home with DC i, users in the range $[\tilde{y}_{i,j}^i, \tilde{y}_{i,j}^j]$ multi-home with DCs i and j, and users in the range $[\tilde{y}_{i,j}^j, L_j]$ single-home with DC j. Accordingly and considering the demand on both sides of a given DC on the Salop circle, the total demand or output for DC i is derived as

$$x_i = \sum_{j=\backslash i} \left[\left| \int_{L_i}^{\tilde{y}_{i,j}^i} dy \right| + \left| \int_{\tilde{y}_{i,j}^i}^{\tilde{y}_{i,j}^j} dy \right| \right], \quad \forall i \in \{1, 2, 3\}. \tag{EC.3}$$

In (EC.3), the summation accounts for the demand on both sides of DC i on the Salop circle as they correspond with the two adjacent DCs (denoted by $j = \backslash i$), the first integral is for the single-homing demand, and the second integral is for the multi-homing demand. We analyze the demand function in detail for the pre-DPR and post-DPR scenarios below.

A.3. Compliance Vector and Proportion of Compliant DCs

Pre-DPR, none of the DCs comply. Post-DPR, users choose whether to consume from DCs based on each DC's decisions about pricing (r^c and r^{nc}) and compliance (ρ). We consider each possible value of ρ separately as a scenario and then study its impact on inverse demand by comparing the scenarios. To denote which DCs are compliant, we consider a vector $\Psi = (\psi_1, \psi_2, \psi_3)$ which represents the compliance of each of the 3 DCs, where $\psi_i \in \{0,1\}$ represents whether DC i is compliant ($\psi_i = 1$) or non-compliant ($\psi_i = 0$). For example, $\Psi = (0,0,0)$ implies that no DC complies, $\Psi = (1,1,0)$ implies that DCs 1 and 2 comply but DC 3 does not comply, and so forth. We can then derive the demand equations for each compliance scenario. In the case with 3 DCs, ρ can take values of 0, 1/3, 2/3, or 1. Therefore, post-DPR there are four possible compliance scenarios: none of the DCs comply ($\rho = 0$), one DC complies ($\rho = 1/3$), two DCs comply ($\rho = 2/3$), or all three DCs comply ($\rho = 1$).

A.4. Pre-DPR Inverse Demand

Under this scenario, there is no DPR, therefore the compliance scenario is $\Psi = (0,0,0)$ with ρ=0. Using (EC.3), the demand for each DC in the presence of network effects is derived as

$$x_i(r_i, \vec{r}_{\setminus i}) = \frac{2[1-\sigma]\big[t^2 + 3\alpha[\sum_{j=\setminus i} r_j] - t\alpha[1+\sigma]\big] + 6v\theta_i\big[t\sigma - \alpha[2\sigma^2+\sigma-1]\big] - 3tv[1-\sigma][\sum_{j=\setminus i}\theta_j]}{3\big[t-2\alpha[2\sigma-1]\big]\big[t-\alpha[\sigma+1]\big]} - \frac{6r_i[t+\alpha[1-3\sigma]]}{3\big[t-2\alpha[2\sigma-1]\big]\big[t-\alpha[\sigma+1]\big]}, \quad \forall i \in \{1,2,3\}. \quad \text{(EC.4)}$$

Solving the system of demand equations in (EC.4) for inverse demand (price), we can derive each DC's pre-DPR inverse demand function (r_i) as

$$r_i(x_i, \vec{x}_{\setminus i}) = \frac{1}{6}\left[3\alpha\big[2\sigma x_i - [1-\sigma]\sum_{j=\setminus i} x_j\big] + t[2-3x_i-2\sigma] + 3v\big[2\sigma\theta_i - [1-\sigma]\sum_{j=\setminus i}\theta_j\big]\right], \quad \forall i \in \{1,2,3\}. \quad \text{(EC.5)}$$

Inspecting the pre-DPR inverse demand function in (EC.5), we can confirm that it increases in capability (that is, $\partial r_i/\partial\theta_i > 0$); decreases in own output (that is, $\partial r_i/\partial x_i < 0$) given that the profit function is concave; and decreases in other DCs' output (that is, $\partial r_i/\partial x_{\setminus i} < 0$). Moreover, inverse demand is linear with respect to own output (that is, $\partial^2 r_i/\partial x_i^2 = 0$). Thereby, Assumption 1(a) is supported. Assumption 1(b) is also supported, because the marginal inverse demand is linear with respect to capability (that is, $\partial^2 r_i/[\partial x_i \partial\theta_i] = 0$). We further verify our assumptions in both pre- and post-DPR scenarios in Section A.6.

A.5. Post-DPR Inverse Demand

Post-DPR, each DC decides on compliance, and as a result, the proportion of compliant DCs, ρ is realized. As discussed above, depending on the compliance decisions, ρ can take values of $\rho \in \{0, 1/3, 2/3, 1\}$. The resulting compliance level affects user utility of both compliant and non-compliant DCs. We study each post-DPR scenario separately below and then compare them to study the impact of ρ on compliant and non-compliant inverse demand functions. Particularly, we consider the following four scenarios: $\Psi = (0,0,0)$, where $\rho = 0$; $\Psi = (1,0,0)$ where $\rho = 1/3$; $\Psi = (1,1,0)$, where $\rho = 2/3$; and $\Psi = (1,1,1)$ where $\rho = 1$. This is without loss of generality, as all other possible scenarios are captured through this analysis. For example, the analysis for scenarios $\Psi = (1,0,0)$, $\Psi = (0,1,0)$, and $\Psi = (0,0,1)$ are equivalent. Moreover, the scenario where no DC complies, $\rho = 0$, is equivalent to the pre-DPR case studied above. The rest of the scenarios are analyzed next. After deriving the inverse demand for these scenarios, we condense the inverse demand function for the scenarios $\Psi = (\psi_1, \psi_2, \psi_3)$.

One DC Complies ($\Psi=(1,0,0)$, $\rho=1/3$) Under this scenario, DC 1 complies, but DCs 2 and 3 do not. Using the demand function in (EC.3), we derive the implicit demand for each DC i. This process is similar to that of the previous scenario, which we omit for brevity and present only the demand function. Intuitively, the compliance of a given DC increases the utility it provides to users, and thereby reduces the demand functions of the two non-compliant DCs. The demand equations for the compliant DC and non-compliant DCs are given as

$$\begin{aligned} x_i^c(r_i,\vec{r}_{\setminus i}) =& \frac{2[1-\sigma]\big[t^2+3\alpha[\sum_{j=\setminus i} r_j]-t\alpha[1+\sigma]\big]+2[3[v+\vartheta]+\mu^c]\theta_i\big[t\sigma-\alpha[2\sigma^2+\sigma-1]\big]}{3\big[t-2\alpha[2\sigma-1]\big]\big[t-\alpha[\sigma+1]\big]} \\ &- \frac{6r_i[t+\alpha[1-3\sigma]]+t[1-\sigma]\big[\sum_{j=\setminus i}[3v+\psi_j\mu^{nc}]\theta_j\big]}{3\big[t-2\alpha[2\sigma-1]\big]\big[t-\alpha[\sigma+1]\big]}, \quad \text{if } i{=}1, \\ x_i^{nc}(r_i,\vec{r}_{\setminus i}) =& \frac{2[1-\sigma]\big[t^2+3\alpha[\sum_{j=\setminus i} r_j]-t\alpha[1+\sigma]\big]+2[3v+\mu^{nc}]\theta_i\big[t\sigma-\alpha[2\sigma^2+\sigma-1]\big]-6r_i[t+\alpha[1-3\sigma]]}{3\big[t-2\alpha[2\sigma-1]\big]\big[t-\alpha[\sigma+1]\big]} \\ &- \frac{t[1-\sigma]\big[\sum_{j=\setminus i}[3[v+\vartheta]+\psi_j\mu^c]\theta_j\big]}{3\big[t-2\alpha[2\sigma-1]\big]\big[t-\alpha[\sigma+1]\big]}, \quad \forall i\in\{2,3\}. \quad \text{(EC.6)} \end{aligned}$$

Post-DPR, as one DC complies with DPR, this impacts not only its own demand function, but also the demand functions of the other two non-compliant DCs. In effect, when a DC goes from non-compliance to compliance, some of the users who previously used another DC exclusively switch to multi-homing and use the compliant DC as well. Additionally, some users that were previously multi-homing switch to single-homing with the compliant DC.

Similar to the previous scenario, using the system of demand functions in (EC.6), we can derive each DC's inverse demand (price) function as

$$\begin{aligned} r_i^c(x_i,\vec{x}_{\setminus i}) =& \frac{1}{6}\Bigg[3\alpha\big[2\sigma x_i-[1-\sigma]\sum_{j=\setminus i} x_j\big]+t[2-3x_i-2\sigma]+3v\big[[1+\vartheta]2\sigma\theta_i-[1-\sigma][\sum_{j=\setminus i}\theta_j]\big]+2\mu^c\sigma\theta_i \\ &-\mu^{nc}[1-\sigma][\sum_{j=\setminus i}\psi_j\theta_j]\Bigg], \quad \text{if } i{=}1, \\ r_i^{nc}(x_i,\vec{x}_{\setminus i}) =& \frac{1}{6}\Bigg[3\alpha\big[2\sigma x_i-[1-\sigma]\sum_{j=\setminus i} x_j\big]+t[2-3x_i-2\sigma]+3v\big[2\sigma\theta_i-[1-\sigma][\sum_{j=\setminus i}[1+\psi_j\vartheta]\theta_j]\big]+2\mu^{nc}\sigma\theta_i \\ &-\mu^c[1-\sigma][\sum_{j=\setminus i}\psi_j\theta_j]\Bigg], \quad \forall i\in\{2,3\}. \quad \text{(EC.7)} \end{aligned}$$

Two DCs Comply ($\Psi=(1,1,0)$, $\rho=2/3$) Under this scenario, DC 1 and DC 2 comply, but DC 3 does not. Again, using (EC.3), we derive the demand function for each DC. This process is similar to that of the previous scenario, which we omit for brevity and derive the DC inverse demand functions as

$$\begin{aligned} r_i^c(x_i,\vec{x}_{\setminus i}) =& \frac{1}{6}\Bigg[3\alpha\big[2\sigma x_i-[1-\sigma]\sum_{j=\setminus i} x_j\big]+t[2-3x_i-2\sigma]+3v\big[[1+\vartheta]2\sigma\theta_i-[1-\sigma][\sum_{j=\setminus i}\theta_j]\big] \\ &+2\mu^c\big[2\sigma\theta_i-[1-\sigma][\sum_{j=\setminus i}\psi_j\theta_j]\big]-2\mu^{nc}[1-\sigma][\sum_{j=\setminus i}\psi_j\theta_j]\Bigg], \quad \forall i\in\{1,2\}, \\ r_i^{nc}(x_i,\vec{x}_{\setminus i}) =& \frac{1}{6}\Bigg[3\alpha\big[2\sigma x_i-[1-\sigma]\sum_{j=\setminus i} x_j\big]+t[2-3x_i-2\sigma]+3v\big[2\sigma\theta_i-[1+\vartheta][1-\sigma][\sum_{j=\setminus i}\theta_j]\big] \\ &+2\mu^{nc}\big[2\sigma\theta_i-[1-\sigma][\sum_{j=\setminus i}\psi_j\theta_j]\big]-2\mu^c[1-\sigma][\sum_{j=\setminus i}\psi_j\theta_j]\Bigg], \quad \text{if } i{=}3. \quad \text{(EC.8)} \end{aligned}$$

Full Compliance ($\Psi=(1,1,1)$, $\rho=1$) Under this scenario, all DCs comply. The DCs' inverse demand functions are derived in a similar process to the previous scenarios as

$$r_i^c(x_i,\vec{x}_{\setminus i},\Psi)=\frac{1}{6}\Bigg[3\alpha\big[2\sigma x_i-[1-\sigma]\sum_{j=\setminus i}x_j\big]+t[2-3x_i-2\sigma]+3v\big[[1+\vartheta]2\sigma\theta_i-[1-\sigma][\sum_{j=\setminus i}\theta_j]\big] + 3\mu^c\big[2\sigma\theta_i-[1-\sigma][\sum_{j=\setminus i}\theta_j]\big]\Bigg],\quad \forall i\in\{1,2,3\}. \quad \text{(EC.9)}$$

Next, we summarize the inverse demand function in pre- and post-DPR scenarios.

Condensed Demand and Inverse Demand Notation ($\Psi=(\psi_1,\psi_2,\psi_3)$, $\rho=[\psi_1+\psi_2+\psi_3]/3$) Considering all four pre- and post-DPR scenarios discussed above in (EC.4), (EC.5), (EC.6), (EC.7), (EC.8), and (EC.9), we can collapse and condense the equations for demand and inverse demand and derive it as a function of compliance vector $\Psi=(\psi_1,\psi_2,\psi_3)$ as

$$x_i(r_i,\vec{r}_{\setminus i},\Psi)=\frac{1}{3\big[t-2\alpha[2\sigma-1]\big]\big[t-\alpha[\sigma+1]\big]}\Bigg[2[1-\sigma]\big[t^2+3\alpha[\sum_{j=\setminus i}r_j]-t\alpha[1+\sigma]\big]-6r_i[t+\alpha[1-3\sigma]] + 2[3[v+\psi_i\vartheta]+\rho\mu^{k_i}]\Big[\theta_i\big[t\sigma-\alpha[2\sigma^2+\sigma-1]\big]-t[1-\sigma]\sum_{j\in\{\setminus i:\ k_j=k_i\}}\theta_j\Big]-\sum_{j\in\{\setminus i:\ k_j=\setminus k_i\}}[3[v+\psi_j\vartheta]+\rho\mu^{\setminus k_i}]\theta_j\Bigg],\quad \forall i\in\{1,2,3\}, \quad \text{(EC.10)}$$

$$r_i(x_i,\vec{x}_{\setminus i},\Psi)=\frac{1}{6}\Bigg[3\alpha\big[2\sigma x_i-[1-\sigma]\sum_{j=\setminus i}x_j\big]+t[2-3x_i-2\sigma]+3v\big[[1+\psi_i\vartheta]2\sigma\theta_i-[1-\sigma]\sum_{j=\setminus i}[1+\psi_j\vartheta]\theta_j\big] + 3\rho\mu^{k_i}[1-\sigma]\sum_{j\in\{\setminus i:\ k_j=k_i\}}\theta_j-3\rho\mu^{\setminus k_i}[1-\sigma]\sum_{j\in\{\setminus i:\ k_j=\setminus k_i\}}\theta_j\Bigg],\quad \forall i\in\{1,2,3\}, \quad \text{(EC.11)}$$

where $k_i\in\{c,nc\}$ represents compliance or non-compliance of DC i. In the above equations, the proportion of compliant DCs, ρ, is derived from compliance vector as $\rho=[\psi_1+\psi_2+\psi_3]/3$. Considering compliant and non-compliant demand and inverse demands, these are determined based on the compliance of the DCs. Specifically, for demand, $x_i^c(\cdot,\Psi)=x_i\big(\cdot,\Psi=(\psi_i=1,\vec{\psi}_{\setminus i})\big)$ and $x_i^{nc}(\cdot,\Psi)=x_i\big(\cdot,\Psi=(\psi_i=0,\vec{\psi}_{\setminus i})\big)$. Similarly, for inverse demand, $r_i^c(\cdot,\Psi)=r_i\big(\cdot,\Psi=(\psi_i=1,\vec{\psi}_{\setminus i})\big)$ and $r_i^{nc}(\cdot,\Psi)=r_i\big(\cdot,\Psi=(\psi_i=0,\vec{\psi}_{\setminus i})\big)$.

Next, we inspect the properties of demand and inverse demand functions and compare them across different compliance scenarios to validate the assumptions of our general-form model.

A.6. Verification of Assumptions

Having derived the demand and inverse demand functions in each of the compliance scenarios in (EC.10) and (EC.11), respectively, we can proceed to test the Assumptions of our general-form model against those derived using the Salop-based utility function.

Assumption 1 Using the inverse demand function for the scenarios above, we can confirm that the inverse demand functions increase in capability (that is, $\partial r_i/\partial\theta_i>0$); decrease in own output (that is, $\partial r_i/\partial x_i<0$) given that the profit function is concave; and decrease in other DCs' output (that is, $\partial r_i/\partial x_{\setminus i}<0$). Moreover, inverse demand is linear with respect to own output (that is, $\partial^2 r_i/\partial x_i^2=0$). Thereby, Assumption 1(a) is satisfied. Additionally, we can see that the marginal inverse demand is linear with respect to capability (that is, $\partial^2 r_i/[\partial x_i\partial\theta_i]=0$), therefore, Assumption 1(b) is satisfied as well.

Assumption 2 To study the impact of ρ on non-compliant DCs, we focus on a non-compliant DC i. We verify that as ρ increases, inverse demand for the non-compliant DC i decreases. For example, considering $i=3$, as we go from scenario $\Psi=(0,0,0)$, $\rho=0$, to scenario $\Psi=(1,0,0)$, $\rho=1/3$, to scenario $\Psi=(1,1,0)$, $\rho=2/3$, non-compliant DC inverse demand decreases. Inspecting the inverse demand in (EC.11), it is straightforward to confirm this. In each step increase in ρ above (that is, an increase of 1/3 in ρ), the inverse demand for the non-compliant DC i ($\psi_i=0$) decreases by $\left[[1-\sigma]\sum_{j=\backslash i}\left[\psi_j[\mu^c+\vartheta]\theta_j+[1-\psi_j]\mu^{nc}\theta_j\right]-2\sigma\mu^{nc}\theta_i\right]/6>0$. This effect is due to the other DCs becoming compliant, which increases the benefit they provide to users compared to the non-compliant DC, and reduces the DC i's inverse demand (price) function. Thus, non-compliant inverse demand decreases in the proportion of compliant DCs (that is, $\partial r_i^{nc}/\partial\rho<0$) and the first part of Assumption 2 is satisfied. Moreover, the above effect does not depend on DC i's output (x_i), implying that marginal non-compliant inverse demand is constant in the proportion of compliant DCs (that is, $\partial^2 r_i^{nc}/[\partial\rho\partial x_i]=0$), therefore, the second part of Assumption 2 is satisfied.

We now show that when some DCs choose to provide the additional feature of portability this does not cause users to leave the market. That is, the increased number and attractiveness of compliant DCs results in users switching from non-compliant DCs to compliant DCs. Without loss of generality, we focus on ρ increasing from scenario $\Psi=(0,0,0)$, $\rho=0$, to scenario $\Psi=(1,0,0)$, $\rho=1/3$, to scenario $\Psi=(1,1,0)$, $\rho=2/3$, and to scenario $\Psi=(1,1,1)$, $\rho=1$. In mathematical terms, using (EC.10), it is straightforward to show that the above condition holds in each step increase in ρ as

$$[x_1(\cdot,\Psi=(1,0,0))-x_1(\cdot,\Psi=(0,0,0))]\geq \\ -\left[[x_2(\cdot,\Psi=(1,0,0))-x_2(\cdot,\Psi=(0,0,0))]+[x_3(\cdot,\Psi=(1,0,0))-x_3(\cdot,\Psi=(0,0,0))]\right],$$

$$[x_1(\cdot,\Psi=(1,1,0))-x_1(\cdot,\Psi=(1,0,0))]+[x_2(\cdot,\Psi=(1,1,0))-x_2(\cdot,\Psi=(1,0,0))]\geq \\ -[x_3(\cdot,\Psi=(1,1,0))-x_3(\cdot,\Psi=(1,0,0))],$$

$$[x_1(\cdot,\Psi=(1,1,1))-x_1(\cdot,\Psi=(1,1,0))]+[x_2(\cdot,\Psi=(1,1,1))-x_2(\cdot,\Psi=(1,1,0))] \\ +[x_3(\cdot,\Psi=(1,1,1))-x_3(\cdot,\Psi=(1,1,0))]\geq 0.$$

The above equations illustrate that the increased number and attractiveness of compliant DCs results in users switching from non-compliant DCs to compliant DCs, and that this results in increased aggregate output for compliant DCs, thus confirming our setup above Assumption 2.

Assumption 4(a) Our results also demonstrate that as capability increases, compliant DCs' inverse demand increases more than the non-compliant DCs' inverse demand. In other words, from the inverse demand function in (EC.11), we find that $\partial r_i^c/\partial\theta_i>\partial r_i^{nc}/\partial\theta_i$. This supports our Assumption 4(a).

A.7. Discussion of User Behavior

Having derived the demand, inverse demand, and their characteristics, we can discuss user behavior in response to changes in the proportion of compliant DCs (ρ) due to imposition of a policy instrument. To discuss the implications, we focus on the representative case in which we compare the scenario where only

DC 1 is compliant, $\Psi=(1,0,0)$, to the scenario where both DC 1 and DC 2 are compliant, $\Psi=(1,1,0)$. We note that our focus on this comparison is without loss of generality, as the components of our discussion can be extended to comparison of any other compliance scenario.

As DC 2 becomes compliant (that is, moving from scenario $\Psi=(1,0,0)$ to scenario $\Psi=(1,1,0)$), per (EC.2), the utility from DC 1 and DC 2 rises, and even though the utility from DC 3 may also rise, it does so less than the utility from DC 1 and DC 2. As a result, the indifference points between the DCs shift as depicted in Figure EC.2. Specifically, $\hat{y}^2_{2,3}$ and $\hat{y}^3_{2,3}$ shift clockwise, $\hat{y}^1_{1,3}$ and $\hat{y}^3_{1,3}$ shift counter-clockwise, and $\hat{y}^1_{1,2}$ and $\hat{y}^2_{1,2}$ may either shift clockwise or counter-clockwise. Due to these shifts, users neighboring the indifference points switch their DCs.

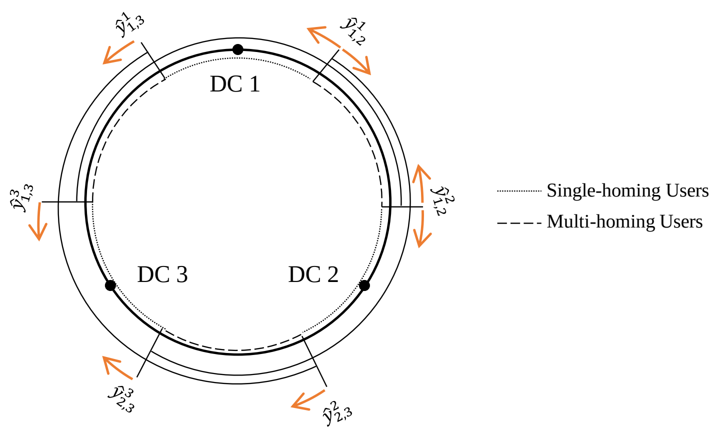


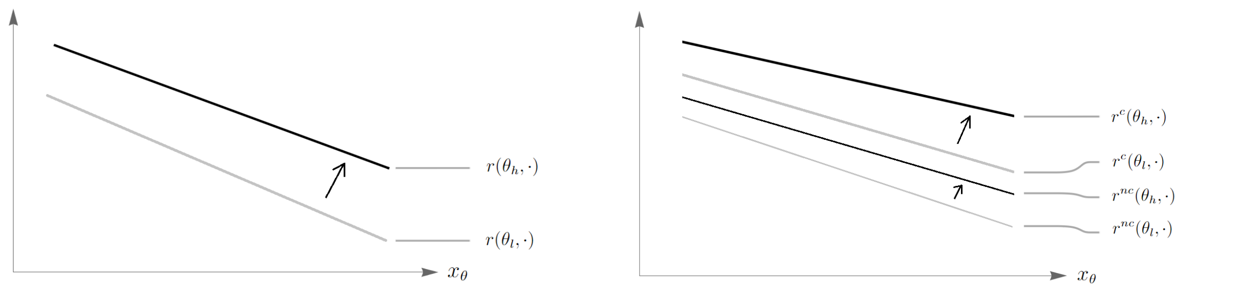
Figure EC.2 User behavior in response to DC 2 becoming compliant ($\Psi=(1,0,0)$ to $\Psi=(1,1,0)$)

Appendix B: Inverse Demand, Optimal Output, and Assumption 4(b)

In this Appendix, we describe the effect of capability on Inverse demand, illustrate the properties of the revenues, explain how output choices are made by a DC given an inverse demand, and provide the basis for Assumption 4(b).

B.1. The Effect of Capability on Inverse Demand

We model a Cournot setting where DCs choose output in order to maximize profits (Tirole 1988, pp. 218-221). Consider a setting where market demand for a compliant DC with capability θ is captured by the compliant inverse demand function, $r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})$. If the same DC θ does not comply with DPR, then its market demand is captured by the non-compliant inverse demand function, $r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})$. Pre-DPR, a more capable DC, θ_h, generates higher inverse demand compared to a less capable DC, θ_l, as illustrated for an example in Figure EC.3(a). Similarly, post-DPR, θ_h generates greater inverse demand from compliance as compared to θ_l; and θ_h generates greater inverse demand from non-compliance as compared to θ_l. The post-DPR inverse demands for θ_h and θ_l are shown in Figure EC.3(b).



(a) Inverse demand (b) Compliant and non-compliant inverse demand

Figure EC.3 Impact of capability on inverse demand functions, $\theta_h > \theta_l$

B.2. Optimal Output Choice and Assumption 4(b)

Payoffs from compliance depend on the compliant inverse demand and cost given output (ignoring compliance costs for simplicity), $\Pi^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta}) = x_\theta r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta}) - C(x_\theta)$. If fines are zero, then payoffs from non-compliance depend on the non-compliant inverse demand and cost, $\Pi^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta}) = x_\theta r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta}) - C(x_\theta)$, where inverse demand is decreasing and concave in output and cost is increasing and convex in output. A DC maximizes profit by choosing the output such that the marginal revenue in the first set of square brackets equals the marginal cost in the second set of square brackets in

$$\frac{\partial \Pi^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})}{\partial x_\theta} = MR^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta}) - MC(x_\theta) = \Big[r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta}) + x_\theta \frac{\partial r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})}{\partial x_\theta}\Big] - \Big[\frac{\partial C(x_\theta)}{\partial x_\theta}\Big]. \tag{EC.12}$$

The effect of increasing output on non-compliant marginal revenues and marginal costs is

$$\frac{\partial \Pi^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})}{\partial x_\theta} = MR^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta}) - MC(x_\theta) = \Big[r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta}) + x_\theta \frac{\partial r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})}{\partial x_\theta}\Big] - \Big[\frac{\partial C(x_\theta)}{\partial x_\theta}\Big]. \tag{EC.13}$$

In general, if compliant inverse demand and non-compliant inverse demand are such that each of the terms within the first set of square brackets in (EC.12) is larger (smaller) than its corresponding term in (EC.13), then optimal output and profits from compliance are larger (smaller). So, compliant optimal output and profits are larger when $r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta}) > r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})$ and $\partial r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})/\partial x_\theta > \partial r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})/\partial x_\theta$ over its domain. The converse is also true. However, if demands are such that only one of $r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta}) > r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})$ and $\partial r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})/\partial x_\theta > \partial r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})/\partial x_\theta$ is true, then it is possible that compliant output may be lower while profits are larger. We now derive the condition under which optimal output for compliance is higher than optimal output for non-compliance. We denote x_θ^c as the optimal output from compliance where inverse demand is $r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})$, and x_θ^{nc} as the optimal output from non-compliance where inverse demand is $r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})$.

Our Assumption 4(b) can be derived as follows. Subtracting (7) from (4), we get

$$\frac{\partial \Pi^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})}{\partial x_\theta} - \frac{\partial \Pi^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})}{\partial x_\theta} = \Big[r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta}) + x_\theta \frac{\partial r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})}{\partial x_\theta} - \frac{\partial C(x_\theta)}{\partial x_\theta} - \frac{\partial \gamma(x_\theta^c, I)}{\partial x_\theta^c}\Big] - \Big[r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta}) + x_\theta \frac{\partial r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})}{\partial x_\theta} - \frac{\partial C(x_\theta)}{\partial x_\theta}\Big].$$

When the above equation is evaluated at $x_\theta = x_\theta^c$, the first sets of square brackets is zero because $\partial \Pi^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})/\partial x_\theta|_{x_\theta = x_\theta^c} = 0$ by the first-order condition. If marginal profit from non-compliance in the second set of square brackets when evaluated at x_θ^c is less than zero, then it is profit maximizing to decrease output below x_θ^c. Thus, for a DC that makes identical profit from compliance and non-compliance, the condition for output from compliance to be larger than output from non-compliance can be restated as

$$\left[r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})+x_\theta\frac{\partial r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})}{\partial x_\theta}-\frac{\partial C(x_\theta)}{\partial x_\theta}\right]\Bigg|_{x_\theta=x_\theta^c}<0.$$

Clearly a variable fine on revenue acts as an externality, further reducing marginal revenue and optimal output from non-compliance. In other words, if marginal profits from non-compliance are negative when evaluated at the optimum output from compliance, then non-compliant output is smaller. This forms the basis of our Assumption 4(b) where we define the space where our theories are applicable. The space is defined as one where for a given DC making identical payoffs from compliance and non-compliance, its marginal revenues from non-compliance are smaller than its marginal revenues from compliance. This condition does not have to hold throughout the range of θ, but rather at the θ where payoffs from compliance are equal to payoffs from non-compliance.

Appendix C: Specific-Form Examples

Our model captures a wide variety of possible industry and competition settings given the generality of its assumptions. In this Appendix, we demonstrate stylized, specific-form models based on standard additive inverse demand functions with the characteristics assumed in our general model. We demonstrate how such inverse demand functions yield similar basic results as provided in our general model. Given the limitations of specific-form modeling, we cannot include all of the features of our general model into one specific-form example. Instead, we propose two separate models: one which captures the interaction of many DCs in terms of their compliance and cross-DC network effects without considering competition among DCs, and one which captures competition between two DCs in a Cournot setting. Even though these models do not have the generalizability of our main model and their ensuing results may not be as rich, they serve to demonstrate how our general model based on inverse demands can be set up with a specific functional form.

For the purpose of the specific-form examples, we consider a quadratic business cost function as

$$C_i = K + cx_i^2, \tag{EC.14}$$

where K is the fixed business costs and c is the per-unit-of-output business costs. We assume that K is set so that the least capable DC ($\theta = 0$) breaks even (makes a profit of zero). This does not impact our results, but simplifies the exposition. As for compliance costs, we consider

$$\gamma_i(x_i, I) = Gx_i[1 - I], \tag{EC.15}$$

where G is the coefficient for compliance costs, and $I \in [0,1]$ is the policy-maker's level of investment to reduce compliance cost. This compliance cost function is decreasing in investments in total and at the margin, as is assumed in Assumption 3(a). Further, the combined business and compliance costs are convex, as per Assumption 3(b).

C.1. Specific-Form Example with Many DCs in the Industry

We start with the inverse demand functions for pre-DPR, compliant, and non-compliant cases.

C.1.1. Pre-DPR We follow the standard additive inverse demand function with network effects proposed in the seminal work of Katz and Shapiro (Katz and Shapiro 1985, p. 427). Particularly, we assume the inverse demand function pre-DPR as

$$r = A + [\theta + \beta]x - ax,$$

where β is the network effect due to additional DSs present at a DC, and A and a are the coefficients of the inverse demand function, set so that the inverse demand function is downward sloping in output x. This requires $a > \theta + \beta$. It is easy to inspect that this inverse demand function satisfies Assumption 1: increasing in capability as well as decreasing and concave in output; and marginal inverse demand is increasing in capability. Even though this inverse demand function does not capture the effect from other DCs' output on a given DC's inverse demand, it satisfies the assumptions of our model.

The revenue is derived as xr. The profit function prior to imposition of DPR, that is, Π, is derived by subtracting business costs from the revenue, that is, $\Pi = xr - C$, with business costs C defined in (EC.14). A given DC with capability θ maximizes profit with respect to its output x_θ.

$$\max_{x_\theta} \Pi = x_\theta r - C = x_\theta \big[A + [\theta + \beta]x_\theta - ax_\theta\big] - [K + cx_\theta^2].$$

From the first-order condition we have:

$$\frac{\partial \Pi}{\partial x_\theta} = 0 \implies x_\theta^* = \frac{A}{2[a + c - \beta - \theta]}.$$

We can confirm the second-order condition holds, as we have

$$\frac{\partial^2 \Pi}{\partial x_\theta^2} = -2[a + c - \beta - \theta] < 0.$$

Therefore, the optimal output for each DC is given as $x_\theta^* = A/2[a + c - \beta - \theta]$.

C.1.2. Post-DPR Post-DPR, given the assumptions in our model, we take compliant and non-compliant inverse demand functions as

$$r^c = A + \big[\theta + \beta - \lambda[\Theta - \theta]\big]x - ax \quad \text{and} \quad r^{nc} = A + [\theta + \beta - \delta\rho]x - ax,$$

where δ is the marginal elasticity of the non-compliant inverse demand with respect to the proportion of compliant DCs. It captures the rate at which non-compliant DCs lose, and this depends on the proportion of compliant DCs, ρ. In the above inverse demand functions, Θ is capability of the DC that loses as many DSs as it gains if it complies, thus the porting of DSs does not impact it as DPR is enforced. Finally, λ is the extent to which DCs are impacted by porting of DSs. Compliant DCs with $\theta < \Theta$ suffer a net loss of DSs as DPR is imposed, and compliant DCs with $\theta > \Theta$ benefit from a net gain of DSs as DPR is imposed.

The parameter δ in the above non-compliant inverse demand function captures the magnitude of cross-DC network effect, which reduces the revenue of the non-compliant DCs. On the other hand, the parameter λ captures the degree to which porting impacts the compliant DCs. Both δ and λ depend on the porting effectiveness: the more effective the porting, the higher the losses from non-compliance, and the more the compliant DCs are impacted by porting. In other words, higher porting effectiveness manifests itself in higher δ and λ. Equivalently, if a parameter η is considered as porting effectiveness, then it interacts with the term λ in r^c and the term δ in r^{nc}. Because one can define the new parameters $\delta' = \eta\delta$ and $\lambda' = \eta\lambda$, considering η does not have a qualitative impact on our results, thus we do not include it in our model. We assume $a > \beta + \theta - \lambda[\Theta - 1]$ and $a > \beta + \theta - \delta\rho$, so that the inverse demand is downward sloping in output for all DCs.

The inverse demand functions r^c and r^{nc} provided above, in addition to satisfying Assumption 1, satisfy Assumption 2: non-compliant inverse demand and marginal non-compliant inverse demand are decreasing in the proportion of compliant DCs. Further, the compliant and non-compliant inverse demand functions above satisfy Assumption 4(a): capability increases compliant inverse demand more than the non-compliant inverse demand; and Assumption 4(b): marginal revenues from non-compliance are smaller than marginal revenues pre-DPR.

The payoff for the compliant DC is given as $xr^c - C - \gamma$, with compliance costs γ defined in (EC.15). The compliant DC with capability θ sets output that maximizes its payoff as

$$\max_{x_\theta} \Pi^c = x_\theta\Big[A + \big[\theta + \beta - \lambda[\Theta - \theta]\big]x_\theta - a x_\theta\Big] - [K + c x_\theta^2] - G x_\theta[1 - I]. \tag{EC.16}$$

Using the first-order and second-order conditions, the compliant DC's optimal output is given as

$$x_\theta^{c^*} = \frac{A - G[1 - I]}{2[a + c - \beta - \theta + \lambda[\Theta - \theta]]}. \tag{EC.17}$$

On the other hand, the payoff for a non-compliant DC is given as $[1 - f]xr^{nc} - C - F$. The non-compliant DC with capability θ sets output that maximizes its payoff as

$$\max_{x_\theta} \Pi^{nc} = [1 - f]x_\theta\Big[A + [\theta + \beta - \delta\rho]x_\theta - a x_\theta\Big] - [K + c x_\theta^2] - F. \tag{EC.18}$$

Using the first-order and second-order conditions, the non-compliant DC's optimal output is given as

$$x_\theta^{nc^*} = \frac{A[1 - f]}{2[1 - f][a - \beta - \theta + \delta\rho] + 2c}. \tag{EC.19}$$

We find analytically in closed-form the DC that is indifferent between complying and not complying ($\tilde{\theta}$) by setting the profit from compliance (EC.16) and non-compliance (EC.18) at their respective equilibrium outputs (EC.17) and (EC.19) to be equal. Given the complexity of the resulting equation for $\tilde{\theta}$, we do not report it here. We then substitute $\rho = 1 - \tilde{\theta}$, thereby internalizing the proportion of compliant DCs and making the ensuing results independent of ρ. Figure EC.4 which is based on the closed-form solution, shows the optimal profit of the DCs according to their capability pre-DPR and from compliance and non-compliance.

As expected, we confirm that this results in the segmentation as defined in our general model; and that fines and investments increase compliance consistent with Lemma 2, and decrease participation consistent with Theorem 1.

C.2. Specific-Form Example with Cournot Competition in a Duopoly

We start with the inverse demand functions for pre-DPR, compliant, and non-compliant cases. These specifications are similar to those in the model provided in Section C.1 with two major changes. First, the analysis is limited to two DCs. Second, to capture competition between DCs, we include a negative term from the competing DC's output in the inverse demand of the focal DC, which results in a standard Cournot competition model, as we describe below.

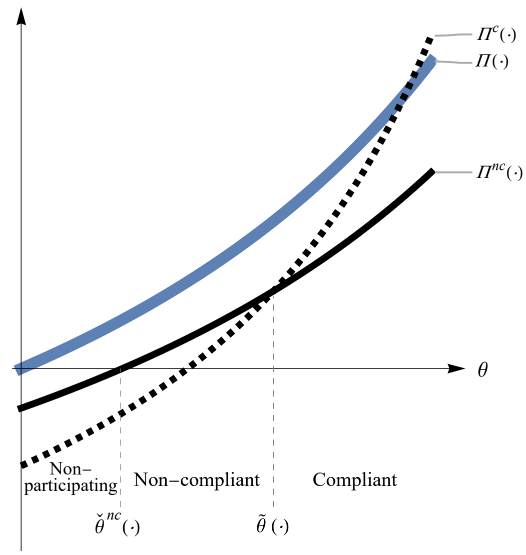


Figure EC.4 Pre-DPR, compliant, and non-compliant payoffs

C.2.1. Pre-DPR We use the same additive inverse demand function with network effects as in Section C.1, but consider this for two DCs, DC 1 and DC 2 with capabilities θ_1 and θ_2, respectively. Considering a standard Cournot setting, we also include the negative impact of the other DC's output on the inverse demand as

$$r_i = A + [\theta_i + \beta]x_{\theta_i} - ax_{\theta_i} - bx_{\theta_{\setminus i}}, \quad \forall i \in \{1,2\},$$

where $b \in \mathbb{R}_{>0}$ is the inverse demand term that captures the competition between DCs in the industry. The inverse demand function is set so that the inverse demand is downward sloping in output x_{θ_i}, which requires $a > \theta_i + \beta$, $\forall i \in \{1,2\}$. This inverse demand function satisfies Assumption 1: increasing in capability as well as decreasing and concave in output; and marginal inverse demand is increasing in capability. Contrary to the parametric model in Section C.1, inverse demand of each DC is strictly decreasing in output from the other DC.

The revenue for each DC i is derived as $x_{\theta_i} r_i$. The profit function prior to imposition of DPR for each DC i, that is, Π_i, is derived by subtracting business costs from the revenue, that is, $\Pi_i = x_{\theta_i} r_i - C_i$, with business costs C_i defined in (EC.14). In our Cournot setting, the DC i with capability θ_i maximizes profit with respect to its output x_{θ_i},

$$\max_{x_{\theta_i}} \Pi_i = x_{\theta_i} r_i - C_i = x_{\theta_i}\left[A + [\theta_i + \beta]x_{\theta_i} - ax_{\theta_i} - bx_{\theta_{\setminus i}}\right] - [K + cx_{\theta_i}^2], \quad \forall i \in \{1,2\}.$$

From the first-order conditions, each DC's best response output is derived as

$$\frac{\partial \Pi_i}{\partial x_{\theta_i}} = 0 \implies x^*_{\theta_i} = \frac{A - bx_{\theta_{\setminus i}}}{2[a + c - \beta - \theta_i]}, \quad \forall i \in \{1,2\}.$$

We can confirm the second-order condition holds, as we have

$$\frac{\partial^2 \Pi_i}{\partial x_{\theta_i}^2} = -2[a + c - \beta - \theta_i] < 0, \quad \forall i \in \{1,2\}.$$

The Cournot equilibrium can be derived by solving the system of equations from the first-order conditions above as

$$x^{eq}_{\theta_i} = \frac{A[2a - b - 2[\beta + \theta_{\setminus i}]]}{4a^2 - b^2 + 4[\beta + \theta_i][\beta + \theta_{\setminus i}] - 4a[2\beta + \theta_i + \theta_{\setminus i}]}, \quad \forall i \in \{1,2\}.$$

C.2.2. Post-DPR According to the assumptions in our model, we assume compliant and non-compliant inverse demand functions similar to those of the model in Section C.1, with the addition of competition effect as

$$r_i^c = A + \big[\theta_i + \beta - \lambda[\Theta - \theta_i]\big] x_{\theta_i} - a x_{\theta_i} - b x_{\theta_{\setminus i}}, \quad \forall i \in \{1,2\},$$

$$r_i^{nc} = A + [\theta_i + \beta - \delta\rho] x_{\theta_i} - a x_{\theta_i} - b x_{\theta_{\setminus i}}, \quad \forall i \in \{1,2\}.$$

We assume $a > \beta + \theta_i - \lambda[\Theta - 1]$ and $a > \beta + \theta_i - \delta\rho$ so that the inverse demand is downward sloping in output for both DCs. Similar to Section C.1 the r_i^c and r_i^{nc} functions provided above satisfy Assumptions 1, 2, and 4. Moreover, the form of the above inverse demand functions is consistent with the one derived using the Salop-based model provided in Appendix A in (EC.11).

After the imposition of DPR, the payoff for a DC that is compliant is given as $\Pi_i^c = x_{\theta_i} r_i^c - C_i - \gamma_i$, with compliance costs γ_i defined in (EC.15). The compliant DC with capability θ_i sets output that maximizes its payoff as

$$\max_{x_{\theta_i}} \Pi_i^c = x_{\theta_i}\Big[A + \big[\theta_i + \beta - \lambda[\Theta - \theta_i]\big] x_{\theta_i} - a x_{\theta_i} - b x_{\theta_{\setminus i}}\Big] - [K + c x_{\theta_i}^2] - G x_{\theta_i}[1 - I], \quad \forall i \in \{1,2\}. \tag{EC.20}$$

Using the first-order and second-order conditions, a compliant DC's best response output is given as

$$x_{\theta_i}^{c^*} = \frac{A - G[1-I] - b x_{\theta_{\setminus i}}}{2[a + c - \beta - \theta_i + \lambda[\Theta - \theta_i]]}, \quad \forall i \in \{1,2\}.$$

Using the above system of equations, the Cournot equilibrium output for each DC is derived as

$$x_{\theta_i}^{c^{eq}} = \frac{[A - G[1-I]][2a - b + 2[c - \beta - \theta_{\setminus i} + \lambda[\Theta - \theta_{\setminus i}]]]}{4[c - \beta - \theta_i + \lambda[\Theta - \theta_i]][c - \beta - \theta_{\setminus i} + \lambda[\Theta - \theta_{\setminus i}]] - b^2}, \quad \forall i \in \{1,2\}. \tag{EC.21}$$

On the other hand, the payoff for a non-compliant DC is given as $\Pi_i^{nc} = [1-f] x_{\theta_i} r_i^{nc} - C_i - F$. A non-compliant DC with capability θ_i sets output that maximizes its payoff as

$$\max_{x_{\theta_i}} \Pi_i^{nc} = [1-f] x_{\theta_i}\Big[A + [\theta_i + \beta - \delta\rho] x_{\theta_i} - a x_{\theta_i} - b x_{\theta_{\setminus i}}\Big] - [K + c x_{\theta_i}^2] - F, \quad \forall i \in \{1,2\}. \tag{EC.22}$$

Using the first-order and second-order conditions, a non-compliant DC's best response output is given as

$$x_{\theta_i}^{nc^*} = \frac{[1-f][A - b x_{\theta_{\setminus i}}]}{2[1-f][a - \beta - \theta_i + \delta\rho] + 2c}, \quad \forall i \in \{1,2\}.$$

Using the above system of equations, the Cournot equilibrium output for each DC is derived as

$$x_{\theta_i}^{nc^{eq}} = \frac{[1-f]A[2a[1-f] - b[1-f] - 2[c - [1-f][\beta + \theta_{\setminus i} - \delta\rho]]]}{[1-f]^2[4a^2 - b^2] + 4a[1-f][2c - [1-f][2\beta + \theta_i - \theta_{\setminus i} - 2\delta\rho]] + \Gamma}, \quad \forall i \in \{1,2\}, \tag{EC.23}$$

where $\Gamma = 4[c - [1-f][\beta + \theta_i - \delta\rho]][c - [1-f][\beta + \theta_{\setminus i} - \delta\rho]]$. At this point, we find the proportion of compliant DCs, ρ, by comparing the profit from compliance (EC.20) and non-compliance (EC.22) at their respective equilibrium outputs (EC.21) and (EC.23). Given that there are only two DCs in the industry, the proportion of compliant DCs in this case takes one of the possible values in $\rho \in \{0, 0.5, 1\}$. Internalizing the proportion of compliant DCs, ρ, makes the ensuing results independent of ρ. Figure EC.5 shows the optimal compliance decision of the two DCs according to their capabilities in an illustrative example.

Where both DCs are highly capable, they both decide to comply. However, if one of the DCs is significantly more capable than the other DC, then only the more capable DC complies and the less capable DC does

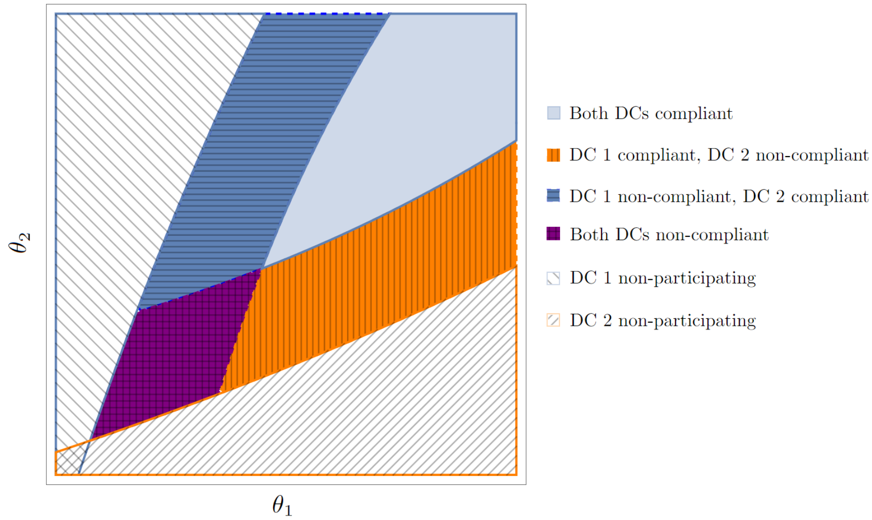


Figure EC.5 Equilibrium compliance decisions in the duopoly case

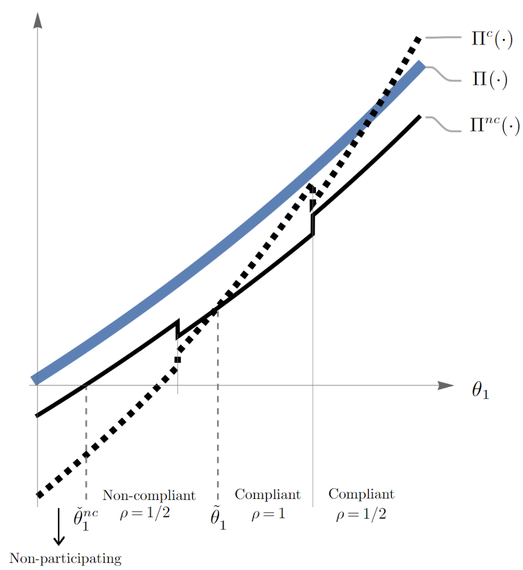


Figure EC.6 Pre-DPR, compliant, and non-compliant payoffs for DC 1 given the capability of DC 2

not comply. Considering these equilibrium compliance decisions, Figure EC.6 shows the optimal pre-DPR, compliant, and non-compliant payoffs for different capabilities of DC 1 (θ_1) given the capability of DC 2 (θ_2). We confirm that fines and investments increase compliance, consistent with Lemma 2, and decrease participation, consistent with Theorem 1.

Appendix D: Proofs of Lemmas and Theorems

We refer to equations in the main paper for the proofs within this section.

Lemma 1: *Payoffs and output increase with capability. Payoffs from compliance increase faster in capability than do payoffs from non-compliance. DCs that are more capable than $\tilde{\theta}(\cdot)$ comply with DPR. The optimal output from compliance for $\tilde{\theta}(\cdot)$ is higher than its optimal output from non-compliance.*

Proof: We begin by proving the output-related parts of the Lemma and then work backwards. Differentiating (4) with respect to capability for compliant DCs, we get

$$\frac{\partial \psi_1(\cdot)}{\partial \theta} = x^c_\theta \frac{\partial^2 r^c(\theta, \rho, x^c_\theta, \vec{x}_{\setminus\theta})}{\partial\theta\partial x^c_\theta} + \frac{\partial r^c(\theta, \rho, x^c_\theta, \vec{x}_{\setminus\theta})}{\partial \theta} > 0,$$

which is positive by Assumptions 1(a) and (b). From (5) and the above equation, and using the implicit function theorem,

$$\frac{\partial x^c_\theta(\rho, \vec{x}_{\setminus\theta}, I)}{\partial\theta} = -\frac{\partial\psi_1(\cdot)/\partial\theta}{\partial\psi_1(\cdot)/\partial x^c_\theta} > 0.$$

Differentiating (7) with respect to the capability for non-compliant DCs, we get

$$\frac{\partial \psi_2(\cdot)}{\partial \theta} = [1-f][x^{nc}_\theta \frac{\partial^2 r^{nc}(\theta, \rho, x^{nc}_\theta, \vec{x}_{\setminus\theta})}{\partial\theta\partial x^{nc}_\theta} + \frac{\partial r^{nc}(\theta, \rho, x^{nc}_\theta, \vec{x}_{\setminus\theta})}{\partial \theta}\Big] > 0,$$

which is again positive by Assumptions 1(a) and (b). Using the implicit function theorem, we have

$$\frac{\partial x^{nc}_\theta(\rho, \vec{x}_{\setminus\theta}, f)}{\partial\theta} = -\frac{\partial\psi_2(\cdot)/\partial\theta}{\partial\psi_2(\cdot)/\partial x^{nc}_\theta} > 0.$$

The numerator is positive, and the denominator is negative from (8), so that $\partial x^{nc}_\theta(\rho, \vec{x}_{\setminus\theta}, f)/\partial\theta > 0$.

Now we compare DC output for compliant and non-compliant DCs. Differentiating payoffs from compliance (3) and non-compliance (6) with respect to output gives

$$\frac{\partial \Pi^c(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta}, I)}{\partial x_\theta} = x_\theta \frac{\partial r^c(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta})}{\partial x_\theta} + r^c(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta}) - \frac{\partial C(x_\theta)}{\partial x_\theta} - \frac{\partial \gamma(x_\theta, I)}{\partial x_\theta}, \quad \text{and}$$

$$\frac{\partial \Pi^{nc}(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta}, F, f)}{\partial x_\theta} = [1-f]\Big[x_\theta \frac{\partial r^{nc}(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta})}{\partial x_\theta} + r^{nc}(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta})\Big] - \frac{\partial C(x_\theta)}{\partial x_\theta}.$$

For the DC that generates the same payoffs from compliance and non-compliance, $\tilde{\theta}$, taking the variable fine as being set to zero, the difference between the above equations is

$$\frac{\partial \Pi^c(\tilde{\theta}, \rho, x_{\tilde{\theta}}, \vec{x}_{\setminus\tilde{\theta}}, I)}{\partial x_{\tilde{\theta}}} - \frac{\partial \Pi^{nc}(\tilde{\theta}, \rho, x_{\tilde{\theta}}, \vec{x}_{\setminus\tilde{\theta}}, F, f)}{\partial x_{\tilde{\theta}}} = -\Big[r^{nc}(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta}) + x_\theta \frac{\partial r^{nc}(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta})}{\partial x_\theta} - \frac{\partial C(x_\theta)}{\partial x_\theta}\Big],$$

which is positive from Assumption 4(b) when evaluated at $x_\theta = x^c_\theta$. Thus, for the DC that makes equal payoffs from compliance and non-compliance, output is higher if it complies. This is reinforced with a positive variable fine. Consequently, for $\tilde{\theta}$, optimal output from compliance is higher than optimal output from non-compliance,

$$x^c_{\tilde{\theta}}(\rho, \vec{x}_{\setminus\tilde{\theta}}, I) > x^{nc}_{\tilde{\theta}}(\rho, \vec{x}_{\setminus\tilde{\theta}}, f). \tag{EC.24}$$

Next, differentiating (9) with respect to $\tilde{\theta}(\cdot)$ yields

$$\frac{\partial \psi_3(\cdot)}{\partial \tilde{\theta}} = x^c_{\tilde{\theta}}(\cdot)\frac{\partial r^c(\tilde{\theta}, \rho, x^c_{\tilde{\theta}}(\cdot), \vec{x}_{\setminus\tilde{\theta}}(\cdot))}{\partial\tilde{\theta}} - x^{nc}_{\tilde{\theta}}(\cdot)\frac{\partial r^{nc}(\tilde{\theta}, \rho, x^{nc}_{\tilde{\theta}}(\cdot), \vec{x}_{\setminus\tilde{\theta}}(\cdot))}{\partial\tilde{\theta}} + f x^{nc}_{\tilde{\theta}}(\cdot)\frac{\partial r^{nc}(\tilde{\theta}, \rho, x^{nc}_{\tilde{\theta}}(\cdot), \vec{x}_{\setminus\tilde{\theta}}(\cdot))}{\partial\tilde{\theta}} > 0. \tag{EC.25}$$

The sum of the first two terms is positive because $x^c_{\tilde\theta}(\rho,\vec{x}_{\setminus\tilde\theta},I) > x^{nc}_{\tilde\theta}(\rho,\vec{x}_{\setminus\tilde\theta},f)$ from EC.24 and $\partial r^c(\cdot)/\partial\tilde\theta > \partial r^{nc}(\cdot)/\partial\tilde\theta$ from Assumption 4(a). The third term is positive from Assumption 1(a) so the above equation can be signed positive. Consequently, $\partial\psi_3(\cdot)/\partial\tilde\theta > 0$, and only DCs with $\theta \geq \tilde\theta(\cdot)$ comply with DPR.

Next, (EC.25) can be rewritten as $\partial\Pi^c(\cdot)/\partial\tilde\theta - \partial\Pi^{nc}(\cdot)/\partial\tilde\theta$ where arguments in the payoffs are as per (3) and (6) except with outputs at optimal value functions, and which from the above discussion is positive. Because (EC.25) holds for all values of $\tilde\theta(\cdot)$, it holds for all values of θ. Hence,

$$\frac{\partial\Pi^c(\cdot)}{\partial\theta} > \frac{\partial\Pi^{nc}(\cdot)}{\partial\theta},$$

and payoffs from compliance increase faster than payoffs from non-compliance. Finally, that payoffs increase in capability is straightforward from (3), (6), and Assumption 1(a) because inverse demand increases in capability but costs, fines, and investments are not functions of capability. □

Lemma 2: *Fixed fines, variable fines, and investments increase the proportion of compliant DCs.*

Proof: Differentiating (9) with respect to variable fines and simplifying using the envelope theorem yields

$$\frac{\partial\psi_3(\cdot)}{\partial f} = x^{nc}_{\tilde\theta}(\cdot)r^{nc}(\tilde\theta,\rho,x^{nc}_{\tilde\theta}(\cdot),\vec{x}_{\setminus\tilde\theta}(\cdot)) > 0,$$

because a participating DC's revenue is positive. Then, using (EC.25), and by the implicit function theorem

$$\frac{\partial\tilde\theta(\cdot)}{\partial f} = -\frac{\partial\psi_3(\cdot)/\partial f}{\partial\psi_3(\cdot)/\partial\tilde\theta} < 0.$$

Now, differentiating (9) with respect to fixed fines yields $\partial\psi_3(\cdot)/\partial F = 1$. By the implicit function theorem, it is straightforward that

$$\frac{\partial\tilde\theta(\cdot)}{\partial F} = -\frac{\partial\psi_3(\cdot)/\partial F}{\partial\psi_3(\cdot)/\partial\tilde\theta} < 0.$$

The relative effect of fixed and variable fines on compliance can be quantified as

$$\frac{\partial\tilde\theta(\cdot)}{\partial f} = x^{nc}_{\tilde\theta}(\cdot)r^{nc}(\tilde\theta,\rho,x^{nc}_{\tilde\theta}(\cdot),\vec{x}_{\setminus\tilde\theta}(\cdot))\frac{\partial\tilde\theta(\cdot)}{\partial F}.$$

Finally, differentiating (9) with respect to investments and using the envelope theorem yields $\partial\psi_3(\cdot)/\partial I = -\partial\gamma(x^c_{\tilde\theta}(\cdot),I)/\partial I > 0$. By the implicit function theorem,

$$\frac{\partial\tilde\theta(\cdot)}{\partial I} = -\frac{\partial\psi_3(\cdot)/\partial I}{\partial\psi_3(\cdot)/\partial\tilde\theta} < 0.$$

The result follows from $d\rho(\cdot)/d\tilde\theta < 0$. □

Lemma 3: *For non-compliant DCs, output decreases in (a) the proportion of compliant DCs, and (b) fixed fines, variable fines, and investments.*

Proof: Part *(a)*: Differentiating (7) with respect to the proportion of compliant DCs, we get

$$\frac{\partial\psi_2(\cdot)}{\partial\rho} = -[1-f]\Big[x^{nc}_\theta\frac{\partial^2 r^{nc}(\theta,\rho,x^{nc}_\theta,\vec{x}_{\setminus\theta})}{\partial\rho\partial x^{nc}_\theta} + \frac{\partial r^{nc}(\theta,\rho,x^{nc}_\theta,\vec{x}_{\setminus\theta})}{\partial\rho}\Big] < 0,$$

which is negative by Assumption 2. Then, using (8), by the implicit function theorem, we have

$$\frac{\partial x_\theta^{nc}(\rho,\vec{x}_{\setminus\theta},f)}{\partial\rho}=-\frac{\partial\psi_2(\cdot)/\partial\rho}{\partial\psi_2(\cdot)/\partial x_\theta^{nc}}<0.$$

Part *(b)*: Differentiating (7) with respect to investments, we get

$$\frac{\partial\psi_2(\cdot)}{\partial I}=-[1-f]\Big[x_\theta^{nc}\frac{\partial^2 r^{nc}(\theta,\rho,x_\theta^{nc},\vec{x}_{\setminus\theta})}{\partial\rho\partial x_\theta^{nc}}+\frac{\partial r^{nc}(\theta,\rho,x_\theta^{nc},\vec{x}_{\setminus\theta})}{\partial\rho}\Big]\frac{\partial\rho(\cdot)}{\partial I}<0,$$

which is negative by Assumption 2 and Lemma 2. Using (8), by the implicit function theorem,

$$\frac{\partial x_\theta^{nc}(\rho,\vec{x}_{\setminus\theta},f)}{\partial I}=-\frac{\partial\psi_2(\cdot)/\partial I}{\partial\psi_2(\cdot)/\partial x_\theta^{nc}}<0.$$

Differentiating (7) with respect to fixed fines, we get

$$\frac{\partial\psi_2(\cdot)}{\partial F}=-[1-f]\Big[x_\theta^{nc}\frac{\partial^2 r^{nc}(\theta,\rho,x_\theta^{nc},\vec{x}_{\setminus\theta})}{\partial\rho\partial x_\theta^{nc}}+\frac{\partial r^{nc}(\theta,\rho,x_\theta^{nc},\vec{x}_{\setminus\theta})}{\partial\rho}\Big]\frac{\partial\rho(\cdot)}{\partial F}<0,$$

which is negative by Assumption 2 and Lemma 2. Using (8), by the implicit function theorem,

$$\frac{\partial x_\theta^{nc}(\rho,\vec{x}_{\setminus\theta},f)}{\partial F}=-\frac{\partial\psi_2(\cdot)/\partial F}{\partial\psi_2(\cdot)/\partial x_\theta^{nc}}<0.$$

Finally, differentiating (7) with respect to variable fines and applying the envelope theorem to eliminate the effect of fines on output, we get

$$\begin{aligned}\frac{\partial\psi_2(\cdot)}{\partial f}=&-\Big[x_\theta^{nc}\frac{\partial r^{nc}(\theta,\rho,x_\theta^{nc},\vec{x}_{\setminus\theta})}{\partial x_\theta^{nc}}+r^{nc}(\theta,\rho,x_\theta^{nc},\vec{x}_{\setminus\theta})\Big]\\&-[1-f]\Big[x_\theta^{nc}\frac{\partial^2 r^{nc}(\theta,\rho,x_\theta^{nc},\vec{x}_{\setminus\theta})}{\partial\rho\partial x_\theta^{nc}}+\frac{\partial r^{nc}(\theta,\rho,x_\theta^{nc},\vec{x}_{\setminus\theta})}{\partial\rho}\Big]\frac{\partial\rho(\cdot)}{\partial f}<0,\end{aligned}$$

which is negative because marginal revenues are positive at the optimal output, and by Assumption 2 and Lemma 2. Again using (8), by the implicit function theorem,

$$\frac{\partial x_\theta^{nc}(\rho,\vec{x}_{\setminus\theta},f)}{\partial f}=-\frac{\partial\psi_2(\cdot)/\partial f}{\partial\psi_2(\cdot)/\partial x_\theta^{nc}}<0.\quad\square$$

Lemma 4: *There are two ways that DCs can be segmented: (a) partial compliance where DCs are segmented by capability into non-participating DCs, participating non-compliant DCs, and participating compliant DCs; (b) full compliance where DCs are segmented by capability into non-participating DCs, and participating compliant DCs.*

Proof: Partially differentiating (11) with respect to $\check{\theta}^c(\cdot)$ and applying the envelope theorem yields

$$\frac{\partial\psi_5(\cdot)}{\partial\check{\theta}^c}=x_{\check{\theta}^c}^c(\cdot)\frac{\partial r^c(\check{\theta}^c,\rho(\cdot),x_{\check{\theta}^c}^c(\cdot),\vec{x}_{\setminus\check{\theta}^c}(\cdot))}{\partial\check{\theta}^c}>0,\tag{EC.26}$$

which is positive from Assumption 1(a). Thus, $\partial\psi_5(\cdot)/\partial\check{\theta}^c>0$, and because $\check{\theta}^c(\cdot)$ generates zero payoffs from compliance, DCs that are more capable than $\check{\theta}^c(\cdot)$ generate positive payoffs from compliance. Now partially differentiating (10) with respect to $\check{\theta}^{nc}(\cdot)$ yields

$$\frac{\partial\psi_4(\cdot)}{\partial\check{\theta}^{nc}}=[1-f]x_{\check{\theta}^{nc}}^{nc}(\cdot)\frac{\partial r^{nc}(\check{\theta}^{nc}(\cdot),\rho(\cdot),x_{\check{\theta}^{nc}}^{nc}(\cdot),\vec{x}_{\setminus\check{\theta}^{nc}}(\cdot))}{\partial\check{\theta}^{nc}}>0,\tag{EC.27}$$

which is signed positive from Assumption 1(a). Given that $\check{\theta}^{nc}$ generates zero payoffs, non-compliant DCs that are more (less) capable than $\check{\theta}^{nc}(\cdot)$ generate positive (negative) payoffs and participate (do not participate).

From Lemma 1, the DCs' payoffs from compliance increase faster with capability than do payoffs from non-compliance. Thus, the condition that defines $\tilde{\theta}(\cdot)$, equal payoffs in (9), defines $\tilde{\theta}(\cdot)$ uniquely. This is the single crossing condition. There are two ways that DCs can be segmented:

(a): If (9) holds where payoffs to $\tilde{\theta}(\cdot)$ are positive, then from Lemma 1, $\check{\theta}^{nc}(\cdot) < \check{\theta}^{c}(\cdot) < \tilde{\theta}(\cdot)$.

(b): If (9) holds where payoffs to $\tilde{\theta}(\cdot)$ are (weakly) negative, then from Lemma 1, $\tilde{\theta}(\cdot) \leq \check{\theta}^{c}(\cdot) \leq \check{\theta}^{nc}(\cdot)$.

Consider first (a), where the payoff for the indifferent DC $\tilde{\theta}(\cdot)$ is positive and $\check{\theta}^{nc}(\cdot) < \check{\theta}^{c}(\cdot) < \tilde{\theta}(\cdot)$. Then, the least capable DCs, $\theta < \check{\theta}^{nc}(\cdot)$, do not participate because of negative payoffs. The set of DCs defined by $\check{\theta}^{nc}(\cdot) < \theta < \tilde{\theta}(\cdot)$ participate but do not comply because they make positive payoffs from non-compliance, and such payoffs are larger than their payoffs from compliance. Finally, DCs with $\tilde{\theta}(\cdot) < \theta$ participate and comply because their payoffs from compliance are positive, and larger than their payoffs from non-compliance.

Next, consider (b), where the payoffs for the indifferent DC $\tilde{\theta}(\cdot)$ are weakly negative and $\tilde{\theta}(\cdot) \leq \check{\theta}^{c}(\cdot) \leq \check{\theta}^{nc}(\cdot)$. Here, DCs with $\theta \leq \check{\theta}^{c}(\cdot)$ do not participate because of negative payoffs, but DCs with $\check{\theta}^{c}(\cdot) < \theta$ participate and comply because they have positive payoffs from compliance, and such payoffs are larger than those that can be achieved through non-compliance. □

Theorem 1: *With partial compliance fixed fines, variable fines, and investments decrease participation.*

Proof: Partially differentiating (10) with respect to the investments and applying the envelope theorem yields

$$\frac{\partial \psi_4(\cdot)}{\partial I} = [1-f]\frac{\partial r^{nc}(\check{\theta}^{nc}, \rho, x^{nc}_{\check{\theta}^{nc}}(\cdot), \vec{x}_{\setminus \check{\theta}^{nc}}(\cdot))}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial I} < 0,$$

which is negative by Assumption 2 and Lemma 2. Using (EC.27) and the above equation, and by the implicit function theorem,

$$\frac{\partial \check{\theta}^{nc}(\cdot)}{\partial I} = -\frac{\partial \psi_4(\cdot)/\partial I}{\partial \psi_4(\cdot)/\partial \check{\theta}^{nc}} > 0.$$

Next, partially differentiating (10) with respect to fixed fines F yields

$$\frac{\partial \psi_4(\cdot)}{\partial F} = -1 + [1-f]\frac{\partial r^{nc}(\check{\theta}^{nc}, \rho, x^{nc}_{\check{\theta}^{nc}}(\cdot), \vec{x}_{\setminus \check{\theta}^{nc}}(\cdot))}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial F} < 0,$$

which is negative by Assumption 2 and Lemma 2. Using (EC.27) and the above equation, and by the implicit function theorem,

$$\frac{\partial \check{\theta}^{nc}(\cdot)}{\partial F} = -\frac{\partial \psi_4(\cdot)/\partial F}{\partial \psi_4(\cdot)/\partial \check{\theta}^{nc}} > 0.$$

Partially differentiating (10) with respect to the variable fine f we have

$$\frac{\partial \psi_4(\cdot)}{\partial f} = -x^{nc}_{\check{\theta}^{nc}}(\cdot) r^{nc}(\check{\theta}^{nc}, \rho, x^{nc}_{\check{\theta}^{nc}}(\cdot), \vec{x}_{\setminus \check{\theta}^{nc}}(\cdot)) + [1-f]\frac{\partial r^{nc}(\check{\theta}^{nc}, \rho, x^{nc}_{\check{\theta}^{nc}}(\cdot), \vec{x}_{\setminus \check{\theta}^{nc}}(\cdot))}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial f} < 0,$$

which is negative because revenues are positive for a participating DC, and by Assumption 2 and Lemma 2. Then, using (EC.27) and the above equation, and by the implicit function theorem,

$$\frac{\partial \check{\theta}^{nc}(\cdot)}{\partial f} = -\frac{\partial \psi_4(\cdot)/\partial f}{\partial \psi_4(\cdot)/\partial \check{\theta}^{nc}} > 0. \quad \square \tag{EC.28}$$

Theorem 2: *(a) With full compliance, investments increase participation. (b) A necessary condition for full participation and full compliance is DPR-induced demand expansion. (c) Conditional on the necessary condition, the sufficient condition for full participation and full compliance can be attained by policy-maker investment but not by fixed or variable fines.*

Proof: We begin by partially differentiating (11) with respect to investment,

$$\frac{\partial\psi_5(\check{\theta}^c,\rho(\cdot),x^c_{\check{\theta}^c}(\cdot),\vec{x}_{\setminus\check{\theta}^c}(\cdot)I)}{\partial I}=-\frac{\partial\gamma(x^c_{\check{\theta}^c}(\cdot),I)}{\partial I}>0,$$

which is positive from Assumption 3(a). Now using (EC.26) and the above equation, and by the implicit function theorem,

$$\frac{\partial\check{\theta}^c(\cdot)}{\partial I}=-\frac{\partial\psi_5(\cdot)/\partial I}{\partial\psi_5(\cdot)/\partial\check{\theta}^c}<0.$$

We prove the necessary condition in part (b) by contradiction. Consider the case where there is no demand expansion for the least capable DC that complies so that $r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})<r(\theta,x_\theta,\vec{x}_{\setminus\theta})|_{\theta=0}$. Then, payoffs from compliance to the least capable DC captured in (3) are negative because compliance costs are positive and pre-DPR profits for $\theta=0$ are zero, $\Pi(\theta,\vec{x}(\cdot))|_{\theta=0}=0$, as described prior to Assumption 1. So the least capable DC cannot comply profitably. Therefore, $r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})>r(\theta,x_\theta,\vec{x}_{\setminus\theta})$ ensures that $\theta=0$ can participate and comply.

If the above necessary condition is met ($r^c(\theta,\rho,x_\theta,\vec{x}_{\setminus\theta})>r(\theta,x_\theta,\vec{x}_{\setminus\theta})$), then payoffs from compliance in the absence of compliance costs are positive for $\theta=0$. In the presence of large enough compliance costs, the payoffs from compliance for $\theta=0$ are negative. Because compliance cost decreases in investment by Assumption 3(a), if investment is set so that $\Pi^c(\cdot)|_{\theta=0}\geq 0$, then the DC $\theta=0$ generates positive payoffs.

The payoffs from non-compliance for the least capable DC are negative because $\Pi(\theta,\vec{x}(\cdot))|_{\theta=0}=0$ and non-compliant inverse demand is lower than pre-DPR inverse demand from the discussion above Assumption 1. Because $\partial\Pi^c(\cdot)/\partial\theta>\partial\Pi^{nc}(\cdot)/\partial\theta$ from Lemma 1, the payoff from compliance increases more with capability than the payoff from non-compliance. If the least capable DC generates negative payoffs from non-compliance and positive payoffs from compliance, then by Lemma 1, the payoffs from compliance are larger than the payoffs from non-compliance $\forall\theta>0$. Further, payoffs from compliance are increasing in θ by Lemma 1, (3) is positive $\forall\theta>0$, and there is full participation.

In the case of full compliance, only $\check{\theta}^c(\cdot)$ is material as $\check{\theta}^c(\cdot)<\theta$ participate and comply and $\theta<\check{\theta}(\cdot)$ do not participate by Lemma 4, and the fine-induced movements of $\tilde{\theta}(\cdot)$ and $\check{\theta}^{nc}(\cdot)$ have no consequence for the equilibrium. Thus, further increasing fines has no impact on participation. □

Theorem 3: *Fixed fines, variable fines, and investments increase industry concentration.*

Proof: The structure of each of (13), (14), (15) is similar – each consists of four terms. We begin with (13) where the second term represents a decrease in participation (Theorem 1) which results in lost output, and the second term is negative. In the third term, the policy-maker instrument increases compliance (ρ), which in turn decreases non-compliant DCs' output by Lemma 3, and the third term is negative. Next, the first term captures the increase in compliance (Lemma 2), which leads to increased output (Lemma 1) so the first term is positive. Finally, considering the first and the fourth terms together, we can make the following observation based on our setup described above Assumption 2: when some DCs choose to provide the additional feature of portability, we take that this does not cause users to leave the market. Then, the aggregate users lost by non-compliant DCs due to increased compliance (third term) are served by compliant DCs (the sum of the first and fourth terms). In other words, the increase in aggregate output of compliant DCs (including the newly compliant ones) is at least as large as the decrease in aggregate output of non-compliant DCs. In mathematical terms

$$[x^{nc}_{\tilde{\theta}}(\cdot) - x^{c}_{\tilde{\theta}}(\cdot)]\frac{\partial\tilde{\theta}(\cdot)}{\partial F} + \int_{\tilde{\theta}(\cdot)}^{1} \frac{\partial x^{c}_{\theta}(\cdot)}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial F} d\theta \geq -\int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} \frac{\partial x^{nc}_{\theta}(\cdot)}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial F} d\theta. \tag{EC.29}$$

We move on to the additional terms within the second set of square brackets in (14) and (15). Compared to fixed fines in (13), variable fines have an additional effect on aggregate output in (14). This is the second term within the second set of square brackets in (14), $\partial x^{nc}_{\theta}(\cdot)/\partial f$. This term is negative from Lemma 3. Thus, both terms under the second set of square brackets in (14) is negative, and the third term is negative. The additional effect in (14) compared to (13) is a further decrease in the third term (decrease in aggregate output of non-compliant DCs). Therefore, similar to the effect of fixed fines, as variable fines increase, the increase in aggregate output of compliant DCs (including the newly compliant ones) is at least as large as the decrease in aggregate output of non-compliant DCs. In mathematical terms

$$[x^{nc}_{\tilde{\theta}}(\cdot) - x^{c}_{\tilde{\theta}}(\cdot)]\frac{\partial\tilde{\theta}(\cdot)}{\partial f} + \int_{\tilde{\theta}(\cdot)}^{1} \frac{\partial x^{c}_{\theta}(\cdot)}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial f} d\theta \geq -\int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} \left[\frac{\partial x^{nc}_{\theta}(\cdot)}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial f} + \frac{\partial x^{nc}_{\theta}(\cdot)}{\partial f}\right] d\theta.$$

Next, compared to fixed fines in (13), investments have an additional effect on aggregate output (15). This is in the second term within the last set of square brackets in (15), $\partial x^{c}_{\theta}(\cdot)/\partial I$, which is the direct effect of investments on compliant DCs' output. To evaluate this direct effect, we differentiate (4) with respect to investments and use the envelope theorem to get

$$\frac{\partial \psi_1(\cdot)}{\partial I} = -\frac{\partial^2 \gamma(x^{c}_{\theta}, I)}{\partial x^{c}_{\theta}\partial I} > 0,$$

which is positive by Assumption 3(a). Using (5), by the implicit function theorem,

$$\frac{\partial x^{c}_{\theta}(\rho, \vec{x}_{\setminus\theta}, I)}{\partial I} = -\frac{\partial \psi_1(\cdot)/\partial I}{\partial \psi_1(\cdot)/\partial x^{c}_{\theta}} > 0.$$

Therefore, the additional effect in (15) compared to (13) is an increase in the fourth term (increase in aggregate output of compliant DCs). Therefore, similar to the effect of fixed and variable fines, as investments increase, the increase in aggregate output of compliant DCs (including the newly compliant ones) is at least as large as the decrease in aggregate output of non-compliant DCs. In mathematical terms

$$[x^{nc}_{\tilde{\theta}}(\cdot) - x^{c}_{\tilde{\theta}}(\cdot)]\frac{\partial\tilde{\theta}(\cdot)}{\partial I} + \int_{\tilde{\theta}(\cdot)}^{1} [\frac{\partial x^{c}_{\theta}(\cdot)}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial I} + \frac{\partial x^{c}_{\theta}(\cdot)}{\partial I}] d\theta \geq -\int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} \frac{\partial x^{nc}_{\theta}(\cdot)}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial I} d\theta.$$

Therefore we have shown that in (13), (14), and (15), the second and third terms are negative (output of non-compliant DCs decreases), and the sum of the first and fourth terms are positive (aggregate output of compliant DCs increases). Further, from Lemma 1, the output increases with capability and the output of compliant DCs ($\tilde{\theta}(\cdot) \leq \theta$) is higher than the output of non-compliant DCs ($\theta < \tilde{\theta}(\cdot)$). Therefore industry concentration increases with fixed fines, variable fines, and investments. □

Theorem 4: *a) Compared to variable fines and investments, the use of fixed fines to achieve a predetermined level of compliance has a larger collateral effect on participation. b) Compared to variable fines and investments, the use of fixed fines to achieve a predetermined level of compliance has a smaller collateral effect on industry concentration from participating DCs.*

Proof: First consider a target level of compliance, $\rho^t = 1 - \tilde{\theta}^t$, that is achieved by the policy-maker through a fixed fine of F^t so that $\tilde{\theta}^t$ generates the same payoffs from compliance and non-compliance. The fixed fine F^t is paid by all non-compliant DCs. Because variable fine for $\tilde{\theta}(\cdot)$ is the proportion of its revenue from non-compliance, the target variable fine f^t that accomplishes the same level of compliance as fixed fines above is defined by $F^t = f^t x_{\tilde{\theta}}^{nc} r^{nc}(\tilde{\theta}, \rho, x_{\tilde{\theta}}, \vec{x}_{\setminus \tilde{\theta}})$. Then, the variable fine paid by the non-compliant DCs is $f^t x_{\theta}^{nc} r^{nc}(\theta, \rho, x_{\theta}, \vec{x}_{\setminus \theta})$. Because $\tilde{\theta}^t$ is the most capable non-compliant DC from Lemma 1, and inverse demand (and therefore revenues) increase in capability by Assumption 1(a), the variable fines paid by the non-compliant DCs are smaller than F^t. Comparing fixed fines and investments, because the payoffs to $\check{\theta}^{nc}(\cdot)$ do not directly depend on investments, investments have a smaller effect on participation where a predetermined level of compliance is of interest. This leads to Theorem 4(a).

Now consider industry concentration. Comparing (13), (14), and (15), if the policy-maker increases fixed fines, variable fines, and investments so as to achieve the desired increase in compliance, then the terms through $\tilde{\theta}(\cdot)$ and $\rho(\cdot)$ which capture the direct and indirect effects through compliance are equal. This leaves the direct effects of variable fines on non-compliant DC output ($\partial x_{\theta}^{nc}(\cdot)/\partial f$, a negative effect) and the direct effect of investments on compliant DC output ($\partial x_{\theta}^{c}(\cdot)/\partial I$, a positive effect). Fixed fines do not have this direct effect, and thus have a smaller collateral effect on industry concentration from participating DCs. □

Corollary 1: *Fines and investments increase welfare produced from larger DCs and decreases welfare produced from smaller DCs. Thus DPR can increase social welfare.*

Proof: Social welfare (SW) consists of DCS without fines, and US,

$$SW(F, f, I) = DCS_{-f}(F, f, I) + US(X(F, f, I)).$$

The effect of fixed fines on social welfare is $dSW(\cdot)/dF = dDCS_{-f}(\cdot)/dF + US'(X(\cdot))dX(\cdot)/dF$, which we derive in the following equation by differentiating (20) with respect to the fixed fine, and substituting for $dX(\cdot)/dF$ from (13). Similarly for the effect of variable fines and investments on social welfare, substituting for $dX(\cdot)/df$ from (14) and $dX(\cdot)/dI$ from (15), respectively. We begin by differentiating social welfare with respect to fixed fines,

$$\begin{aligned}\frac{dSW(F,f,I)}{dF} =& -\frac{\partial\check{\theta}^{nc}(\cdot)}{\partial F}[x^{nc}_{\check{\theta}^{nc}}(\cdot)r^{nc}(\check{\theta}^{nc},\rho,x^{nc}_{\check{\theta}^{nc}}(\cdot),\vec{x}_{\setminus\check{\theta}^{nc}}(\cdot)) - C(x^{nc}_{\check{\theta}^{nc}}(\cdot))]\\
&+\frac{\partial\tilde{\theta}(\cdot)}{\partial F}\Big[x^{nc}_{\tilde{\theta}}(\cdot)r^{nc}(\tilde{\theta},\rho,x^{nc}_{\tilde{\theta}}(\cdot),\vec{x}_{\setminus\tilde{\theta}}(\cdot)) - C(x^{nc}_{\tilde{\theta}}(\cdot))\\
&-[x^{c}_{\tilde{\theta}}(\cdot)r^{c}(\tilde{\theta},\rho,x^{c}_{\tilde{\theta}}(\cdot),\vec{x}_{\setminus\tilde{\theta}}(\cdot)) - C(x^{c}_{\tilde{\theta}}(\cdot)) - \gamma(x^{c}_{\tilde{\theta}}(\cdot),I)]\Big]\\
&-\int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} x^{nc}_{\theta}(\cdot)\frac{\partial r^{nc}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial F}d\theta + \int_{\tilde{\theta}(\cdot)}^{1} x^{c}_{\theta}(\cdot)\frac{\partial r^{c}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial F}d\theta\\
&+US'(X(F,f,I))\Big[[x^{nc}_{\tilde{\theta}}(\cdot)-x^{c}_{\tilde{\theta}}(\cdot)]\frac{\partial\tilde{\theta}(\cdot)}{\partial F} - x^{nc}_{\check{\theta}^{nc}}(\cdot)\frac{\partial\check{\theta}^{nc}(\cdot)}{\partial F}\\
&+\int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)}\frac{\partial x^{nc}_{\theta}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial F}d\theta + \int_{\tilde{\theta}(\cdot)}^{1}\frac{\partial x^{c}_{\theta}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial F}d\theta\Big].\end{aligned} \tag{EC.30}$$

The effect of variable fines on $SW(F,f,I)$ is

$$\begin{aligned}\frac{dSW(F,f,I)}{df} =& -\frac{\partial\check{\theta}^{nc}(\cdot)}{\partial f}[x^{nc}_{\check{\theta}^{nc}}(\cdot)r^{nc}(\check{\theta}^{nc},\rho,x^{nc}_{\check{\theta}^{nc}}(\cdot),\vec{x}_{\setminus\check{\theta}^{nc}}(\cdot)) - C(x^{nc}_{\check{\theta}^{nc}}(\cdot))]\\
&+\frac{\partial\tilde{\theta}(\cdot)}{\partial f}\Big[x^{nc}_{\tilde{\theta}}(\cdot)r^{nc}(\tilde{\theta},\rho,x^{nc}_{\tilde{\theta}}(\cdot),\vec{x}_{\setminus\tilde{\theta}}(\cdot)) - C(x^{nc}_{\tilde{\theta}}(\cdot))\\
&-[x^{c}_{\tilde{\theta}}(\cdot)r^{c}(\tilde{\theta},\rho,x^{c}_{\tilde{\theta}}(\cdot),\vec{x}_{\setminus\tilde{\theta}}(\cdot)) - C(x^{c}_{\tilde{\theta}}(\cdot)) - \gamma(x^{c}_{\tilde{\theta}}(\cdot),I)]\Big]\\
&-\int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} x^{nc}_{\theta}(\cdot)\frac{\partial r^{nc}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial f}d\theta + \int_{\tilde{\theta}(\cdot)}^{1} x^{c}_{\theta}(\cdot)\frac{\partial r^{c}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial f}d\theta\\
&+US'(X(F,f,I))\Bigg[[x^{nc}_{\tilde{\theta}}(\cdot)-x^{c}_{\tilde{\theta}}(\cdot)]\frac{\partial\tilde{\theta}(\cdot)}{\partial f} - x^{nc}_{\check{\theta}^{nc}}(\cdot)\frac{\partial\check{\theta}^{nc}(\cdot)}{\partial f}\\
&+\int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)}[\frac{\partial x^{nc}_{\theta}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial f} + \frac{\partial x^{nc}_{\theta}(\cdot)}{\partial f}]d\theta + \int_{\tilde{\theta}(\cdot)}^{1}\frac{\partial x^{c}_{\theta}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial f}d\theta\Bigg].\end{aligned} \tag{EC.31}$$

Finally, differentiating $SW(F,f,I)$ with respect to investment,

$$\begin{aligned}\frac{dSW(F,f,I)}{dI} =& -\frac{\partial\check{\theta}^{nc}(\cdot)}{\partial I}[x^{nc}_{\check{\theta}^{nc}}(\cdot)r^{nc}(\check{\theta}^{nc},\rho,x^{nc}_{\check{\theta}^{nc}}(\cdot),\vec{x}_{\setminus\check{\theta}^{nc}}(\cdot)) - C(x^{nc}_{\check{\theta}^{nc}}(\cdot))]\\
&+\frac{\partial\tilde{\theta}(\cdot)}{\partial I}\Big[[x^{nc}_{\tilde{\theta}}(\cdot)r^{nc}(\tilde{\theta},\rho,x^{nc}_{\tilde{\theta}}(\cdot),\vec{x}_{\setminus\tilde{\theta}}(\cdot)) - C(x^{nc}_{\tilde{\theta}}(\cdot))]\\
&-[x^{c}_{\tilde{\theta}}(\cdot)r^{c}(\tilde{\theta},\rho,x^{c}_{\tilde{\theta}}(\cdot),\vec{x}_{\setminus\tilde{\theta}}(\cdot)) - C(x^{c}_{\tilde{\theta}}(\cdot)) - \gamma(x^{c}_{\tilde{\theta}}(\cdot),I)]\Big]\\
&-\int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} x^{nc}_{\theta}(\cdot)\frac{\partial r^{nc}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial I}d\theta + \int_{\tilde{\theta}(\cdot)}^{1} x^{c}_{\theta}(\cdot)\frac{\partial r^{c}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial I}d\theta - \int_{\tilde{\theta}(\cdot)}^{1}\frac{\partial\gamma(x^{c}_{\theta}(\cdot),I)}{\partial I}d\theta - 1\\
&+US'(X(F,f,I))\Bigg[[x^{nc}_{\tilde{\theta}}(\cdot)-x^{c}_{\tilde{\theta}}(\cdot)]\frac{\partial\tilde{\theta}(\cdot)}{\partial I} - x^{nc}_{\check{\theta}^{nc}}(\cdot)\frac{\partial\check{\theta}^{nc}(\cdot)}{\partial I}\\
&+\int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)}[\frac{\partial x^{nc}_{\theta}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial I}]d\theta + \int_{\tilde{\theta}(\cdot)}^{1}[\frac{\partial x^{c}_{\theta}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial I} + \frac{\partial x^{c}_{\theta}(\cdot)}{\partial I}]d\theta\Bigg].\end{aligned} \tag{EC.32}$$

The structures of (EC.30), (EC.31), and (EC.32) are similar. The first four lines of each equation contain the effect of fines and investments on DCS_{-f}, and the last two lines are the effect of fines and investments on US. The first terms in each of the above equations capture decreases in participation and the resulting decrease in welfare. The second terms capture the marginal effect of an increase in compliance on $DCS_{-f}(F,f,I)$.

The second line contains the payoffs to $\tilde{\theta}(\cdot)$ from non-compliance, but without subtracting fines, whereas the third line contains the payoffs to $\tilde{\theta}(\cdot)$ from compliance. From (9), after subtracting fines, the payoffs to $\tilde{\theta}(\cdot)$ from non-compliance are equal to its payoffs from compliance. Thus, the second term (on the second and third lines) is negative, and captures the decrease in welfare from adding a constraint of fines for non-compliance. The third and fourth terms capture the externalities caused by increased compliance due to fines. The third term captures the decreased revenues to non-compliant DCs that are caused by increased compliance, whereas the fourth term captures the changes in revenues to compliant DCs that are caused by increased compliance. Investments have an additional effect on DCS_{-f} compared to fines, as provided in the fifth term (on the fourth line) in (EC.32). This captures the impact of investments on decreasing compliance costs. Finally, the last term (on the fifth and sixth lines) is the change in US from a change in output caused by fines. This change in output occurs because of DCs' increased output when converting from non-compliance to compliance, lost output from DCs that cease to participate, decreased output from non-compliant DCs due to increased compliance and the fine externality, and increased output from compliant DCs due to increased compliance. We can now ascertain the condition under which it is welfare maximizing to eliminate non-compliance through the use of fines. From (EC.30), (EC.31), and (EC.32), we see that all the gains to social welfare from increased fines accrue from more capable DCs, $\tilde{\theta}(\cdot) < \theta$, whereas the losses to social welfare from increased fines are from less capable DCs, $\theta \leq \tilde{\theta}(\cdot)$. If the gains are larger than the losses, then (EC.30), (EC.31), and (EC.32) can be signed positive. □

Appendix E: Social Welfare

Before analyzing social welfare, a closer inspection of the impact of policy-maker instruments on DC surplus is helpful. Several terms cancel out or drop to zero leading to the equations (17), (18), and (19). First, payoffs from compliance and non-compliance for $\tilde{\theta}(\cdot)$ are the same by definition. Second, the decrease in participation with an increase in fines $(\partial\check{\theta}^{nc}(\cdot)/\partial f)$, does not affect DCS because these DCs generate zero payoffs – thus, their non-participation has no effect on DCS. Third, the payoff function $\Pi^{nc}(\theta, \rho(\cdot), x_\theta(\cdot), \vec{x}_{\setminus\theta}(\cdot), F, f)$ contains $x_\theta^{nc}(\rho, \vec{x}_{\setminus\theta}, f)$, which is an indirect maximal value function in variable fines, f. In other words, $\Pi^{nc}(\theta, \rho(\cdot), x_\theta(\cdot), \vec{x}_{\setminus\theta}(\cdot), F, f)$ is an envelope for $x_\theta^{nc}(\cdot)$, such that $\partial\Pi^{nc}(\cdot)/\partial x_\theta^{nc} = 0$ in order for $\Pi^{nc}(\cdot)$ to be maximal. Therefore, the equations (17), (18), and (19) quantify the instantaneous rate of change in payoffs with respect to the variable fine, and are independent of the indirect effect of fines on payoffs through output.