Management Science

Consequences of Resorting to Fines and Investments to Regulate Data Portability

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Many jurisdictions have implemented data portability regulation (DPR) that requires that Data Controllers (DCs) to enable users to download their personal data so that they can port their data to competing DCs. The intention of DPR is to return partial control of data to users, improve user choice of DCs, and increase DC participation in the market and reduce industry concentration. To achieve this, if non-monetary corrective measures (e.g., warnings, orders to comply) to obtain portability compliance fails, then DPR allows policy-makers to impose fixed or variable (based on revenue) fines on DCs that do not comply. Additionally, policy-makers may invest to decrease compliance costs for DCs. We model this interaction as a two-stage game where in the first stage the policy-maker sets fines and makes investments. In the second stage DCs decide whether to participate in the market, and if so whether to comply with DPR. Contrary to the current regulatory objectives, we find that with partial compliance both fines and investment decrease DC participation and increase industry concentration. Comparing the use of fines and investment to achieve a predetermined level of compliance, the use of fixed fines has a smaller (larger) collateral effect on concentration (participation) than either variable fines or investment. Once all DCs that participate comply – full compliance – then additional investment increases participation. Moreover, full compliance and full participation can occur only if there is a DPR-induced demand expansion, such as from multi-homing, and investment is the only instrument that can attain this outcome.

Keywords: Data Portability, Regulation, Fines, Investments, Data Controllers.
History: Presented at the Workshop on Information Systems and Economics (WISE) in Munich, December 2019, and the ICIS Doctoral Consortium, December 2020 (online).

1. Introduction

Data Controllers (DCs) such as Facebook (in social media) and Strava (in fitness apps) are able to leverage the personal data of users to provide personalized value-added features[1]. This personal data provides a competitive advantage for DCs. For example, Facebook uses personal data to provide customized news feeds, friend suggestions, and auto-tagging of friends. Facebook's capability is in monetizing this use of personal data through targeted advertising to users. In fitness apps Strava provides individual activity and progress reports, and exploits this capability to convert users to paying subscribers and charge a higher subscription price. Competitors to Facebook – such as Flickr, X, and Gettr; and to Strava – such as Komoot and Endomondo; are at a disadvantage in providing the same level of service without access to a given user's personal data.

Some policy-makers view this as user lock-in where a DC's use of user personal data hinders users from moving to another DC that they might otherwise prefer (European Political Strategy Centre 2017). This lock-in is thought to have undesirable implications for DC participation, industry concentration, user surplus, and welfare. In part, the E.U. passed the General Data Protection Regulation (GDPR, Council of European Union 2016) to alleviate these issues – this regulation requires that DCs allow users to download their personal data and easily port it to a competing DC. DCs that violate DPR can be subject to fines of up to 20M EUR, or variable fines of up to 4% of the total worldwide revenue. The State of California's Consumer Privacy Act (CCPA, California State Legislature 2018) has similar data portability requirements from DCs. We refer to such regulatory interventions requiring DCs to enable data portability as *data portability regulations* (DPR).

Moreover, policy-makers plan to invest in processes and standards for porting of data to decrease compliance costs for DCs. For example, the Digital Markets Act in the E.U. specifies future investments in developing tools and specialized standards for data portability, which are to be developed by European standardization bodies (Council of European Union 2022, Article 96). Current examples of investments to decrease the cost of DPR compliance include government-developed tools to port energy consumption data from smart meters (OECD 2021, p. 37) and transfer of banking data via open banking (Competition and Markets Authority 2021, Australian Banking Association 2025).

The U.S. ACCESS Act of 2021 mandates analogous regulations on data portability, the objectives of which are similar to the GDPR and the CCPA. The act has been ordered to be introduced in the U.S. House of Representatives (United States House Committee on the Judiciary 2021), which adds urgency to the need for an evaluation of the effects of DPR. Apart from providing context by explaining the mechanism through which fines and investments affect participation,

[1] Following terminology from the Council of European Union (2016), we define a data controller (DC) as the body which "determines the purposes and means of processing of personal data"

concentration, compliance, and welfare, we provide novel and actionable insights to policy-makers by answering the following research questions. First, under what conditions may an instrument (e.g., fines, investment) increase or decrease participation? Second, which of fixed fines or variable fines to enforce DPR or investments made to decrease compliance costs have larger collateral effects on participation and on industry concentration?

We follow DPR policy-makers and define a DC as compliant with DPR if it allows its users to download their data so that they can port it to other DCs (Council of European Union 2016, Article 20). For example, Strava allows bulk download of user activities through the GPX standard, which captures all of the activity information in a single file including route map, speed, and heart rate data (Strava 2024). A non-compliant DC does not allow its users to download their data. By requiring that DCs make their data easily portable to competing DCs, DPR is expected to diminish lock-in and restore competition in the digital economy by giving a measure of control over personal data to users. The basis for imposing DPR with fines for at-fault DCs and investments to decrease compliance costs is that portability hinders the market power of large DCs, increasing participation and decreasing concentration (Council of European Union 2016, Article 4, United States House of Representatives 2020, p. 20 and pp. 40-44, Cyphers and O'Brien 2018, Seamans and Bytes 2018).

We use a general model to study the implications of DPR where DCs differ in their capability and decide on their output and compliance. We define capability as the ability to generate more revenue per unit of output. Although we illustrate our setting using the social media and fitness tracking industries, our analysis applies to any set of competing DCs that derive value from personal data. The policy-maker implements DPR with the help of three instruments: fixed and variable fines for non-compliant DCs, and investment to reduce the cost of compliance for DCs. Each DC maximizes profit by choice of output, and decides if it should participate in the market, and whether to comply with DPR or not comply and pay the fine. Then we characterize the effects of policy-maker instruments on the structure of the industry, including on participation, concentration, and compliance, as well as on consumer surplus and social welfare.

We consider four effects on DCs from the imposition of DPR, of which the first two pertain to non-compliant DCs and the next two apply to compliant DCs. The first effect is fixed and variable (as proportion of revenue) fines for non-compliant DCs. The second effect is the loss in revenue resulting from a reduction in appeal of non-compliant DCs due to the lack of portability as a feature. This effect is moderated by the proportion of compliant DCs. The third effect is the gain or loss in revenue of compliant DCs due to the ability of users to port their data. The fourth effect is the cost of compliance for compliant DCs, which can be reduced by policy-maker investment.

Contrary to the intention of the regulation, we find that these regulations and related instruments may instead decrease participation and increase concentration. We begin by describing the broad effects of fines and investments on participation and concentration before describing our findings related to the main research questions outlined above.

On participation: Not only do we find that with partial compliance fixed fines and variable fines decrease participation from DCs, but that investments also decrease participation: the least capable DCs exit, the moderately capable DCs participate but do not comply with DPR and pay the fines, and the most capable DCs participate and comply. This is in stark contrast with the policy objective of increased participation. The mechanism is not through disproportionate costs of compliance for less capable DCs, extent of data collection, or what data can be ported as seen in prior literature, but rather because portability itself may be detrimental to the demand generated by less capable DCs.

On concentration: We also find that each instrument further decreases the output of DCs that have smaller market shares and increases the aggregate output of DCs that have greater market shares, thereby increasing industry concentration. Again, this is in contrast with the policy objective of lessened industry concentration. The increase in concentration is independent of the decrease in participation and is due to the effect on demand of a fundamental and underlying process that is specific to some DCs enabling portability.

Thus, resorting to fines and investments to increase compliance with DPR can come with the collateral effect of decreasing participation and increasing concentration. We now turn our attention to addressing our primary research questions.

On whether an instrument can increase participation: Firstly, we find that once full compliance is achieved the effect of investments on participation reverses, and investments now increase participation. Thus, the elimination of non-compliance is required for investment to increase participation. Secondly, we find that the policy-maker cannot necessarily achieve full compliance and full participation with the instruments available. Instead, market expansion is necessary to achieve this outcome. Market expansion can happen when users multi-home so that they continue to consume services from the focal DC as well as from the DC that they port their data to. The market can also expand when users from another industry port their data to the focal industry, thereby consuming services from both industries. In other words, multi-homing softens the collateral effects of fines and investment on participation. Conditional on market expansion, the only instrument that can achieve full compliance and full participation is investment.

On comparison of instruments: The effect of each instrument on participation and concentration differs. To achieve any pre-determined level of compliance, fixed fines have a larger collateral effect on participation as compared to variable fines and to investments. On the other hand, both variable fines and investments have a larger collateral effect on concentration as compared to fixed fines. Thus, the policy-maker has to choose between lesser participation or greater industry concentration when deciding which instrument to employ.

Our results hold irrespective of network effects and the degree of porting effectiveness, and consequently apply to a wide array of industry settings. Moreover, our results are robust to whether users single-home or multi-home. Indeed, full compliance and full participation mentioned above can only be achieved if the gains from portability to the least capable DC are non-negative, which can occur when the market expands, for instance, when users multi-home.

2. Literature Review

Firms in many industries use customer data to improve their products and attract more customers. This provides a competitive advantage to incumbent firms (Hagiu and Wright 2023), which policy-makers aim to address through DPR (Council of European Union 2016, California State Legislature 2018). The academic research on DPR finds mixed results. Using arguments in competition law, Graef et al. (2013) and Swire and Lagos (2012) suggest that DPR could stifle competition, innovation, and investments, and go on to suggest that DPR can lead to a decrease in consumer welfare. Further, Lam and Liu (2020) find that if DPR encourages users to share more data with their current DC because of the prospect of easier porting, then this could strengthen the incumbent and raise the entry barrier for new DCs. Christensen et al. (2013) estimate the financial impact of data protection regulation, including DPR, on firms within the E.U.. They consider the costs of compliance and lack of access to data and estimate a significant negative impact on firms and the economy as a result of enforcement of DPR. Wohlfarth (2019) considers the impact of DPR on the amount of data that DCs collect on users, finding that in some situations the increase in data collection due to DPR enforcement may harm users. We extend this stream of literature and uncover the mechanisms by which fines and investments influence a DC's decisions about output levels, DPR compliance, as well as competition, user surplus, and DC surplus. We find that fines on DCs for violations of DPR and investments to decrease compliance costs can have unintended implications for the structure of the industry. Contrary to the previous literature, our findings do not rely on the financial costs of compliance that disproportionately impact smaller firms or the impacts through changes in data collection. Instead, we uncover mechanisms that are mainly due to the impact of regulation on DC revenues as result of their compliance decisions.

Our analysis is also related to the literature on asset ownership, which we extend to include data as an asset. Hart and Moore (1990) show that, in the presence of incomplete contracts, asset ownership should reside with the party that is most able to generate value from it. If this is not the case, then there is resulting under-investment. Brynjolfsson (1994) and Bakos and Nault (1997) apply the Hart-Moore framework to information assets and electronic networks, respectively. Along with the right to data portability, GDPR provides users with the right to access, erase, and restrict the processing of their data by any DC (Council of European Union 2016). Given that Hart and Moore (1990) define asset ownership as the right to exclude others from its use, GDPR can be viewed as a partial transfer of data asset ownership from DCs to users, which may impact DC investments. Similarly, the actions of DCs can be evaluated through the lens of the principal-agent model (Hölmstrom 1979, Lambert 2001). The principal (user) assigns an agent (DC) to create value from their data – this value is then shared between the user and DC. With DPR, the nature of the contract between the two parties changes – the user has the ability to port their data to a different DC, thereby potentially changing the actions of the DC.

The structure of our assumptions is related to Nault and Zimmermann (2019), where DC (edge provider in their model) costs and profits change with decisions made in earlier stages. Our use of inverse demand (price) and profit functions in a Cournot setting is related to an established stream of research that enables a focus on a firm's production choices and interactions between external parties and the firm (Jehle and Reny 2011, pp. 147-150, Tirole 1988, pp. 218-226, Nault 1996, Levi and Nault 2004, Nault and Zimmermann 2019). Our theoretical contribution to this literature is the measurement of change in revenues when DPR is implemented, which enable us to examine the intricacies of the impact of DPR on the industry.

Finally, our work contributes to the emerging literature on the impact of data on competition. Braulin and Valletti (2016) consider the exclusivity of data sales by a monopolist data broker to two competing retailers and find that the data broker sells data exclusively to either the high-quality or the low-quality retailer. Kim et al. (2019) study the impact of data on horizontal mergers and its implications for consumer surplus. de Corniere and Taylor (2020) propose a competition-in-utilities framework for studying the impact of data on competition, specifically in the contexts of data-based algorithms, targeted advertising, price discrimination, and data-driven mergers. There is also an established literature on the competitive advantages that firms can generate from customer data and its effects on competition between firms (Farboodi et al. 2019, Hagiu and Wright 2023). This stream focuses on the competitive effects from exclusive access to data, but does not reserve a right for customers to access or port their data. We extend this literature by considering the implications of enabling users to port their data on competition, concentration, compliance, and welfare.

3. Notation and Assumptions

Following Dixit and Stiglitz (1977), Melitz (2003) and Nocco et al. (2014), we analyze an industry that consists of competing heterogeneous DCs. We use the term *capability*, which we define to be a DC's ability to generate more revenue per unit of output, and which describes the dimension along which DCs are distributed. This is consistent with a widely used measure in media and other industries – average revenue per user (ARPU, Kenton 2022, Deshpande and Narahari 2014, Rodriguez 2019). For instance, Gal-Or et al. (2018) model firms that have different targeting capabilities, Cho et al. (2016) model firms that differ in the revenue rate per unit of content, and Mei et al. (2022) model firms that differ in their ARPU. In our model, capability is a representation of a DC's production technology, marketing expertise, and/or ability to estimate user preference, and can include product quality, process productivity and efficiency, expertise in application development, and expertise in data analytics and user acquisition, all of which lead to higher ARPU. We denote DC capability by θ, which is normalized to be in $[0,1]$, and is uniformly distributed, $g(\theta) \sim U[0,1]$, so that the density is positive over its support, $g(\theta) > 0 \,\forall\, \theta \in [0,1], G(0) = 0$, and $G(1) = 1$. The policy-maker knows the distribution of θ but cannot infer the capability of a specific DC. Other than capability, we allow users to have horizontal preferences for DCs. That is, users have a common ranking of DCs by capability but have different rankings of DCs on other dimensions so that users choose different DCs in equilibrium.

In the context of social media and fitness tracking, more capable DCs may provide better services and user interface to users or be better at marketing and user acquisition. For example, Facebook is dominant in this respect compared to its rivals (Rodriguez 2019, Goldman 2016). Competitors to Facebook include well known DCs such as X and Flickr, as well as lesser known DCs such as Foursquare Swarm and Gettr which provide differentiated services, content, and connectivity making them the preferred choice for some users. Similar to Facebook, Strava is considered a dominant DC in its industry due to its superior interface, ease of use, and marketing (McGuire 2021). Even then, many users prefer Komoot for fitness tracking over Strava based on their preferences and tastes for aspects such as design, user interface, and connectivity.

DCs provide products or services to users. We denote a generic unit of revenue-generating output, that we hereafter refer to as *output*, by $x \in [0, \bar{x}]$. An example of output can be the number of users (Yoo et al. 2007) or user impressions and clicks which are monetized by DCs on a cost per impression or cost per click basis. We denote DC output with the subscript θ so that x_θ represents output from the DC with capability θ. We refer to the vector of DC outputs over the support of θ as $\vec{x} = (x_\theta, \vec{x}_{\setminus\theta})$ where $\vec{x}_{\setminus\theta}$ is a vector of outputs from DCs other than θ.

For each DC the revenue is given as $x_\theta r(\theta, x_\theta, \vec{x}_{\setminus\theta})$ where $r(\theta, x_\theta, \vec{x}_{\setminus\theta}) \in \mathbb{R}$ is the inverse demand (price) function. The inverse demand function specifies the relationship between price and output for a given θ. For example, for Strava, the inverse demand function specifies the subscription price that is required to achieve a desired output in terms of users; whereas for Facebook, it specifies the ad density and data disclosure in secondary markets in lieu of prices. This inverse demand function depends on capability, own output, and output from other DCs. We take the inverse demand of a DC with zero capability as zero, $r(\theta=0, x_\theta, \vec{x}_{\setminus\theta}) = 0$. Our first assumption defines reasonable properties of $r(\theta, x_\theta, \vec{x}_{\setminus\theta})$. For more information on inverse demands, we refer the reader to the established stream of work on the use of inverse demand and profit functions in a Cournot setting (Jehle and Reny 2011, pp. 147-150, Tirole 1988, pp. 218-226, Nault 1996, Levi and Nault 2004, Nault and Zimmermann 2019). We provide a parameterized model of user decision making which results in our assumed inverse demands in Appendix A.

ASSUMPTION 1 **(Inverse Demand)**. *(a) DC inverse demand is increasing in capability, decreasing and concave in output, and weakly decreasing in output from other DCs; (b) marginal inverse demand is increasing in capability.*

Mathematically the parts of Assumption 1 are

$$(a)\ \frac{\partial r(\theta, x_\theta, \vec{x}_{\setminus\theta})}{\partial \theta} > 0,\ \frac{\partial r(\theta, x_\theta, \vec{x}_{\setminus\theta})}{\partial x_\theta} < 0,\ \frac{\partial^2 r(\theta, x_\theta, \vec{x}_{\setminus\theta})}{\partial x_\theta^2} \leq 0,\ \frac{\partial r(\theta, x_\theta, \vec{x}_{\setminus\theta})}{\partial x_{\setminus\theta}} \leq 0;$$

$$(b)\ \frac{\partial^2 r(\theta, x_\theta, \vec{x}_{\setminus\theta})}{\partial \theta \partial x_\theta} \geq 0.$$

In Assumption 1(a), we take inverse demand to be decreasing and concave in output. Further, inverse demand is decreasing in other DCs' output as is characteristic in Cournot competition (pp. 221-224 Tirole 1988, Bhargava 2021a). Allowing DC inverse demand to decrease in output from other DCs means that the resulting profit function can accommodate almost any form of DC competition as we show in Section 4.1.

Assumption 1(a) also defines the effect of DC capability in our model: users prefer more capable DCs and such DCs have higher revenue per unit of output as per our definition of capability. This is effectively a demand shift whereby a higher capability DC receives higher revenue per unit of output at each level of output. In Assumption 1(b) more capable DCs generate greater marginal inverse demand. See Appendix B.1 for an example of the effect of capability on inverse demand.

Network Effects As a demand-side network effect, the presence of demand from users makes a DC more desirable to other users. This network effect can exist in a one-sided market where the value enjoyed by a user depends on the number of other users on the DC (Asvanund et al. 2004, Gu et al. 2007). For example, social networks such as Facebook become more desirable as more users join. In an inverse demand function, this can be captured as a positive argument which is increasing in output (Yoo et al. 2007). Thus, this effect softens the standard negative effect of output on inverse demand. In other words, if network effects are large, then the extent to which inverse demand decreases in output is lessened, that is, $\partial r(\theta, x_\theta, \vec{x}_{\setminus\theta})/\partial x_\theta$ becomes less negative. Given that these network effects are such that the inverse demand remains decreasing in output (Bhargava 2021b, Yoo et al. 2007, Economides and Katsamakas 2006, Asvanund et al. 2004), our model captures such demand-side network effects in a general way and our analysis is not impacted by the extent of network effects. A parameterized example of user decision making that demonstrates this and our other assumptions is provided in Appendix A.

3.1. Imposition of DPR: Fines and Investments

As outlined in Section 1, the imposition of DPR has four effects, the first two of which apply to non-compliant DCs. The first is that DCs that do not comply with DPR are fined. Following GDPR and CCPA, we model both fixed fines, $F \in \mathbb{R}_{\geq 0}$, and variable fines as a proportion of revenues, $f \in [0, 1]$. The policy-maker chooses the level of fines. There is no fine for compliant DCs. The second effect is that a given DC is less attractive to users if it does not comply compared to if it does, because portability is an additional feature.

The third and fourth effects concern DCs that comply. The third effect is that users using a compliant DC can port their data to another DC. Such porting can be single-homing, in which case the user ports and no longer uses the origin DC; or multi-homing, where the user ports but uses both the origin and destination DCs. Thus, for DCs that comply, there is potentially either decreased demand (users port to other DCs in net) or increased demand (users port from other DCs in net). The fourth effect is the compliance cost that compliant DCs incur, and the policy-maker can invest to decrease this cost.

Pre-DPR, when DCs have not yet enabled portability, given distributions of DCs by capability, an equilibrium occurs when users choose a DC. Post DPR, this equilibrium changes because the user valuation of DCs changes as some DCs comply with DPR. As described above, compliance with DPR implies the provision of the additional feature of portability. This increases the value that a user can gain from each competing compliant DC. We make the reasonable presumption that the compliant DCs' decision to provide the additional feature of portability does not cause users to leave the market.

Compliance or non-compliance results in new inverse demand functions – that is, new prices, after DPR. We denote the *compliant inverse demand* function as $r^c(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta}) \in \mathbb{R}$, which depends on DC capability, the proportion of DCs that comply, where for the moment we use ρ to denote the proportion of DCs that comply, and the output of all DCs. The compliant inverse demand can be higher, lower, or similar to the inverse demand prior to DPR as the third effect described above can cause compliant DCs to lose or gain business to or from other DCs. Similarly, we denote the *non-compliant inverse demand* function as $r^{nc}(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta}) \in \mathbb{R}$, which also depends on DC capability, the proportion of DCs that comply, and the output of all DCs. Non-compliant inverse demand is lower than the inverse demand prior to DPR due to the second effect described above.

Our formulation also incorporates cross-DC network effects whereby the proportion of compliant DCs, ρ, affects inverse demand as portability enables the movement of users among DCs. As the proportion of compliant DCs increases, there is a negative cross-DC network effect on non-compliant DCs because compliant DCs have the added feature of portability. This causes non-compliant inverse demand to decrease. This effect is in total and at the margin as detailed in our Assumption 2 below.

ASSUMPTION 2 **(Proportion of Compliant DCs)**. *Non-compliant inverse demand and marginal non-compliant inverse demand are decreasing in the proportion of compliant DCs.*

Mathematically the parts of Assumption 2 are

$$\frac{\partial r^{nc}(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta})}{\partial \rho} < 0; \; \frac{\partial^2 r^{nc}(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta})}{\partial \rho \partial x_\theta} \leq 0.$$

Assumption 2 implies that non-compliant DC inverse demand and marginal non-compliant inverse demand decrease in the proportion of compliant DCs because there are more alternative compliant DCs for users to choose from. The lack of portability on the part of non-compliant DCs in conjunction with an increase in the proportion of compliant DCs leads to lower inverse demand for non-compliant DCs. A parameterized example of user decision making that demonstrates this assumption is provided in Appendix A. The proportion of compliant DCs, ρ, is derived endogenously in our model as result of each DC's decision on compliance, as we discuss in Section 4.2.

Business and Compliance Costs: DCs face a *business cost* which depends solely on own output, $C(x_\theta) \in \mathbb{R}_{\geq 0}$. Business costs include costs of business operations, financing, and user acquisition, and are convex (Bhargava 2022, p. 5237). Compliant DCs also face *compliance costs*, $\gamma(x_\theta, I) \in \mathbb{R}_{>0}$, which are costs to enable users to port their data, and where I is investments defined below. Compliance costs include the costs of development of additional processes, database capabilities, and administrative tasks that are needed to comply with the standards and requirements for porting that the policy-maker sets.

As an instrument, the policy-maker can decrease the cost of compliance that DCs incur by investing in standards, protocols, and tools for porting of data. Using the term *investments*, we define $I \in \mathbb{R}_{\geq 0}$ to represent policy-maker investment to decrease compliance costs. These investments may include creating standards, APIs, or platforms for porting of data such as those for porting energy and banking data described in the Introduction, or initiatives similar to Data Transfer Initiative[2] and the Universal Digital Profile[3] developed by the policy-maker. Such investments substitute in part for DC compliance costs. Next, we characterize the two types of DC costs.

[2] `https://dtinit.org/`

[3] `https://techcrunch.com/2018/05/22/the-birth-of-the-universal-digital-profile/`

Assumption 3 **(Cost)**. *(a) DC compliance costs are decreasing in investments in total and at the margin; and (b) total costs are convex in output.*

Mathematically the parts of Assumption 3 are

$$(a)\ \frac{\partial \gamma(x_\theta, I)}{\partial I} < 0,\ \ \frac{\partial^2 \gamma(x_\theta, I)}{\partial I \partial x_\theta} < 0;\ \ (b)\ \frac{\partial^2 C(x_\theta)}{\partial x_\theta^2} + \frac{\partial^2 \gamma(x_\theta, I)}{\partial x_\theta^2} > 0.$$

Assumption 3(a) is the main effect of the investment instrument. Assumption 3(b) takes total costs to be convex in output, implying that acquisition of users becomes harder as more users are acquired, which is a standard assumption. A large proportion of DC costs are typically apportioned to convex costs. For example, Meta reports that in 2021, their costs of revenue, selling and marketing, and general and administrative – typically convex costs – were \$46.5B (Meta Platforms Inc. 2021). At the same time depreciation and amortization related to their capital assets, including technology and buildings – possibly linear or concave costs – were \$8B.

Next we consider the relative effects of capability on compliant versus non-compliant inverse demand, and of output on marginal profits from non-compliance.

Assumption 4 **(Relative Effects)**. *(a) Capability increases compliant inverse demand more than it does non-compliant inverse demand and (b) for a DC that makes identical payoffs from compliance and non-compliance, marginal profits from non-compliance are negative when evaluated at the optimal output from compliance,* x_θ^c.

We use $\Pi^c(\cdot)$ and $\Pi^{nc}(\cdot)$ to denote payoffs from compliance and non-compliance, respectively, the arguments of which are defined later in Section 4.2. Mathematically, Assumption 4 is

$$(a)\ \frac{\partial r^c(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta})}{\partial \theta} > \frac{\partial r^{nc}(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta})}{\partial \theta};$$

$$(b)\ r^{nc}(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta}) + x_\theta \frac{\partial r^{nc}(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta})}{\partial x_\theta} - \frac{\partial C(x_\theta)}{\partial x_\theta}\bigg|_{x_\theta = x_\theta^c} < 0 \quad if\ \Pi^c(\cdot) = \Pi^{nc}(\cdot).$$

From Assumption 1(a), inverse demand increases in capability for both non-compliant and compliant DCs. Given that compliant DCs allow for data portability, they experience additional gains and losses of users. The benefits to users from DCs that comply with DPR also depend on DC capability. In other words, the additional value from portability for compliant DCs is also positive and increasing in capability. Thus, in Assumption 4(a) as capability increases the inverse demand of compliant DCs increases more than that of non-compliant DCs.

Assumption 4(b) states that for a given DC that makes identical payoffs from compliance and non-compliance, it generates negative marginal profit from non-compliance at x_θ^c, the optimal output from compliance. In practice, this assumption implies that for a DC that makes identical payoffs

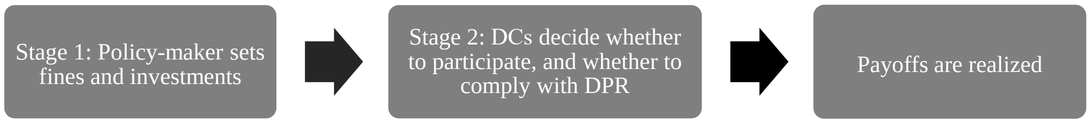


Figure 1 Stages of the game

from compliance and non-compliance, the optimal output from non-compliance is smaller than the optimal output from compliance. Moreover, a positive variable fine further decreases marginal revenue, and consequently optimal output from non-compliance. In Appendix B we characterize our inverse demand functions, derive optimal output, and provide a basis for our Assumption 4(b).

Data portability does not enable the perfect transfer of the data that a DC has on a user because some of the richness of, the inferences on, and the social networking aspects of the data could be lost during the transfer. This results in varying levels of porting effectiveness: Porting effectiveness increases the value from porting, thereby increasing the compliant inverse demand and decreasing the non-compliant inverse demand. These differences are captured by our general model through the magnitudes of the inverse demand functions, therefore our results and insights are not qualitatively impacted by the level of porting effectiveness.

4. The Effects of Data Portability

Our goal is to explain the effect of fines and investments to encourage data portability on the structure of the DC industry. We analyze a setting where DCs have complete information and we use the terms *participating* to denote DCs that make positive profits and *non-participating* to denote DCs that do not. These latter DCs choose zero output and exit the industry.

We model the process of policy-maker choices of instruments, and DC compliance and participation as a two-stage game where the latter stage has two decisions. In Stage 1 the policy-maker sets fines and investments. In Stage 2, DCs decide on participation, and if they participate, whether to comply with DPR. Finally, payoffs are realized (Figure 1). We work backwards by first solving the DC compliance decision on the basis of optimal production (output) when complying with DPR and not, and next choosing whether to participate. Then we solve the policy-maker's decision on fines and investments, and analyze the effect of fines and investments on consumer surplus (user surplus), producer surplus (DC surplus), and social welfare.

Given that the purpose of DPR is to enable users to port their data to a different DC by increasing the value provided by competing DCs, we first consider the status quo as the equilibrium prior to the imposition of DPR. We then consider the setting where the imposition of DPR results in some users porting to other DCs. Following Tirole (1988, pp. 218-226) and Nault and Zimmermann (2019) we consider quantity (Cournot) competition and use reduced form inverse demand, revenue, and profit functions as the key units of analysis. Just as demand functions abstract away from preferences and utilities, revenue and profit functions abstract away from demand functions, thereby enabling models to focus on a DC's external interactions rather than on how demand aggregates.

4.1. Pre-DPR

Prior to the imposition of DPR each DC maximizes profits by choice of own output,

$$\max_{x_\theta} \Pi(\theta, x_\theta, \vec{x}_{\setminus\theta}) = \max_{x_\theta}[x_\theta r(\theta, x_\theta, \vec{x}_{\setminus\theta}) - C(x_\theta)], \tag{1}$$

and the resulting set of first-order and second-order conditions are

$$\frac{\partial \Pi(\theta, x_\theta, \vec{x}_{\setminus\theta})}{\partial x_\theta} = x_\theta \frac{\partial r(\theta, x_\theta, \vec{x}_{\setminus\theta})}{\partial x_\theta} + r(\theta, x_\theta, \vec{x}_{\setminus\theta}) - \frac{\partial C(x_\theta)}{\partial x_\theta} = 0, \ \forall\ \theta \in [0,1], \quad \textit{and} \tag{2}$$

$$\frac{\partial^2 \Pi(\theta, x_\theta, \vec{x}_{\setminus\theta})}{\partial x_\theta^2} = x_\theta \frac{\partial^2 r(\theta, x_\theta, \vec{x}_{\setminus\theta})}{\partial x_\theta^2} + 2\frac{\partial r(\theta, x_\theta, \vec{x}_{\setminus\theta})}{\partial x_\theta} - \frac{\partial^2 C(x_\theta)}{\partial x_\theta^2} < 0, \ \forall\ \theta \in [0,1].$$

The second order conditions are satisfied by Assumptions 1(a) and 3(b). With concavity of the profit function and output defined in (2) (continuous over a compact set), the first-order conditions lead to pre-DPR Nash equilibrium output for all DCs, $x_\theta^{pre}(\vec{x}_{\setminus\theta})$, where we use the superscript *pre* to denote output pre-DPR. Thus, (2) defines the equilibrium output for all DCs in a generalized Cournot setting where every DC's output affects a given DC's inverse demand.

Next, we move to the analysis post-DPR and study the DC decisions on compliance and participation.

4.2. Compliance

DCs that Comply with DPR: If they comply, then payoffs for DCs are revenues from compliance less business and compliance costs. Compliant DCs are not fined. The payoff maximization problem for a compliant DC is

$$\max_{x_\theta} \Pi^c(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta}, I) = \max_{x_\theta}[x_\theta r^c(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta}) - C(x_\theta) - \gamma(x_\theta, I)]. \tag{3}$$

Using $\Pi^c(\cdot)$ to capture the arguments in the left-hand side of (3), the first-order condition is

$$\frac{\partial \Pi^c(\cdot)}{\partial x_\theta^c} = x_\theta^c \frac{\partial r^c(\theta, \rho, x_\theta^c, \vec{x}_{\setminus\theta})}{\partial x_\theta^c} + r^c(\theta, \rho, x_\theta^c, \vec{x}_{\setminus\theta}) - \frac{\partial C(x_\theta^c)}{\partial x_\theta^c} - \frac{\partial \gamma(x_\theta^c, I)}{\partial x_\theta^c} = 0 = \psi_1(\theta, \rho, x_\theta^c, \vec{x}_{\setminus\theta}, I), \tag{4}$$

where $\psi_1(\theta, \rho, x_\theta^c, \vec{x}_{\setminus\theta}, I) = 0$ implicitly defines $x_\theta^c(\rho, \vec{x}_{\setminus\theta}, I)$, which is an optimal value function denoting output of a compliant DC. Economizing on notation so that $\psi_1(\theta, \rho, x_\theta^c, \vec{x}_{\setminus\theta}, I) = \psi_1(\cdot)$, and differentiating (4) with respect to output we get

$$\frac{\partial^2 \Pi^c(\cdot)}{\partial [x_\theta^c]^2} = \frac{\partial \psi_1(\cdot)}{\partial x_\theta^c} = x_\theta^c \frac{\partial^2 r^c(\theta, \rho, x_\theta^c, \vec{x}_{\setminus\theta})}{\partial [x_\theta^c]^2} + 2\frac{\partial r^c(\theta, \rho, x_\theta^c, \vec{x}_{\setminus\theta})}{\partial x_\theta^c} - \frac{\partial^2 C(x_\theta^c)}{\partial [x_\theta^c]^2} - \frac{\partial^2 \gamma(x_\theta^c, I)}{\partial [x_\theta^c]^2} < 0, \tag{5}$$

which is negative by Assumptions 1(a) and 3(b).

DCs that Do Not Comply with DPR: If they do not comply, then payoffs for DCs are revenues from non-compliance adjusted by the variable fine on revenues, less business costs and the fixed fine. In the payoff maximization problem for a non-compliant DC below, f is the proportion of DC revenues paid as variable fines, and F is the fixed fine. The payoff maximization is

$$\max_{x_\theta} \Pi^{nc}(\theta,\rho,x_\theta,\vec{x}_{\backslash\theta},F,f) = \max_{x_\theta} \big[[1-f][x_\theta r^{nc}(\theta,\rho,x_\theta,\vec{x}_{\backslash\theta})] - C(x_\theta) - F\big]. \tag{6}$$

Using $\Pi^{nc}(\cdot)$ to capture the arguments in the left-hand side of (6), the first-order condition is

$$\frac{\partial \Pi^{nc}(\cdot)}{\partial x_\theta^{nc}} = [1-f]\Big[x_\theta^{nc}\frac{\partial r^{nc}(\theta,\rho,x_\theta^{nc},\vec{x}_{\backslash\theta})}{\partial x_\theta^{nc}} + r^{nc}(\theta,\rho,x_\theta^{nc},\vec{x}_{\backslash\theta})\Big] - \frac{\partial C(x_\theta^{nc})}{\partial x_\theta^{nc}} = 0 = \psi_2(\theta,\rho,x_\theta^{nc},\vec{x}_{\backslash\theta},f), \tag{7}$$

where $\psi_2(\theta,\rho,x_\theta^{nc},\vec{x}_{\backslash\theta},f)=0$ implicitly defines $x_\theta^{nc}(\rho,\vec{x}_{\backslash\theta},f)$, which denotes optimal output if not complying. Further economizing on notation so that $\psi_2(\theta,\rho,x_\theta^{nc},\vec{x}_{\backslash\theta},f)=\psi_2(\cdot)$ and differentiating with respect to output we get

$$\frac{\partial \psi_2(\cdot)}{\partial x_\theta^{nc}} = \frac{\partial^2 \Pi^{nc}(\cdot)}{\partial [x_\theta^{nc}]^2} = [1-f]\Big[x_\theta^{nc}\frac{\partial^2 r^{nc}(\theta,\rho,x_\theta^{nc},\vec{x}_{\backslash\theta})}{\partial [x_\theta^{nc}]^2} + 2\frac{\partial r^{nc}(\theta,\rho,x_\theta^{nc},\vec{x}_{\backslash\theta})}{\partial x_\theta^{nc}}\Big] - \frac{\partial^2 C(x_\theta^{nc})}{\partial [x_\theta^{nc}]^2} < 0, \tag{8}$$

which is negative from Assumptions 1(a) and 3(b).

With each DC's decision of whether to comply, the combination of (4) and (7) across DCs yields a Nash equilibrium in output. The payoffs for DCs from compliance are as in (3) where outputs are stated as optimal value functions $x_\theta^c(\rho,\vec{x}_{\backslash\theta},I)=x_\theta^c(\cdot)$. On the other hand, the payoff for DCs from non-compliance are as in (6) where output is $x_\theta^{nc}(\rho,\vec{x}_{\backslash\theta},f)=x_\theta^{nc}(\cdot)$. Given a level of fines and investments, each DC compares its payoff from compliance against its payoff from non-compliance. To find the DC that is indifferent between complying and not complying with DPR, denoted by $\tilde{\theta}$, we equate the payoffs to compliance and non-compliance so that

$$x_{\tilde\theta}^c(\cdot)r^c(\tilde\theta,\rho,x_{\tilde\theta}^c(\cdot),\vec{x}_{\backslash\tilde\theta}(\cdot)) - C(x_{\tilde\theta}^c(\cdot)) - \gamma(x_{\tilde\theta}^c(\cdot),I) = [1-f]x_{\tilde\theta}^{nc}(\cdot)r^{nc}(\tilde\theta,\rho,x_{\tilde\theta}^{nc}(\cdot),\vec{x}_{\backslash\tilde\theta}(\cdot)) - C(x_{\tilde\theta}^{nc}(\cdot)) - F.$$

Re-arranging so that the difference between the payoffs from compliance and non-compliance equal zero, we have

$$\begin{aligned} &x_{\tilde\theta}^c(\cdot)r^c(\tilde\theta,\rho,x_{\tilde\theta}^c(\cdot),\vec{x}_{\backslash\tilde\theta}(\cdot)) - C(x_{\tilde\theta}^c(\cdot)) - \gamma(x_{\tilde\theta}^c(\cdot),I) - x_{\tilde\theta}^{nc}(\cdot)r^{nc}(\tilde\theta,\rho,x_{\tilde\theta}^{nc}(\cdot),\vec{x}_{\backslash\tilde\theta}(\cdot)) \\ &+ f x_{\tilde\theta}^{nc}(\cdot)r^{nc}(\tilde\theta,\rho,x_{\tilde\theta}^{nc}(\cdot),\vec{x}_{\backslash\tilde\theta}(\cdot)) + C(x_{\tilde\theta}^{nc}(\cdot)) + F = 0 = \psi_3(\tilde\theta,\rho,x_{\tilde\theta}^c(\cdot),x_{\tilde\theta}^{nc}(\cdot),\vec{x}_{\backslash\tilde\theta}(\cdot),F,f,I), \end{aligned} \tag{9}$$

where $\psi_3(\tilde\theta,\rho,x_{\tilde\theta}^c(\cdot),x_{\tilde\theta}^{nc}(\cdot),\vec{x}_{\backslash\tilde\theta}(\cdot),F,f,I) = 0 = \psi_3(\cdot)$ implicitly defines the indifferent DC, $\tilde\theta(\rho,x_{\tilde\theta}^c(\cdot),x_{\tilde\theta}^{nc}(\cdot),\vec{x}_{\backslash\tilde\theta}(\cdot),F,f,I)$, which we denote by $\tilde\theta(\cdot)$. Our first Lemma relates the rate at which payoffs from compliance and payoffs from non-compliance increase with capability, as well as the significance of the indifferent DC, $\tilde\theta(\cdot)$. Proofs for all Lemmas and Theorems are in Appendix D.

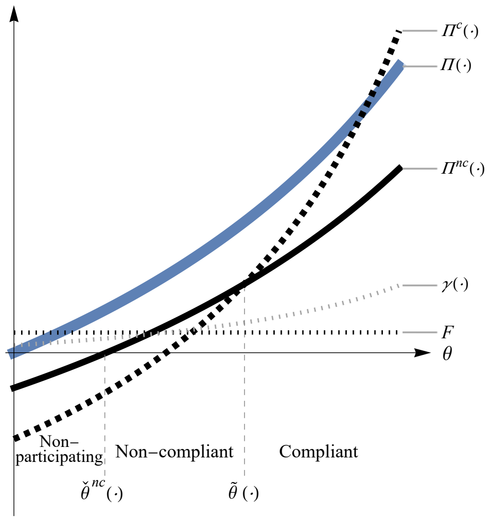


Figure 2 DC payoff from compliance and non-compliance: An illustrative example

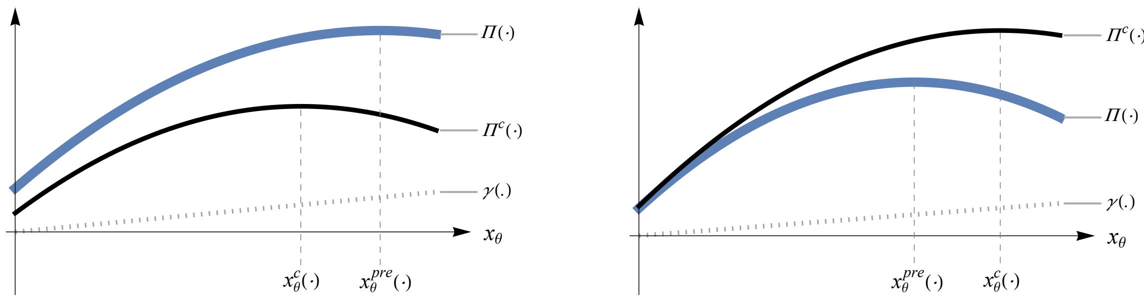
Lemma 1. *Payoffs and output increase with capability. Payoffs from compliance increase faster in capability than do payoffs from non-compliance. DCs that are more capable than $\tilde{\theta}(\cdot)$ comply with DPR. The optimal output from compliance for $\tilde{\theta}(\cdot)$ is higher than its optimal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

The essence of Lemma 1 is a single crossing condition, $\partial\Pi^c(\cdot)/\partial\theta > \partial\Pi^{nc}(\cdot)/\partial\theta$. To discern the intuition behind this Lemma, consider when variable fines and investments are zero, so that only fixed fines are in effect. Figure 2 provides an illustration of DC payoffs from compliance and non-compliance, $\Pi^c(\cdot)$ and $\Pi^{nc}(\cdot)$ from (3) and (6), respectively; profits pre-DPR, $\Pi(\cdot)$; compliance costs, $\gamma(\cdot)$; all of which include outputs as optimal value functions; and fixed fines, F. The intersection of $\Pi^c(\cdot)$ and $\Pi^{nc}(\cdot)$ defines $\tilde{\theta}(\cdot)$. For this DC, $x^c_{\tilde{\theta}}(\rho, \vec{x}_{\setminus\tilde{\theta}}) > x^{nc}_{\tilde{\theta}}(\rho, \vec{x}_{\setminus\tilde{\theta}}, f)$ from Lemma 1. Because compliant inverse demand increases more than non-compliant inverse demand from Assumption 4(a), the payoff from compliance increases more with capability than does the payoff from non-compliance (Lemma 1). Therefore, the payoff from compliance for any DC that is more capable than $\tilde{\theta}(\cdot)$ is higher than its payoff from non-compliance.

We can now define the proportion of DCs that comply as the set of DCs between $\tilde{\theta}(\cdot)$ and 1, so that with $\theta \sim U[0,1]$ we can determine $\rho(\tilde{\theta}(\cdot)) = 1 - \tilde{\theta}(\cdot)$ and $d\rho(\cdot)/d\tilde{\theta} = -1 < 0$. Therefore, the proportion of compliant DCs, $\rho(\tilde{\theta}(\cdot))$, is derived endogenously as result of the DCs' decision on compliance through $\tilde{\theta}(\cdot)$. We now analyze the impact of fixed fines, variable fines, and investments on DC compliance.

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

The indifferent DC $\tilde{\theta}(\cdot)$ decreases in all policy-maker instruments (that is, moves to the left in the capability continuum), so that $\partial\tilde{\theta}(\cdot)/\partial F$, $\partial\tilde{\theta}(\cdot)/\partial f$, $\partial\tilde{\theta}(\cdot)/\partial I < 0$. For exposition we write



(a) Loss of payoff from compliance (b) Gain in payoff from compliance

Figure 3 DC output and payoffs from compliance: An illustrative example

$\partial\rho(\cdot)/\partial F$, $\partial\rho(\cdot)/\partial f$, $\partial\rho(\cdot)/\partial I > 0$. The effect of the fixed fine can be inferred from Figure 2 – any increase in the fixed fine decreases the payoffs from non-compliance, shifting the indifferent DC, $\tilde{\theta}(\cdot)$, to the left. With a positive variable fine, a proportion $f \in [0,1]$ of revenues from non-compliance is transferred to the policy-maker. This implies that the variable fine decreases the payoff from non-compliance further from what is illustrated in Figure 2, thereby moving $\tilde{\theta}(\cdot)$ further to the left. If $\Pi^c(\cdot)$ contains non-zero compliance costs, then investments have the effect of decreasing compliance costs thereby increasing $\Pi^c(\cdot)$. This moves $\tilde{\theta}(\cdot)$ to the left, although the mechanism is through increased payoffs from compliance rather than decreased payoffs from non-compliance. A comparison of the rate at which investments decrease compliance to the rate at which fines decrease compliance simplifies to the following two equations:

$$\frac{\partial\tilde{\theta}(\cdot)/\partial I}{\partial\tilde{\theta}(\cdot)/\partial F} = -\frac{\partial\gamma(\cdot)}{\partial I}, \quad \text{and} \quad \frac{\partial\tilde{\theta}(\cdot)/\partial I}{\partial\tilde{\theta}(\cdot)/\partial f} = -\frac{\partial\gamma(\cdot)/\partial I}{x_{\tilde{\theta}}^{nc}(\cdot)r^{nc}(\tilde{\theta}, \rho, x_{\tilde{\theta}}^{nc}(\cdot), \vec{x}_{\setminus\tilde{\theta}}(\cdot))}.$$

Compared to fixed fines, the effectiveness of investments in increasing compliance depends solely on the rate at which compliance costs decrease with investments. However, compared to variable fines, the effectiveness of investments depends on both the rate at which compliance costs decrease with investments and the revenues of $\tilde{\theta}(\cdot)$. We can also quantify the relative effect of fixed and variable fines on compliance,

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

In other words, the extent of the move to the left through variable fines is weighted by the revenues generated by the indifferent DC, $\tilde{\theta}(\cdot)$, that is, $x_{\tilde{\theta}}^{nc}(\cdot)r^{nc}(\cdot)$.

We now analyze the effect of policy-maker instruments on compliant and non-compliant DC output. Pre-DPR profit is optimized at $x_\theta^{pre}(\cdot)$. We first use Figure 3 to describe the compliant DC output, which is derived by solving (4). This figure illustrates the payoffs from compliance for a particular DC, θ, with output on the horizontal axis. Depending on a DC's capability, the compliant inverse demand can be lower ($r^c(\cdot) < r(\cdot)$ as seen in Figure 3a), or higher ($r^c(\cdot) > r(\cdot)$ as in

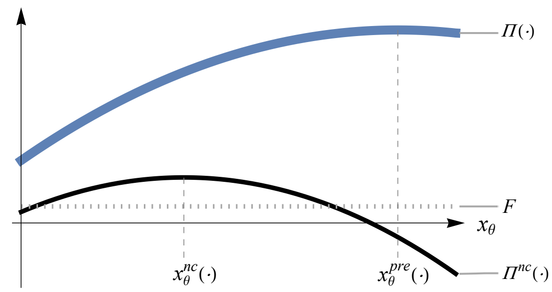


Figure 4 DC output and payoffs from non-compliance: An illustrative example

Figure 3b), which results in a consequently lower or higher payoff and output from compliance. On the other hand, Figure 4 describes the non-compliant optimal output that DCs choose by solving (7). After imposition of DPR, non-compliance results in a decrease in revenues from $x_\theta^{pre}(\cdot)r(\cdot)$ to $x_\theta^{nc}(\cdot)r^{nc}(\cdot)$, and a decrease in output from $x_\theta^{pre}(\cdot)$ to $x_\theta^{nc}(\cdot)$.

In our next Lemma, we describe the effect of policy-maker instruments and increased compliance on output.

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

Mathematically, this Lemma states that

$$(a)\ \partial x_\theta^{nc}(\cdot)/\partial\rho \le 0, \ \ \textit{and}\ \ (b)\ \partial x_\theta^{nc}(\cdot)/\partial F,\ \partial x_\theta^{nc}(\cdot)/\partial f,\ \partial x_\theta^{nc}(\cdot)/\partial I \le 0.$$

The underlying cause of the decrease in optimal output is the decrease in the non-compliant inverse demand or marginal revenue. In Lemma 3(a) the proportion of compliant DCs decreases the non-compliant inverse demand by Assumption 2, which decreases output.

Moving to Lemma 3(b), from Lemma 2 each of fixed fines, variable fines, and investments increase the proportion of compliance DCs, which in turn decreases non-compliant output by the above Lemma 3(a). In addition, variable fines decrease marginal revenue from non-compliance as can be seen in (7), thereby further decreasing output. In other words, variable fines also have a direct effect on non-compliant DC output.

4.3. Participation

Here we analyze the mechanisms through which fines and investments impact DC participation. We denote the DC that generates zero payoffs from non-compliance by $\check{\theta}^{nc}$. This DC is determined by setting (6) to zero where outputs are stated as optimal value functions, so

$$\begin{aligned}\Pi^{nc}(\check{\theta}^{nc},\rho(\cdot),x_{\check{\theta}^{nc}}^{nc}(\cdot),\vec{x}_{\setminus\check{\theta}^{nc}}(\cdot),F,f) =&[1-f]x_{\check{\theta}^{nc}}^{nc}(\cdot)r^{nc}(\check{\theta}^{nc},\rho,x_{\check{\theta}^{nc}}^{nc}(\cdot),\vec{x}_{\setminus\check{\theta}^{nc}}(\cdot))-C(x_{\check{\theta}^{nc}}^{nc}(\cdot))-F=0\\ =&\psi_4(\check{\theta}^{nc},\rho(\cdot),x_{\check{\theta}^{nc}}^{nc}(\cdot),\vec{x}_{\setminus\check{\theta}^{nc}}(\cdot),F,f), \end{aligned} \tag{10}$$

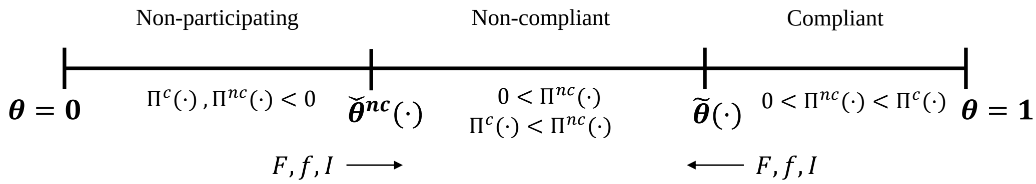


Figure 5 DC segmentation in the case of partial compliance: An illustration

where $\psi_4(\breve{\theta}^{nc}, \rho(\cdot), x^{nc}_{\breve{\theta}^{nc}}(\cdot), \vec{x}_{\setminus\breve{\theta}^{nc}}(\cdot), F, f) = 0$ implicitly defines $\breve{\theta}^{nc}(\rho(\cdot), x^{nc}_{\breve{\theta}^{nc}}(\cdot), \vec{x}_{\setminus\breve{\theta}^{nc}}(\cdot), F, f)$, or $\breve{\theta}^{nc}(\cdot)$.

The compliant DC that is indifferent between participating and not participating also realizes zero payoffs. This indifferent DC, $\breve{\theta}^c$, is determined by setting (3) equal to zero and with outputs stated as optimal value functions so that

$$\begin{aligned}\Pi^c(\breve{\theta}^c, \rho(\cdot), x^c_{\breve{\theta}^c}(\cdot), \vec{x}_{\setminus\breve{\theta}^c}(\cdot), I) &= x^c_{\breve{\theta}^c}(\cdot) r^c(\breve{\theta}^c, \rho(\cdot), x^c_{\breve{\theta}^c}(\cdot), \vec{x}_{\setminus\breve{\theta}^c}(\cdot)) - C(x^c_{\breve{\theta}^c}(\cdot)) - \gamma(x^c_{\breve{\theta}^c}(\cdot), I) = 0 \\ &= \psi_5(\breve{\theta}^c, \rho(\cdot), x^c_{\breve{\theta}^c}(\cdot), \vec{x}_{\setminus\breve{\theta}^c}(\cdot), I), \end{aligned} \tag{11}$$

where $\psi_5(\breve{\theta}^c, \rho(\cdot), x^c_{\breve{\theta}^c}(\cdot), \vec{x}_{\setminus\breve{\theta}^c}(\cdot), I) = 0$ implicitly defines $\breve{\theta}^c(\rho(\cdot), x^c_{\breve{\theta}^c}(\cdot), \vec{x}_{\setminus\breve{\theta}^c}(\cdot), I)$, or $\breve{\theta}^c(\cdot)$.

We now describe how DCs are segmented facing fines and investments to encourage DPR.

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.*

All DCs that are more capable than $\breve{\theta}^{nc}(\cdot)$ generate positive payoffs from non-compliance, while all DCs that are more capable than $\breve{\theta}^c(\cdot)$ generate positive payoffs from compliance. Lemma 4 defines two sets of segmentations, *partial compliance* and *full compliance*. The segmentation for partial compliance is illustrated in Figure 5, where, by Lemma 1, compliant DCs lie on the right side of $\tilde{\theta}(\cdot)$, and non-compliant DCs lie on the left side of $\tilde{\theta}(\cdot)$. If payoffs to $\tilde{\theta}(\cdot)$ are positive, then partial compliance in Lemma 4(a) is obtained. Here, DCs between 0 and $\breve{\theta}^{nc}(\cdot)$ do not participate because of negative payoffs, DCs between $\breve{\theta}^{nc}(\cdot)$ and $\tilde{\theta}(\cdot)$ participate but do not comply, and DCs between $\tilde{\theta}(\cdot)$ and 1 participate and comply. On the other hand, if payoffs to $\tilde{\theta}(\cdot)$ are negative the segmentation for full compliance is obtained per Lemma 4(b), and as illustrated later on in Figure 7, all DCs that participate comply: DCs between 0 and $\breve{\theta}^c(\cdot)$ do not participate and DCs between $\breve{\theta}^c(\cdot)$ and 1 participate and comply.

By Lemma 2, each policy-maker instrument increases compliance. Our first Theorem describes the collateral effect of fixed fines, variable fines, and investments on participation.

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

Theorem 1 is an important result: if there is partial compliance, then any use of policy-maker instruments decreases participation. This occurs even if the policy-maker uses investments as their instrument of choice.

Fixed fines, variable fines, and investments increase the proportion of compliant DCs (Lemma 2), which in turn lowers the non-compliant inverse demand by Assumption 2. This indirect effect is the underlying cause for participation to decrease in investments. Separately, the direct effect of an increase in fixed fines is to decrease the payoff to $\check{\theta}^{nc}(\cdot)$ from non-compliance so that $\check{\theta}^{nc}(\cdot)$ now generates negative payoffs and ceases to participate. Variable fines also have a direct effect on non-compliant payoffs – similar to fixed fines. From (10), the payoffs to $\check{\theta}^{nc}(\cdot)$ do not directly depend on investments.

Figure 6 illustrates the impact of increased fixed fines on DC compliance and participation in the case of *partial compliance*. Consider a regime with low-fines l and one with high-fines h. Using subscripts to denote the regime, the intersection of $\Pi_l^{nc}(\cdot)$ and the horizontal axis (where payoff is zero) gives the DC that generates zero payoffs from non-compliance, $\check{\theta}_l^{nc}(\cdot)$. DCs that are more capable than $\check{\theta}_l^{nc}(\cdot)$ generate positive payoffs from non-compliance. Similarly, the intersection of $\Pi^c(\cdot)$ with the horizontal axis gives $\check{\theta}^c(\cdot)$, the DC that generates zero payoffs from compliance. DCs that are more capable than $\check{\theta}^c(\cdot)$ generate positive payoffs from compliance. Because payoffs from compliance increase faster with capability than do payoffs from non-compliance by Lemma 1, $\Pi^c(\cdot)$ and $\Pi_l^{nc}(\cdot)$ intersect only once and the location of intersection defines the DC that is indifferent between complying and not complying under the low-fines regime, $\tilde{\theta}_l(\cdot)$.

An increase in fixed fines decreases payoffs from non-compliance from $\Pi_l^{nc}(\cdot)$ to $\Pi_h^{nc}(\cdot)$. As fines increase, $\tilde{\theta}(\cdot)$ moves to the left (Lemma 2), the payoffs to $\tilde{\theta}(\cdot)$ decrease, and $\check{\theta}^{nc}(\cdot)$ moves to the right (Theorem 1). With a sufficient increase in fines, the limit to where partial compliance transitions to full compliance is reached where payoffs to $\tilde{\theta}(\cdot)$ are zero and at this point $\check{\theta}^{nc}(\cdot) = \check{\theta}^c(\cdot) = \tilde{\theta}(\cdot)$. In sum, when the payoffs to $\tilde{\theta}(\cdot)$ are (weakly) negative, full compliance is obtained. The segmentation for full compliance is illustrated in Figure 7, where DCs that are more capable than $\check{\theta}^c(\cdot)$ participate and comply, but the others do not participate. Further increases in fixed fines moves $\tilde{\theta}(\cdot)$ further to the left and $\check{\theta}^{nc}(\cdot)$ further to the right in Figure 6. The ordering is then $\tilde{\theta}(\cdot) < \check{\theta}^c(\cdot) < \check{\theta}^{nc}(\cdot)$, the indifferent DC, $\tilde{\theta}(\cdot)$, has negative payoffs, and full compliance is maintained. However, once full compliance is reached, only $\check{\theta}^c(\cdot)$ is material as shown in Figure 7, and the fine-induced movements of $\tilde{\theta}(\cdot)$ to the left and $\check{\theta}^{nc}(\cdot)$ to the right have no consequence for the equilibrium. Thus, with full compliance, further increasing fines has no impact on participation or output.

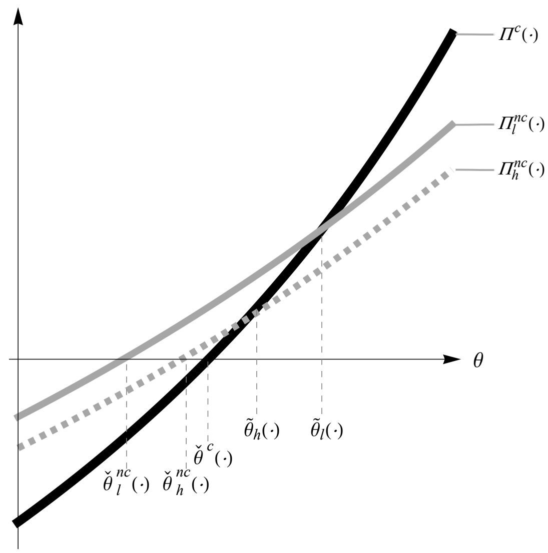


Figure 6 Impact of fines on DC compliance and participation: An illustrative example

In Theorem 1 and Figure 5 we showed that full compliance can be achieved through the use of any policy-maker instrument by simultaneously reducing participation and converting DCs from non-compliant to compliant; this is true even if investments are used in order to increase compliance. Once full compliance has been achieved the effect of investments on participation reverses and investments begin to increase participation. Even so, investments cannot ensure that all DCs participate and comply unless a specific market-based condition is satisfied. The policy-maker may be interested in the conditions under which their stated objective of increasing competition can be achieved while ensuring compliance. To this end, in our next Theorem we examine whether and how all DCs can comply profitably. We term such an outcome as full participation and full compliance.

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.*

Theorem 2 shows that once full compliance has been achieved, investments increase participation. Thus, the elimination of non-compliance is a pre-requisite for investments to increase participation.

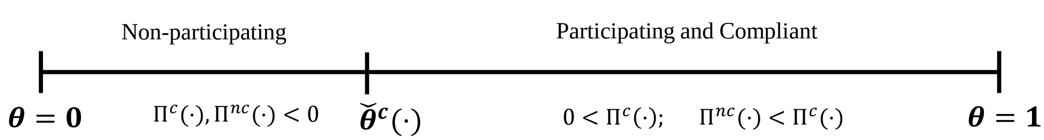


Figure 7 DC segmentation in the case of full compliance: An illustration.

An important finding from this Theorem is that investments by the policy-maker cannot achieve full participation and compliance without the right market conditions. Full compliance and full participation is a special case of full compliance described in Figure 7, but with $\check{\theta}^c(\cdot) = 0$. This requires that inverse demand increases for $\theta = 0$ if it complies with DPR so that $r^c(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta}) > r(\theta, x_\theta, \vec{x}_{\setminus\theta})|_{\theta=0}$. This is a necessary condition for full participation and full compliance.

This necessary condition occurs when the market expands as a result of DPR. Multi-homing can be such an instance of market expansion, where less capable DCs do not lose users if they comply. Instead, users copy their data over to another DC, thereby consuming services with two DCs. A second instance is a market expansion through a generic inflow of users into the focal DC industry from another industry. Such users bring their data with them and enjoy the added value from the focal DC industry as a result of DPR. If such incoming users highly value portability, then the compliant inverse demand function can be positive throughout the domain of θ.

Although the above market condition is necessary, it may not be sufficient because with higher compliance costs, the sufficient condition, $\Pi^c(\cdot)|_{\theta=0} \geq 0$, may not be met. However, investments decrease compliance costs so that subject to the necessary market-based condition being met, full compliance and full participation can be achieved through policy-maker investments. Fines can be used to eliminate non-compliance. However, because fines have no effect on the equilibrium once full compliance is achieved, they cannot be used to achieve full compliance and full participation. For the remainder of the analysis we focus on partial compliance because with full compliance, further increases in fines have no impact on participation or output.

5. Fines and Investments

In Stage 1, the policy-maker decides the level of fines and investments. In our setup, user surplus (US) is a measure of consumer surplus and is increasing in aggregate output, $X(F, f, I) \in \mathbb{R}_{>0}$ that we define below, so that $\partial US(X(\cdot))/\partial X > 0$. DC surplus (DCS) is a measure of producer surplus and is the aggregate payoffs to DCs after transfers to policy-makers (such as fines). Because fines are a transfer, they do not affect social welfare directly. Therefore, for the purposes of deriving social welfare, in Section 5.3, we develop a measure of DCS without fines, DCS_{-f}. In this section, we first analyze the effect of fines and investments on each of US and DCS and then on social welfare.

5.1. Aggregate Output and Industry Concentration

Aggregate output consists of the output of DCs between $\tilde{\theta}(\cdot)$ and 1 that participate and comply with DPR so individual DC output is $x^c_\theta(\cdot)$ and the output of DCs between $\check{\theta}^{nc}(\cdot)$ and $\tilde{\theta}(\cdot)$ that participate but do not comply with DPR so each DC produces $x^{nc}_\theta(\cdot)$,

$$X(F, f, I) = \int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} x^{nc}_\theta(\cdot) d\theta + \int_{\tilde{\theta}(\cdot)}^{1} x^c_\theta(\cdot) d\theta. \tag{12}$$

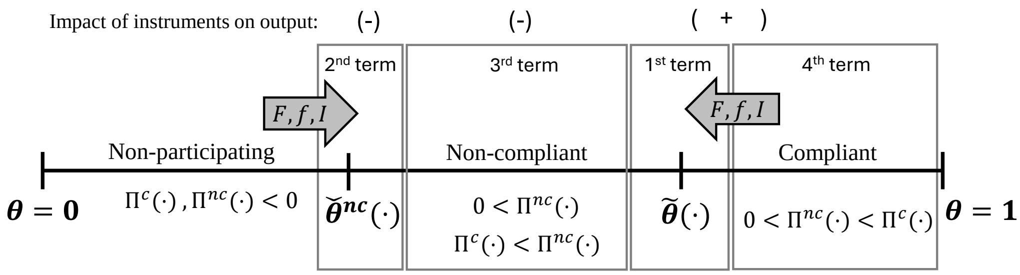


Figure 8 **The effects of fixed fines, variable fines, and investments on DC output**

DCs that do not participate, $\theta \in [0, \check{\theta}^{nc}(\cdot)]$, do not produce any output.

We now totally differentiate aggregate output in (12) with respect to fixed fines, variable fines, and investments to analyze the impact of these on output. We begin with fixed fines, apply Leibnitz's rule, and drop the terms that are zero to get

$$\begin{aligned}\frac{dX(\cdot)}{dF} = [x^{nc}_{\tilde{\theta}}(\cdot) - x^{c}_{\tilde{\theta}}(\cdot)]\frac{\partial\tilde{\theta}(\cdot)}{\partial F} - x^{nc}_{\check{\theta}^{nc}}(\cdot)\frac{\partial\check{\theta}^{nc}(\cdot)}{\partial F}\\ + \int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} \frac{\partial x^{nc}_{\theta}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial F}d\theta + \int_{\tilde{\theta}(\cdot)}^{1}\frac{\partial x^{c}_{\theta}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial F}d\theta,\end{aligned} \tag{13}$$

where we simplify the notation for aggregate output using $X(\cdot)$. Next, we totally differentiate (12) with respect to variable fines, to get

$$\begin{aligned}\frac{dX(\cdot)}{df} =& [x^{nc}_{\tilde{\theta}}(\cdot) - x^{c}_{\tilde{\theta}}(\cdot)]\frac{\partial\tilde{\theta}(\cdot)}{\partial f} - x^{nc}_{\check{\theta}^{nc}}(\cdot)\frac{\partial\check{\theta}^{nc}(\cdot)}{\partial f}\\ &+ \int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} \left[\frac{\partial x^{nc}_{\theta}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial f} + \frac{\partial x^{nc}_{\theta}(\cdot)}{\partial f}\right]d\theta + \int_{\tilde{\theta}(\cdot)}^{1}\frac{\partial x^{c}_{\theta}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial f}d\theta.\end{aligned} \tag{14}$$

Finally, we totally differentiate (12) with respect to investments, so that

$$\begin{aligned}\frac{dX(\cdot)}{dI} =& [x^{nc}_{\tilde{\theta}}(\cdot) - x^{c}_{\tilde{\theta}}(\cdot)]\frac{\partial\tilde{\theta}(\cdot)}{\partial I} - x^{nc}_{\check{\theta}^{nc}}(\cdot)\frac{\partial\check{\theta}^{nc}(\cdot)}{\partial I}\\ &+ \int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} \frac{\partial x^{nc}_{\theta}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial I}d\theta + \int_{\tilde{\theta}(\cdot)}^{1}[\frac{\partial x^{c}_{\theta}(\cdot)}{\partial\rho}\frac{\partial\rho(\cdot)}{\partial I} + \frac{\partial x^{c}_{\theta}(\cdot)}{\partial I}]d\theta.\end{aligned} \tag{15}$$

On the basis of the above equations, we construct our next Theorem where we describe the collateral effect of the use of the instruments to increase compliance on industry concentration. As described in Section 1, industry concentration measures the extent to which market shares are concentrated among DCs.

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

Theorem 3 is an important result: any use of the policy-maker's instruments increases industry concentration – in stark contrast to the intent of DPR.

The structures of (13), (14), and (15) are similar – each consists of four terms, and the effect captured by each of these terms is illustrated in Figure 8. Working from left to right in Figure 8, each instrument decreases participation from the least capable DCs thereby losing their output (second term in (13), (14), and (15)), decreases the output of non-compliant DCs (third term), and converts non-compliant DCs into compliant DCs and increases the aggregate output of compliant DCs (first and fourth terms). Moreover, by Lemma 1, more capable DCs produce greater output and the output of compliant DCs ($\tilde{\theta}(\cdot) \leq \theta$) is higher than the output of non-compliant DCs ($\theta < \tilde{\theta}(\cdot)$). Thus, any increases in fixed fines, variable fines, and investments increase the aggregate output of compliant DCs and decrease the output of non-compliant DCs, thereby increasing industry concentration.

Even though each policy-maker instrument decreases participation (Theorem 1), and increases industry concentration (Theorem 3), the magnitude of the effect of each instrument differs. Compared to fixed fines in (13), variable fines have an additional effect on aggregate output in (14). This is an infra-marginal *direct effect* captured by the second expression within the third term, $\partial x_\theta^{nc}(\cdot)/\partial f$. This expression is negative from Lemma 3 – variable fines decrease output for each non-compliant DC that continues to participate because variable fines decrease marginal revenues. Thus, both expressions under the third term in (14) are negative. Next, compared to fixed fines in (13), investments also have an additional effect on aggregate output in (15), but this time on compliant DC output as seen in the last expression in the fourth term, $\partial x_\theta^{c}(\cdot)/\partial I$. Investments decrease compliant DCs' marginal compliance costs and therefore increase output. We formalize these implications in our next Theorem.

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.*

Theorem 4 considers when the policy-maker has a target level of compliance: the policy-maker has to choose between greater industry concentration or lesser participation depending on the instrument chosen.

Both fixed and variable fines decrease payoffs from non-compliance. However, because less capable DCs pay the same fixed fine as more capable DCs, fixed fines disproportionately affect less capable DCs. In other words, the impact of variable fines on the extent to which participation decreases is partly moderated by $x_\theta^{nc} r^{nc}(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta})$, that is, the (low) revenues from non-compliance of the least capable participating DC. The same is not the case with fixed fines. For this reason, compared to variable fines, the use of fixed fines to achieve a pre-determined level of compliance has a larger collateral effect on participation. In addition, each of fixed fines, variable fines, and investments have an indirect negative effect on participation through the proportion of compliant DCs. Because investments have no direct effect on non-compliant DC payoffs, they have the least negative effect on participation of the three instruments. However, investments do come at a cost to the policy-maker, which should be accounted for. Figure 9 illustrates the differences in the collateral effects on participation from the policy instruments in achieving a pre-determined level of compliance.

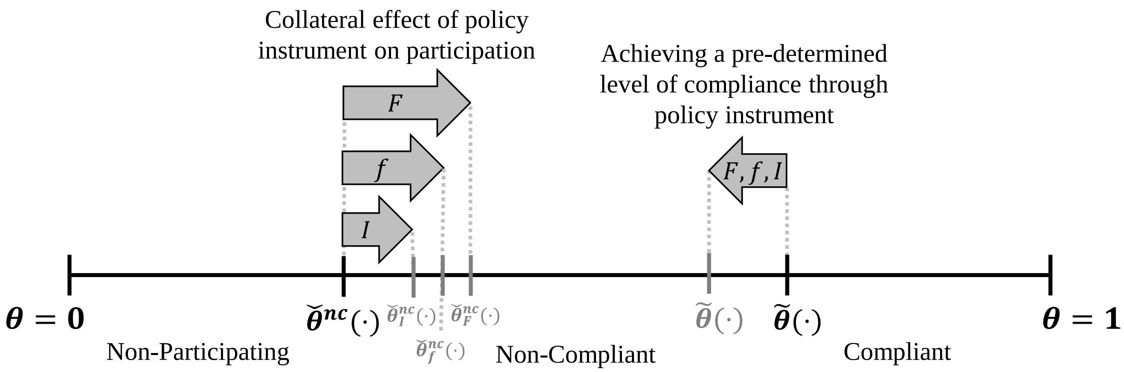


Figure 9 Achieving a predetermined level of compliance through the use of fixed fines, variable fines and investments: collateral effects on participation. Fixed fines have the largest collateral effect on participation.

Consider now the effects of the different instruments on industry concentration. Fixed fines, variable fines, and investments increase the proportion of compliant DCs thereby *indirectly* affecting output. These are captured in the terms through $\rho(\cdot)$ under the integrals in (13), (14), and (15). In addition, there are *direct effects* whereby variable fines decrease the marginal revenues of non-compliant DCs thereby decreasing their output, whereas investments decrease the marginal compliance costs of compliant DCs thereby increasing their output. For participating DCs, each of these direct and indirect effects lead to increased concentration. However, fixed fines is the only instrument that does not have a direct effect on marginal revenues or costs, making it the most benign in terms of its effect on industry concentration as we explain below.

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 $\rho(\cdot)$ in (13), (14), and (15), which capture the direct and indirect effects on output through compliance, are equal. This leaves the direct effects of variable fines on non-compliant DC output (a negative effect) and the direct effect of investments on compliant DC output (a positive effect). In other words, variable fines have a direct effect on output because a proportion of marginal revenues are transferred to the policy-maker leading to lower output from non-compliant DCs. Investments decrease marginal compliance cost for compliant DCs, which then respond by increasing output. The only policy-maker instrument that does not have a direct effect on marginal revenue or marginal cost is fixed fines. Figure 10 illustrates the differences in the collateral effect on DC output when each of fixed fines, variable fines and investments are used to achieve a pre-determined level of compliance.

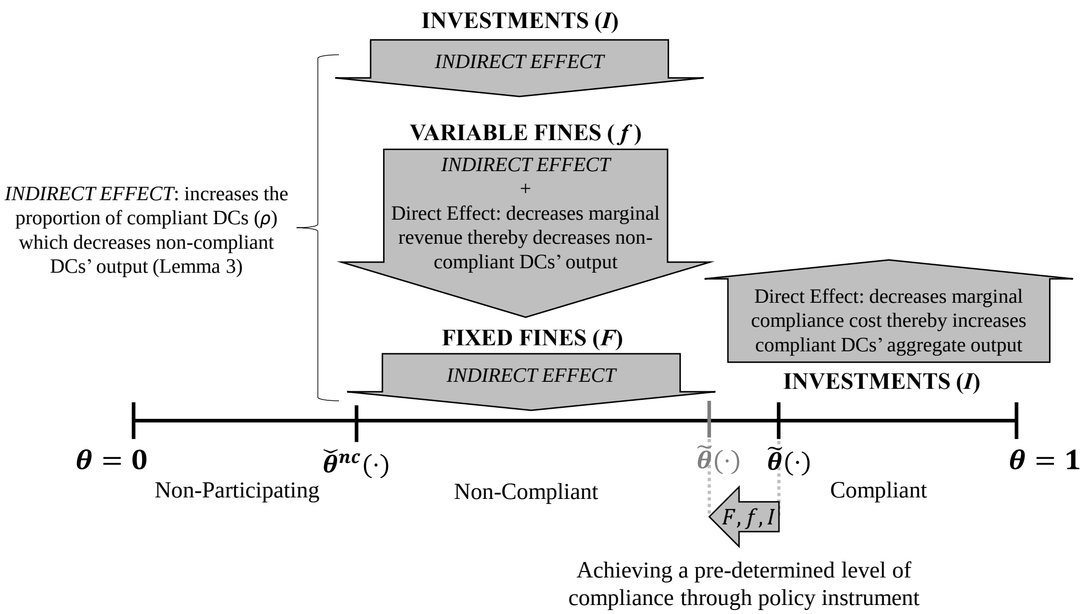


Figure 10 Achieving a predetermined level of compliance through the use of fixed fines, variable fines and investments: collateral effects on DC output. Fixed fines have the smallest collateral effect on industry concentration.

5.2. DC Surplus

DC surplus is the aggregate payoff to compliant and non-compliant DCs, so that

$$DCS(F,f,I) = \int_{\breve{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} \Pi^{nc}(\theta,\rho(\cdot),x_\theta(\cdot),\vec{x}_{\setminus\theta}(\cdot),F,f)d\theta + \int_{\tilde{\theta}(\cdot)}^{1} \Pi^{c}(\theta,\rho(\cdot),x_\theta(\cdot),\vec{x}_{\setminus\theta}(\cdot),I)d\theta. \quad (16)$$

The payoffs from non-compliance are as defined in (6) but with optimal outputs $x_\theta^{nc}(\cdot)$, whereas payoffs from compliance are defined by (3) with optimal output for compliance, $x_\theta^{c}(\cdot)$. We now evaluate the effect of fixed fines, variable fines, and investments on DCS. Totally differentiating DCS with respect to fixed fines and applying the envelope theorem we have

$$\frac{dDCS(\cdot)}{dF} = \int_{\breve{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} \left[[1-f]x_\theta^{nc}(\cdot)\frac{\partial r^{nc}(\cdot)}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial F} - 1\right]d\theta + \int_{\tilde{\theta}(\cdot)}^{1} x_\theta^{c}(\cdot)\frac{\partial r^{c}(\cdot)}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial F}d\theta. \quad (17)$$

Now totally differentiating DCS with respect to variable fines we have

$$\frac{dDCS(\cdot)}{df} = \int_{\breve{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} \left[[1-f]x_\theta^{nc}(\cdot)\frac{\partial r^{nc}(\cdot)}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial f} - x_\theta^{nc}(\cdot)r^{nc}(\cdot)\right]d\theta + \int_{\tilde{\theta}(\cdot)}^{1} x_\theta^{c}(\cdot)\frac{\partial r^{c}(\cdot)}{\partial \rho}\frac{\partial \rho(\cdot)}{\partial f}d\theta. \quad (18)$$

Finally, totally differentiating DCS with respect to investments,

$$\frac{dDCS(\cdot)}{dI} = \int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} [1-f] x_\theta^{nc}(\cdot) \frac{\partial r^{nc}(\cdot)}{\partial \rho} \frac{\partial \rho(\cdot)}{\partial I} d\theta + \int_{\tilde{\theta}(\cdot)}^{1} \left[x_\theta^c(\cdot) \frac{\partial r^c(\cdot)}{\partial \rho} \frac{\partial \rho(\cdot)}{\partial I} - \frac{\partial \gamma(x_\theta^c(\cdot), I)}{\partial I} \right] d\theta. \tag{19}$$

Several terms cancel out or drop to zero leading to the equations (17), (18), and (19), the details of which are provided in Appendix E. In each of these equations the first term under the first integral captures the increased compliance due to fines or investments, which leads to lower non-compliant inverse demand. The second term under the first integration sign in (17) and (18) are the increased fines transferred to the policy-maker. In (18), this is $x_\theta^{nc}(\cdot) r^{nc}(\cdot)$ instead of 1 in (17), because the effect of an increase in variable fines depends on the revenues from non-compliance. These losses apply to non-compliant (and therefore less capable) DCs, $\check{\theta}^{nc}(\cdot) < \theta \leq \tilde{\theta}(\cdot)$. The first term under the second integral captures the increased compliance from each policy-maker instrument which changes the compliant inverse demand. The second term under the second integral in (19) captures the decreased compliance costs to compliant DCs due to investment, which increases their payoffs. In summary, the effect of fines and investments is to decrease the payoffs to non-compliant DCs and potentially increase the payoffs to compliant DCs.

5.3. Social Welfare

We defined DCS as the aggregate payoffs to DCs after subtracting fines. As fines are a transfer, they do not directly impact social welfare. For this reason, we create a measure of DCS without transfers,

$$\begin{aligned} DCS_{-f}(F, f, I) = &\int_{\check{\theta}^{nc}(\cdot)}^{\tilde{\theta}(\cdot)} [x_\theta^{nc}(\cdot) r^{nc}(\theta, \rho, x_\theta^{nc}(\cdot), \vec{x}_{\setminus\theta}(\cdot)) - C(x_\theta^{nc}(\cdot))] d\theta \\ &+ \int_{\tilde{\theta}(\cdot)}^{1} [x_\theta^c(\cdot) r^c(\theta, \rho, x_\theta^c(\cdot), \vec{x}_{\setminus\theta}(\cdot)) - C(x_\theta^c(\cdot)) - \gamma(x_\theta^c(\cdot), I)] d\theta, \end{aligned} \tag{20}$$

so that social welfare (SW) consists of DCS without fines and US less the investment, $SW(F, f, I) = DCS_{-f}(F, f, I) + US(X(F, f, I)) - I$. Thus, the effect of fixed fines on social welfare is $dSW(F, f, I)/dF = dDCS_{-f}(F, f, I)/dF + US'(X(F, f, I)) dX(F, f, I)/dF$, which we derive by differentiating (20) with respect to the fixed fine, and substituting for $dX(F, f, I)/dF$ from (13). The effects through variable fines and investments are similar. In the below Corollary to Theorems 1 and 3, we describe the sources of gains and losses to social welfare from the use of fines and investments to enforce DPR.

Corollary 1. *Fines and investments increase welfare produced from more capable DCs and decreases welfare produced from less capable DCs. Thus DPR can increase social welfare.*

Noting that output increases in capability from Lemma 1, all the gains to social welfare accrue from more capable DCs, $\tilde{\theta}(\cdot) < \theta$, whereas the losses to social welfare are from less capable DCs, $\theta \leq \tilde{\theta}(\cdot)$. If the gains are larger than the losses, then the social welfare increases due to DPR. In particular, from Theorems 1 and 3, the use of fines or investments to regulate DPR causes the least capable participating DCs, $\check{\theta}^{nc}(\cdot)$, to cease participating, and decreases the output generated by the less capable DCs that continue to participate, $\check{\theta}(\cdot)^{nc} < \theta < \tilde{\theta}(\cdot)$. Each of these contribute negatively to social welfare. On the other hand, each instrument increases the output of the most capable DCs ($\tilde{\theta}(\cdot) \leq \theta \leq 1$), which leads to an increase in the social welfare generated by these DCs.

6. Discussion and Conclusion

Underlying data portability regulation (DPR) are a variety of different policy objectives including compliance, industry concentration, participation, and user data ownership. DPR legislation including the E.U.'s GDPR, California's CCPA, and the U.S.'s ACCESS Act allow for the use of fixed and variable fines as instruments to ensure compliance. We analyze the effect on the above policy objectives in a setting where the policy-maker resorts to the consistent use of such fines, as well as the use of investments to decrease compliance costs.

We model a setting where the policy-maker can choose fixed and variable fines to enforce DPR and can invest to decrease compliance costs. Whereas non-compliant DCs face fines, they also face a loss of revenue from non-compliance due to users moving to DCs that comply with DPR because portability is viewed by users as an additional feature. In addition to any compliance costs, DCs that comply can gain from users moving from other DCs but can also face a loss of users that move to more capable DCs.

Even though DPR provides remedies such as warnings, reprimands, and orders to comply prior to imposing fines on non-compliant DCs, the credible threat of fines is ultimately the motivation for DC compliance. Therefore, fines are the focus of our analysis in addition to investments to decrease compliance costs. Our model is formulated using general functions governed by curvature conditions and describes the choices by the policy-maker and incentives of DCs through a two-stage game. In the first stage the policy-maker sets fixed and variable fines for DCs that do not comply with DPR and sets investments to decrease compliance cost. In the second stage DCs choose their output, whether to participate in the market, and whether to comply with DPR.

If fines are consistently applied for non-compliant DCs, then there may be unintended consequences for the structure of the industry. First, resorting to fines or investing in portability standards can decrease participation in the market. This is because more capable DCs comply, less capable DCs do not comply but continue participating, and the least capable DCs cease participating. Thus, for the policy-maker, increasing fines incentivizes non-compliant DCs to comply with

DPR, but also decreases participation by forcing the least capable DCs to exit. Therefore, fines squeeze the set of non-compliant DCs from two sides – more capable non-compliant DCs are motivated to comply, whereas the least capable non-compliant DCs cease to participate. Essentially, fines can decrease DC participation, thereby decreasing options for users to choose from.

Another important consequence of fines and investments is an increase in industry concentration, which occurs due to a decrease in the output of less capable DCs and an increase in the output of more capable DCs. Several mechanisms lead to this consequence. Variable fines decrease the marginal profits for non-compliant DCs thereby decreasing non-compliant DC output, while investments increase the marginal profits for compliant DCs thereby increasing their output. This result is in addition to indirect effects caused by an increase in compliance from each instrument. These effects together result in an increase in the aggregate output of DCs with the largest output and a decrease in the output of DCs with the smallest output. The consequence is an increase in industry concentration, which may be in conflict with the objectives of DPR.

Perhaps of greatest importance to policy-makers and in answering our main research questions, we find that each instrument has different magnitudes of unintended consequences for participation and concentration. We find that fixed fines have the largest collateral effect on participation. Less capable DCs with lower revenues face a proportionately small variable fine, whereas fixed fines can have a large effect on such DCs. Separately, fixed fines have the smallest collateral effect on industry concentration compared to variable fines and investments. Variable fines and investments have direct effects on the marginal profits of DCs, whereas fixed fines do not. Variable fines decrease non-compliant marginal revenues thereby decreasing their output. In contrast, investments decrease compliant DCs' marginal compliance costs thereby increasing their output. In other words, if policy-maker instruments are limited to fixed fines, variable fines or investments, then the policy-maker must choose between decreased participation and increased concentration.

If fines are sufficiently high, then full compliance is reached where all DCs either participate and comply, or do not participate. Once full compliance is reached, increases in fines cease to have any effect but the effect of investments on participation reverses, so that investments now increase participation. In other words, full compliance is necessary for investments to increase participation. However, if the policy-maker's goal is to achieve full participation and full compliance – where all DCs participate and comply, then investments alone cannot accomplish this. A necessary condition for this to occur is market expansion. Market expansion can occur, for instance, with multi-homing when users port their data to another DC, and consume services from more than one DC when they port. This can also happen when there is a net inflow of users along with their data, into the industry.

Our general model yields findings that are robust in a variety of DC competition and portability settings including network effects, multi-homing, and porting effectiveness. Hence, our analysis broadly applies to industries where a set of competing DCs derive value from personal data. Examples of such industries include the travel booking industry within which DCs such as Expedia operate and the financial services industry where initiatives such as open banking represent data portability. These examples are in addition to the social media and fitness apps examples described earlier.

Policy Implications: We show that there may be a disconnect between the policy-makers' goals of increased compliance with DPR, decreased concentration, and increased competition, and the monetary instruments designed to achieve these goals. This disconnect includes regulations that have been implemented such as GDPR and CCPA, and ones currently being discussed such as the ACCESS Act. As we show, the outcomes of DPR may be in direct conflict with these goals if the policy-maker resorts to consistently applied fines, and to investments to decrease compliance costs.

For the policy-maker intent on using fixed fines, variable fines, or investments to enforce data portability, the choice of instrument has different magnitudes of unintended consequences for compliance, participation, concentration, and welfare. Thus, the choice of instrument depends on the policy-maker's tolerance for each of these different collateral effects.

Policy-makers across jurisdictions are concerned about the dominance of a handful of large DCs in today's market and have displayed an interest in creating a more level playing field for competitors. We find that in an environment where users can freely choose DCs for their services and where policy-makers resort to the use of investments, fixed and variable fines that are consistently applied, enforcing DPR can mean users move from less capable DCs to more capable DCs where the latter are usually larger and better resourced. This reinforces the dominance of larger DCs over smaller, less capabale, ones.

Our work has several takeaways for policy-makers. First, the sole use of investments prior to achieving full compliance decreases the profits of the less capable DCs and reduces their participation. Instead, the use of investments can be increased after a high level of compliance is achieved because with high compliance, investments can increase DC participation. Second, DPR-induced market expansion through phenomena such as multi-homing can soften the unintended consequences of fines and investments. Although one form of multi-homing is where users use multiple DCs within the same industry, another form is where users port their data across industries. This occurs, for instance, when users port their data from Facebook (social media) to Expedia (travel booking) in order to get more personalized services from Expedia. A direct policy-maker implication here is on the development of standards. Standards that enable the broad porting of data across different industries are superior to narrow or targeted standards built for specific industries. Third, given that DPR can encourage users to port from less capable to more capable DCs, a simple and direct policy outcome is to focus on improving the capability of smaller and local DCs before implementing DPR. Examples of such interventions include funded regional technology hubs, research and development grants, and innovation funding.

Limitations and Future Research: Even though the effects through porting are modeled using general functions and our general-form results point the policy-maker in the direction of the effects, the magnitude of these effects depend on the specific situation and therefore the parameter estimates from a parameterized model. Future research can focus on parameterizing and estimating the model based on the specific characteristics of each market in question. Moreover, we consider fines that are consistently and fairly imposed across different circumstances of DCs in different industries. In practice, the particular situation of the violating DCs and the nature of violations may play an outsized role in determining the fines. Even though significant deviations are banned in DPR legislation (e.g., both GDPR and the ACCESS Act specify consistency mechanisms and allow for judicial protection and due process to prevent arbitrary imposition of fines), in practice, slight deviations in implementation of the policy are possible. For example, the supervisory authority may decide to be more lenient in imposing a fine on a financially unstable DC. Our model, consistent with the DPR policies currently in place, does not capture such circumstances and idiosyncrasies. Policy-makers may be able to prevent some of the collateral effects that we identify through more nuanced policies or through flexible implementation. Finally, as we incorporate definitions of participation and industry concentration in our analysis that are straightforward analogues of widely-used measures, our analytical results provide testable hypotheses to empirically study the effects of DPR in different jurisdictions.

Acknowledgments

We thank the Social Sciences and Humanities Research Council (SSHRC) of Canada and the Natural Sciences and Engineering Research Council (NSERC) of Canada for support. We also thank Jeanette Burman for helpful editing.

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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.

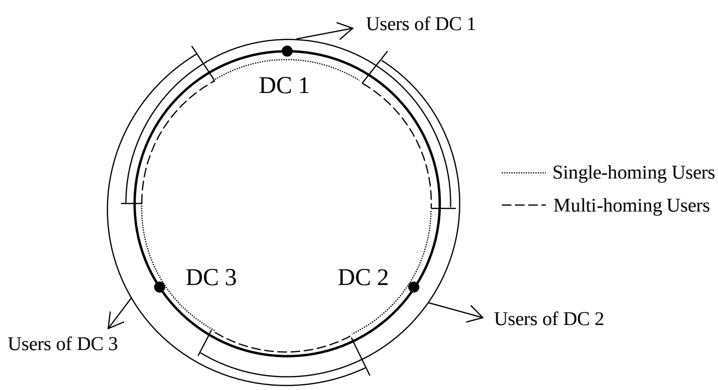


Figure EC.1 DCs and users on Salop circle

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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 $\left[[1-\sigma]\sum_{j=\setminus i}\left[\psi_j[\mu^c+\vartheta]\theta_j+[1-\psi_j]\mu^{nc}\theta_j\right]-2\sigma\mu^{nc}\theta_i\right]/6>0$. 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

$$\begin{aligned}&[x_1(\cdot,\Psi=(1,0,0))-x_1(\cdot,\Psi=(0,0,0))]\geq\\&\qquad-\left[[x_2(\cdot,\Psi=(1,0,0))-x_2(\cdot,\Psi=(0,0,0))]+[x_3(\cdot,\Psi=(1,0,0))-x_3(\cdot,\Psi=(0,0,0))]\right],\end{aligned}$$

$$\begin{aligned}&[x_1(\cdot,\Psi=(1,1,0))-x_1(\cdot,\Psi=(1,0,0))]+[x_2(\cdot,\Psi=(1,1,0))-x_2(\cdot,\Psi=(1,0,0))]\geq\\&\qquad-[x_3(\cdot,\Psi=(1,1,0))-x_3(\cdot,\Psi=(1,0,0))],\end{aligned}$$

$$\begin{aligned}&[x_1(\cdot,\Psi=(1,1,1))-x_1(\cdot,\Psi=(1,1,0))]+[x_2(\cdot,\Psi=(1,1,1))-x_2(\cdot,\Psi=(1,1,0))]\\&\qquad+[x_3(\cdot,\Psi=(1,1,1))-x_3(\cdot,\Psi=(1,1,0))]\geq 0.\end{aligned}$$

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.

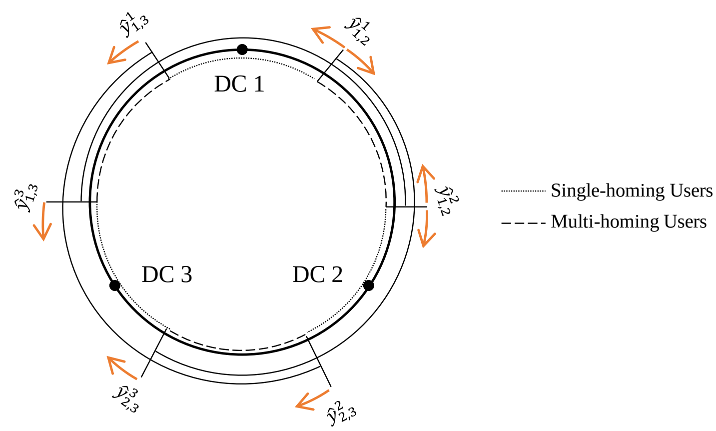


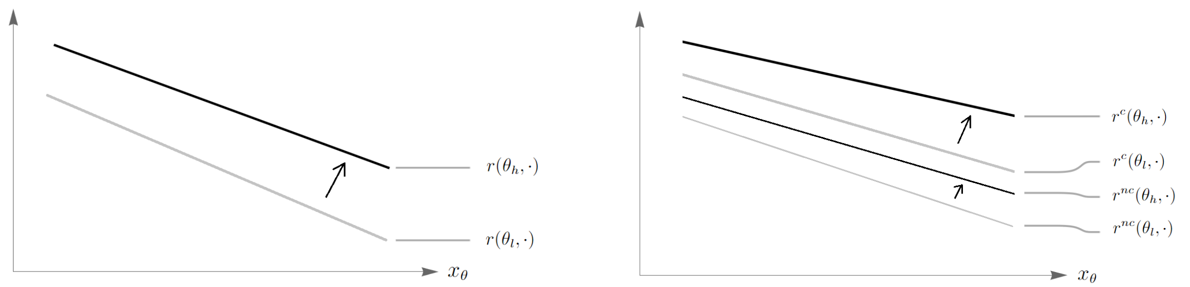
Figure EC.2 User behavior in response to DC 2 becoming compliant ($\Psi = (1, 0, 0)$ to $\Psi = (1, 1, 0)$)

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

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

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

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

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^c_θ as the optimal output from compliance where inverse demand is $r^c(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta})$, and x^{nc}_θ 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

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

When the above equation is evaluated at $x_\theta = x^c_\theta$, the first sets of square brackets is zero because $\partial \Pi^c(\theta, \rho, x_\theta, \vec{x}_{\setminus\theta})/\partial x_\theta|_{x_\theta = x^c_\theta} = 0$ 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

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

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.

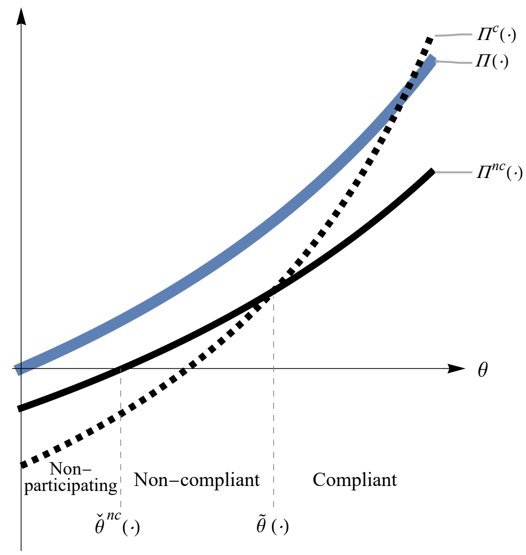


Figure EC.4 Pre-DPR, compliant, and non-compliant payoffs

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

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

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

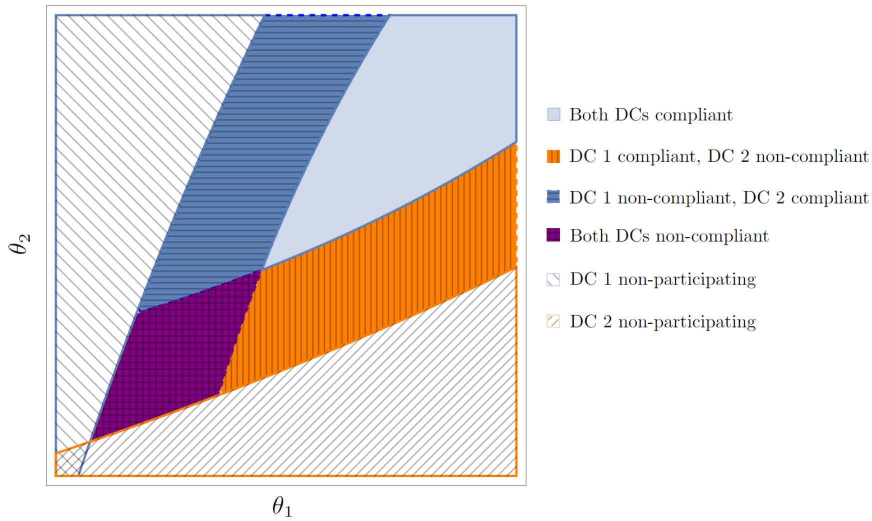


Figure EC.5 **Equilibrium compliance decisions in the duopoly case**

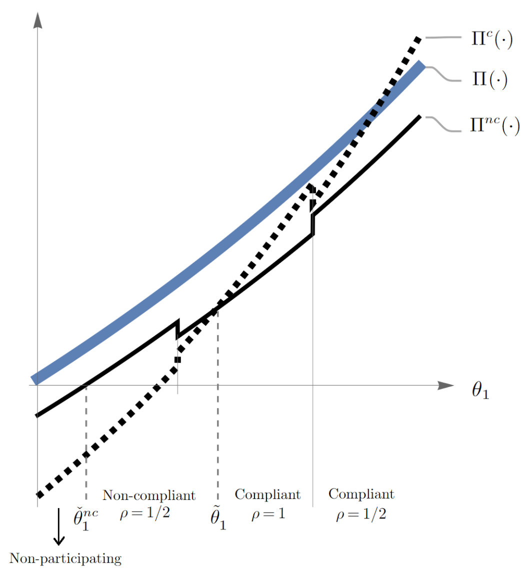


Figure EC.6 **Pre-DPR, compliant, and non-compliant payoffs for DC 1 given the capability of DC 2**

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

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

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

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

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

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

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

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

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

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 $x_\theta = x_\theta^c$. 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,

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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,

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

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

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

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

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

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,

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

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 $F^t = f^t x^{nc}_{\tilde{\theta}} r^{nc}(\tilde{\theta}, \rho, x_{\tilde{\theta}}, \vec{x}_{\setminus \tilde{\theta}})$. Then, the variable fine paid by the non-compliant DCs is $f^t x^{nc}_{\theta} r^{nc}(\theta, \rho, x_{\theta}, \vec{x}_{\setminus \theta})$. 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 ($\partial x^{nc}_{\theta}(\cdot)/\partial f$, a negative effect) and the direct effect of investments on compliant DC output ($\partial x^{c}_{\theta}(\cdot)/\partial I$, 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,

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

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

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

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

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

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. $\square$

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.