Balancing openness and prioritization in a two-tier Internet

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The open Internet is plagued by congestion that restricts the development of sophisticated Internet-based services as was predicted in early work on priority pricing. Broadband and edge providers have proposed a two-tier Internet with fee-based prioritization of traffic in a fast-lane Internet that coexists with the open Internet to overcome these problems. This requires a restriction of Internet openness, also known as network neutrality, in the fast-lane Internet. Opponents of a two-tier Internet believe it would hinder innovation, motivate underinvestment in Internet infrastructure and consequently reduce the quality of service (QoS) of the open Internet. The challenge is for policy to balance a fee-based fast-lane Internet for priority traffic and safeguard the viability of the open Internet. In our model, edge providers choose output levels and which Internet to use, a broadband provider chooses investment in Internet capacity and pricing for prioritizing traffic in the fast-lane Internet, and a policy-maker chooses a mechanism for balancing openness and prioritization in a two-tier Internet. We find edge providers with greater bandwidth requirements per unit of output convert to the fast-lane Internet. The broadband provider has no incentive to invest in Internet capacity and chooses fixed fee pricing. So long as there are no investments in Internet capacity, all end users and edge providers of the open Internet are worse off with a two-tier Internet. To maintain the QoS of the open Internet and to increase social welfare, a two-tier Internet has to be coupled with a policy mechanism whereby a portion of broadband provider profit is invested in Internet capacity.

Keywords: Incentives, Technology Conversion, Fast-Lane Internet, Broadband Provider, Open Internet, Internet Openness, Network Neutrality, Edge Provider, Congestion, Capacity, Investment.

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1. Introduction

Improving policy to foster successful innovation has always been difficult. Nowhere is this truer than with the Internet that has enabled an unprecedented technological, business, and social revolution. There are four classes of participants in the Internet. *Edge providers* are firms that provide content, applications and services over the Internet such as Amazon, Google and Netflix. *End users* are individuals or firms that use broadband access to consume content, applications or services from edge providers. *Broadband providers* are local access providers such as Verizon or Comcast that own the last mile Internet infrastructure and connect end users and some edge providers to the Internet. *Backbone networks* provide interconnected long-haul fiber-optic links and high-speed routers that carry data between themselves, broadband providers, and edge providers and connect some edge providers to the Internet. These definitions are shown in Figure 1.

Edge Providers:	**firms that provide content, applications or services over the Internet (e.g. Amazon, Google, Netflix)**
End Users:	**individuals or firms that use broadband access to consume content, applications or services from edge providers**
Broadband Providers:	**local access providers that connect end users and some edge providers to the Internet (e.g. Verizon, Comcast)**
Backbone Networks:	**providers of interconnected long haul fibre-optic links and high speed routers that carry data across the Internet and connect some edge providers to the Internet**

Figure 1: Definitions (US Court of Appeals 2014)

These classes are not mutually exclusive: end users can act as edge providers creating and sharing content, broadband providers can also run backbone networks, and the commonly used descriptor Internet service provider can act as edge provider or broadband provider or both.

The topic of present regulatory discussion is whether the Internet should remain as a public network with open access for commercial and personal use where all transferred packages are treated equally (FCC 2010). This open access is often referred to as Internet openness, or synonymously as network neutrality. Internet openness is a concept where broadband providers are not allowed to prioritize traffic and consequently do not have control over the content, applications and services that run through their network (Picot and Krcmar 2011). This restricts the incentive for broadband providers to build additional last mile infrastructure to increase Internet capacity because they are not allowed to obtain direct return from offering fee-based quality of service (QoS) agreements beyond pure access to the overall bandwidth. This results in increasing congestion in the open Internet. For instance, Netflix – the edge provider requiring the greatest bandwidth (Reed 2013), causes substantial congestion slowdowns that affect other edge providers and end users of the open Internet (Siegal 2014). Consequently, edge providers have little incentive to develop sophisticated Internet-based offerings that are sensitive to congestion. Good examples include cloud services such as remote health care monitoring and video streaming services.

Early in the development of the commercial Internet, research explored the potential of priority pricing to relieve congestion. In this work edge providers are charged time-of-day or dynamic congestion-based prices by broadband providers and possibly backbone networks in order to level the load on the Internet across time (MacKie-Mason and Varian 1995; Gupta et al. 1997; Gupta et al. 2000, 2011). Such pricing Internet-wide would violate network neutrality

As an alternative to deal with congestion some broadband providers and edge providers have proposed a two-tier Internet where a fast-lane Internet, hereafter fast-lane, represents a logically or physically separate tier (Verizon and Google 2010) that coexists with the open Internet. In the fast-lane a broadband provider can prioritize traffic and offer fee-based QoS agreements. The financial transactions between participants in a two-tier Internet are illustrated in Figure 2.

End users pay broadband providers for broadband access to overall bandwidth as well as pay edge providers for consuming their content, applications, and services (e.g., Netflix for their video

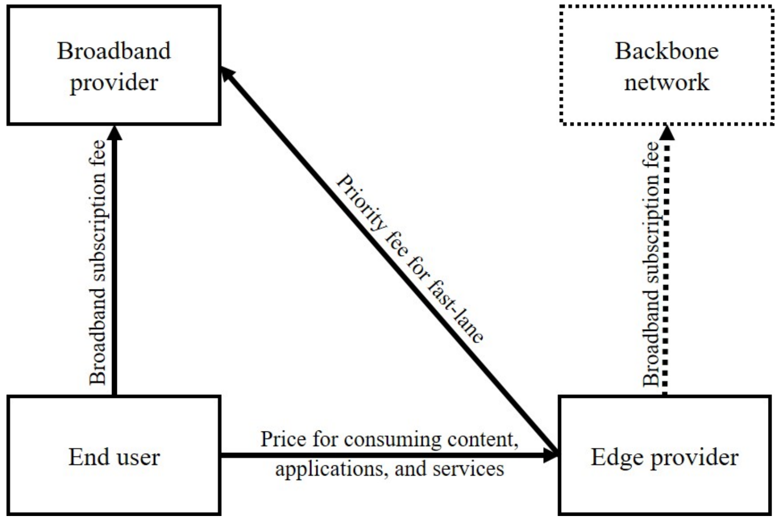

Figure 2: Financial transactions between participants

streaming service). The price for consuming content, applications, and services may differ on whether they are provided through the open or the fast-lane Internet due to different QoS and output levels. Edge providers can further generate revenues from other sources such as advertising. In the fast-lane, edge providers pay broadband providers a fee for transferring their traffic in a prioritized way to end users on the last mile, and more generally edge providers pay backbone networks for broadband access to overall bandwidth. As we describe later, the edge provider's broadband access fee is not relevant for, and thus outside the scope of, our model and is marked with dotted lines in Figure 2.

Opponents of a two-tier Internet argue that a fast-lane would harm the QoS of the open Internet and would hinder innovation as "big, rich companies with the money to pay large fees to broadband providers would be favored over small start-ups with innovative business models – stifling the birth of the next Facebook or Twitter" (Wyatt 2014). Moreover, they argue that broadband providers would have little incentive to invest in Internet infrastructure and continue to underinvest in Internet capacity in order to charge higher fees for the fast-lane (Singham and Ohanian 2014).

The laws governing the Internet are under discussion. In January of 2014, the Federal Communication Commission (FCC) *Open Internet Order* (FCC 2010) that imposes disclosure, anti-blocking, and anti-discrimination requirements on broadband providers was vacated on the basis that the

Open Internet Order imposes common carrier restrictions on broadband providers when they are not classified as such (see U.S. Court of Appeals 2014). In response, the FCC issued a Notice of Proposed Rulemaking (FCC 2014) in May of 2014, which poses the question of whether broadband providers could charge edge providers fees for prioritization of their Internet traffic. That is, the FCC may consider proposing new rules that allow edge providers such as Netflix to pay broadband providers for a fast-lane (Wyatt 2014). Most recently the FCC narrowly voted in favor of classifying the Internet as a public utility such as water, electricity and telephone (FCC 2015), a decision that is already backed by a court judgement (U.S. Court of Appeals 2016). This means that the implementation of a fee-based fast-lane that replaces the open Internet is not legally permissible. However, these regulatory and legal decisions are recent: most prior literature considered the Internet openness debate comparing the welfare effects between Internet openness regime and non-openness regimes. In line with the FCC, the European Commission (EC) also enshrined the principle of Internet openness into European Union (E.U.) law in October 2015 but opened the possibility of a two-tier Internet by allowing broadband providers to offer prioritized services with an enhanced QoS in a coexisting fast-lane as long as this does not impair in a recurring or continuous manner the general quality of the open Internet (EC 2013; EC 2015).

Consequently, the challenge for policy is: *How to balance openness and prioritization in a two-tier Internet to both maintain the QoS of the open Internet and increase social welfare?*

Measuring Value: There are two primary policy considerations when examining the impact of a two-tier Internet on welfare.

The first policy consideration is the impact of a two-tier Internet on productivity and consequently on economic value. Productivity from the Internet comes from content, applications, and services offered by edge providers and consumed by end users. Productivity can be viewed as coming through three channels. The first channel is business-to-consumer (B2C) e-commerce, essentially treating the Internet as a retail channel for physical and information goods (e.g., Netflix, Amazon). B2C e-commerce has been the focus of concern in most of the prior literature examining Internet openness. The second channel is business-to-business e-commerce that uses the Internet as the base layer for cloud computing and interorganizational systems including design collaboration and supply chain coordination. The third channel is internal to firms – many firms use the Internet as the base layer of their internal communications such as virtual private networks. As we show later, we represent the resulting economic value received by edge providers and end users by edge provider surplus and end user surplus, respectively.

The second policy consideration is the potentially negative impact of a two-tier Internet on the social value received by end users which we represent by negative externalities. Social value comes from e-mail, social networking, and information retrieval. Both economic and social value from the Internet are compromised by increasing congestion in the open Internet.

Our Focus: To determine the impact of a two-tier Internet that includes the current open Internet and a coexisting fee-based fast-lane on overall welfare, we construct a model that examines edge provider conversion to a fast-lane, broadband provider's investment and pricing, and a straightforward policy mechanism to balance openness and prioritization in a way that the general quality of the open Internet does not suffer. We begin using an approach whereby edge providers – that can represent a cross-section of the economy – differ in their bandwidth requirement to produce a unit of output. Edge providers make production decisions and decide whether to convert to the fast-lane in order to maximize profits. In this production setting, edge providers may use the Internet to provide Internet-based content, applications, or services to personal and commercial end users. From these decisions we construct a choice of investment in Internet capacity and basic pricing mechanisms to maximize profits of a monopoly broadband provider that owns the last mile facilities. The broadband provider's pricing leads to its profits, as well as output and profits for edge providers individually and in aggregate. Then we incorporate a policy-maker that can choose whether to require that the broadband provider invest an amount of its fast-lane profits into its Internet capacity. In this context the policy-maker considers the effects of its policy on edge provider output (productivity), which in turn affects aggregate end user and edge provider surplus (economic value) as well as negative externalities (social value). Thus, our policy mechanism allows for a two-tier Internet in which the broadband provider can profit from providing fee-based QoS agreements and in which investments in Internet capacity are ensured to safeguard the viability of the open Internet.

Our analysis yields a series of results. First, edge providers with greater bandwidth requirements per unit of output convert to the fast-lane, and those with lesser bandwidth requirements remain with the open Internet. Second, the broadband provider has no incentive to invest in Internet capacity and chooses a fixed fee rather than usage-based pricing for the fast-lane. Third, so long as there are no investments to increase Internet capacity, all end users and edge providers using the open Internet are worse off with a two-tier Internet. This is due to the higher aggregate output of edge providers that use the fast-lane and its spillover effect on congestion in the open Internet. These results support the concerns of Internet openness proponents in that a two-tier Internet motivates broadband providers to underinvest in Internet capacity and all users of the open Internet will suffer from a two-tier Internet, and thus such a two-tier Internet is not feasible as it contravenes recent regulatory decisions of the FCC and EC.

Most importantly, we show that to mitigate the consequences of a two-tier Internet on edge providers and end users that use the open Internet, a two-tier Internet can to be coupled with a policy mechanism whereby a portion of broadband provider profit is invested in Internet capacity. This policy mechanism can be used to maintain the general quality of the open Internet (EC 2013; EC 2015) and to increase welfare so long as the effects of investment in Internet capacity on the indifferent edge provider, as well as on congestion costs and negative externalities through aggregate output of converting firms, are not greatly out of scale.

2. Related Literature

The earliest related literature is on priority pricing in the Internet that implicitly assumes Internet openness is not an issue. Such pricing is based on congestion and includes various mechanisms that generate dynamic prices to allocate scarce capacity that maintain normal profits a broadband provider would make without priority pricing or maximize welfare (MacKei-Mason and Varian 1995; Gupta et al. 1997, 2000).

Later literature focusing on Internet openness examines the effects of dropping Internet openness regulation on social welfare with foci on edge provider surplus (e.g., Economides and Tag 2012; Cheng et al. 2011), on investments by broadband providers in Internet capacity (e.g., Choi and Kim 2010; Cheng et al. 2011; Kraemer and Wiewiorra 2012; Bourreau et al. 2015), on investments by edge providers (e.g., Choi et al. 2015b; Davidson 2015; Peitz and Schuett 2016), on content innovation (e.g., Hermalin and Katz 2007; Guo et al. 2012; Reggiani and Valletti 2016), on Internet fragmentation (e.g., Kourandi et al. 2015; D'Annunzio and Russo 2015), on vertical integration of broadband and edge providers (e.g., Guo et al. 2010), on competition between broadband providers (e.g., Bourreau et al. 2015; Njoroge et al. 2013), and on edge providers' business models (Choi et al. 2015a). We focus on aspects that substantially distinguish our model and findings from existing ones.

Model structure: Most articles above compare the welfare effects of an Internet openness regime with a non-openness regime, and examine the Internet as a content distribution channel from edge providers to end users. They model broadband providers that own the last mile Internet infrastructure as facing a two-sided market with non-competing (e.g., Economides and Tag 2012; Economides and Hermalin 2012) or competing (e.g. Choi and Kim 2010; Cheng et al. 2011) edge providers on one side and end users on the other. End users pay a broadband subscription fee, and edge providers pay a fee to the broadband provider for prioritizing their traffic. The broadband subscription fee paid by edge providers is omitted as edge providers typically pay backbone networks or another broadband provider for broadband access rather than the broadband provider that owns the last mile (e.g. Choi and Kim 2010; Cheng et al. 2012). The priority fee is zero in the Internet openness regime and positive in the non-openness regime. Most of the articles further assume that edge providers offer content for free and generate revenues through advertising, meaning that edge providers do not directly charge end users (e.g. Choi and Kim 2010; Guo et al. 2010; Cheng et al. 2011; Guo et al. 2012; Kourandi et al. 2015; Reggiani and Valletti 2016).

As more products and business processes have been digitized, the Internet evolved from a pure retail channel to an important production factor for almost all firms. Consequently, we consider edge providers that can be any firm that uses the Internet in production – not only content providers – that make production decisions across the economy. Moreover, edge providers' business models have evolved from earning revenues solely from advertising to directly charging end users for content, applications, and services. This market practice is common among streaming firms such as Netflix and providers of "over-the-top" services (Greenstein et al. 2016). To incorporate such business models, we employ a general reduced-form profit function for edge providers which allows for arbitrary sources of revenues and a variety of forms of competition among edge providers.

Consistent with recent regulatory decisions (e.g., the FCC voted to classify the open Internet as a public utility (FCC 2015) which are confirmed by legal judgement (U.S. Court of Appeals 2016)), we do not consider the fast-lane as a substitute for the open Internet but as a logically separate, coexisting tier where traffic prioritization is allowed. This is in line with the EC that enshrines the principle of Internet openness in E.U. law and allows a two-tier Internet as long as the fast-lane does not impair the QoS of the open Internet (EC 2013; EC 2015). Due to these recent regulatory decisions, in combination with a highly inelastic demand for broadband subscription in the U.S. (Duffy-Deno 2003) and in OECD countries (Galperin and Ruzzier 2013), we take the number of end users as fixed. This means that end users could decide not to use a specific content, application, or services as soon as it is priced higher by an edge provider that has converted to the fast-lane, but end users would not unsubscribe from the open Internet as they continue to receive value from other edge providers as well as from communication and social networking. Thus, a two-tier Internet has almost no effect on end users' broadband subscriptions and consequently a broadband provider does not face a typical two-sided market with demand elasticities on each side.

To adequately represent these new regulatory and legal judgments, we use a model structure that is different from prior work to analyze a two-tier Internet and focus on the interaction between a broadband provider and edge providers. The structure of our model is related to that of Brock and Evans (1985) where individual entrepreneurs, edge providers in our model, make production decisions that affect negative externalities, and a policy-maker decides on a tax schedule to maximize welfare. Our model is also related to Nault (1996) and Levi and Nault (2004). Compared to the latter, the structure of a subset of mathematical assumptions is similar, our edge provider decisions are similar to their firm decisions, and our industry response separating edge providers that adopt the fast-lane and those that do not is similar to their firms adopting technology – generic steps that are common. Unlike Levi and Nault (2004) that use the revelation theorem, we have a mid-stage decision where the broadband provider provides and prices a fast-lane. We further have a policy-maker that sets investment incentives, and a congestion externality between the fast-lane and the open Internet.

Pricing in a two-tier Internet: Existing approaches to pricing consider the priority fee either as usage-based fee (Cheng et al. 2011; Guo et al. 2010; Guo et al. 2012; Economides and Tag 2012; Kraemer and Wiewiorra 2012) or fixed fee (Njoroge et al. 2013; Bourreau et al. 2015; Kourandi et al. 2015; Reggiani and Valletti 2016). Gupta et al. (2011) use simulation to compare a dynamic usage-based fee with a fixed fee within a single-lane Internet, finding that net benefits tend to be higher with a usage based fee, but if user value is high relative to unit cost then a fixed fee can result in greater capacity.

We simultaneously consider usage-based and fixed fees to analyze which pricing scheme for the fast-lane is optimal for broadband providers based on a profit maximizing calculus, while maintain an open Internet. We find that a broadband provider chooses fixed fee pricing rather than a usage-based or a two-part fee for the fast-lane.

Investment and policy in a two-tier Internet: Some of the existing articles analyze incentives for broadband providers to invest in their Internet capacity with inconclusive results: Choi and Kim (2010) find ambiguous effects. Cheng et al. (2011) and Njoroge et al. (2013) find that the investment incentive for broadband provider is higher in an Internet openness regime and Gupta et al. (2011), Economides and Hermalin (2012), Kraemer and Wiewiorra (2012), Bourreau et al.

(2015), and Reggiani and Valletti (2016) find that a broadband provider can have an incentive to increase bandwidth in a non-Internet openness regime. We find that the broadband provider has no incentive to invest in Internet capacity in a two-tier Internet, supporting the findings of Cheng et al. (2011) and Njoroge et al. (2013). This finding in combination with the congestion externality of the fast-lane on the open Internet makes all edge providers and end users of the open Internet worse-off. To counteract this effect, we extend the literature by introducing a policy mechanism that requires broadband providers to invest a portion of their fast-lane profits in Internet capacity. This newly proposed policy mechanism can be used to maintain the QoS of the open Internet and to make a two-tier Internet socially beneficial.

In sum, our model makes three novel contributions. First, we introduce a new model structure that takes new regulations and judgments for the Internet into account (e.g., Internet as production factor, open Internet as public utility with inelastic demand, and arbitrary sources of revenue for edge providers). Second, we propose an optimal pricing model for broadband providers to price the fast-lane. Finally, and most importantly, we propose a policy mechanism for governing a two-tier Internet that can be used to maintain the QoS of the open Internet, conforming to recent regulatory and legal decisions, and to make a two-tier Internet socially beneficial.

3. Notation and Assumptions

Our assumptions relate to the participants in a two-tier Internet. We begin with our assumptions on edge providers and congestion externalities they create, and then outline the role of the broadband provider, end users and policy maker.

3.1. Edge providers

In our model, we consider edge providers that are heterogeneous in their production technology.

Assumption 1 **(Heterogeneity and Observability)**. *Edge providers differ in the bandwidth requirements in their production technology, and an individual edge provider's bandwidth requirements per unit of output are not verifiable.*

We denote individual edge provider production technology as θ, which is normalized to be in the interval $[0, 1]$. We take the distribution of θ to be positive over its support, thus, $f(\theta) > 0 \,\forall\, \theta \in [0, 1]$, $F(0) = 0$ and $F(1) = 1$. The production technology θ represents increasing bandwidth requirement per unit of output so that edge providers with $\theta = 0$ are those with the lowest bandwidth requirement per unit of output. Edge providers with $\theta = 1$ are those that require the greatest bandwidth per unit of output. Our employing θ for the production technology related to edge providers' bandwidth requirements does not presuppose the form in which the Internet is used – whether through content, applications, or services. We treat θ as uniformly distributed over its support. This incurs little loss of generality as θ can be scaled as needed. The policy-maker and the broadband provider know the distribution and range of θ, but cannot identify an individual edge provider's type. Effectively, θ identifies an edge provider through the efficiency of its use of bandwidth per unit of output.

We represent edge provider output by $x \in [0, \bar{x}_\theta]$ and in absence of a fast-lane aggregate output is $X(\cdot) = \int_0^1 x(\theta) f(\theta) d\theta$ where individual edge provider output can depend on θ. Thus, an edge provider can choose zero output, and there is an arbitrary maximum profitable output level which may depend on the edge provider's production technology. To keep our model simple we define an edge provider's usage of the Internet as its bandwidth requirement per unit of output times output, θx, and in absence of a fast-lane aggregate bandwidth use is $X^\theta(\cdot) = \int_0^1 \theta x(\theta) f(\theta) d\theta$. Edge provider usage of the Internet is verifiable by the broadband provider, and can be used as part of an instrument such as a usage-based fee. However, edge providers using the Internet are based in a variety of industries and have different business models. Consequently, output is not perfectly correlated with – and cannot be used to infer – an edge provider's bandwidth requirement per unit of output.

Edge Provider Profits: The reduced form profit function of an edge provider using the Internet depends on its production technology, θ, and its output, x. We denote this reduced form profit function by $PR(\theta, x)$, which is bounded from below, $PR(\theta, 0) = 0$. Using our reduced form, we take edge provider profits as increasing in output to its maximum profitable output level, $\bar{x}_\theta$, and concave. We also assume that, with all things equal and for a given level of output, profits are slightly lower – if lower at all – for edge providers with greater bandwidth requirements.

ASSUMPTION 2 **(Profits)**.

$$\frac{\partial PR(\theta,x)}{\partial x} \geq 0, \quad \frac{\partial^2 PR(\theta,x)}{\partial x^2} < 0 \quad \textit{and} \quad \frac{\partial PR(\theta,x)}{\partial \theta} \leq 0.$$

This reduced form profit function abstracts from details of revenue sources such as advertisement or direct payments from end users, abstracts from issues of market structure, and is general enough to represent edge provider profits in industries with various degrees of competition so long as the competition is not strategic. For example, this reduced form could represent Cournot competition among a large but finite number of edge providers.

Following Tirole (1988) and Levi and Nault (2004), we suppress aggregate output in our profit function notation. In this way the profit condition can be written as $PR(\theta,x) \equiv PR_X(\theta,x) = r(X)\,x - g(\theta,x)$, where $r(X)$ is the inverse demand (price) function from end users and is decreasing and concave in aggregate output. The cost of production, $g(\theta,x)$, is increasing and convex in output, and depends on the edge provider's bandwidth requirement such that edge providers that consume more bandwidth to produce a unit of output have slightly higher marginal costs, $\partial^2 g(\theta,x)/\partial\theta\partial x \geq 0$. Using this Cournot form, and accounting for the effect of the edge provider's output on aggregate output, each edge provider's first-order condition for profit maximization is

$$\frac{\partial PR(\theta,x)}{\partial x} = \frac{dPR_X(\theta,x)}{dx} = r(X) - \frac{\partial g(\theta,x)}{\partial x} + r'(X)\frac{dX}{dx} = 0.$$

The second-order conditions follow directly from concave price and convex costs in output. Additional technical conditions can be assumed to obtain existence and uniqueness in pure strategies (see Tirole 1988, 224-226). Implicitly our reduced-form profit function abstracts from price competition in favor of edge providers choosing their levels of output. Nonetheless, the assumptions regarding the behavior of our profit functions with respect to output – increasing and concave – are consistent with most price-competition settings. It is worth noting that we treat end user demand as homogeneous in the above, with edge providers using the open Internet facing congestion costs separate from the reduced form profit function. We provide more details on $r(X)$ in subsection 3.3.

Congestion: In the open Internet, each individual edge provider faces costs that come from congestion. These costs include not only direct costs internal to an edge provider, but also opportunity costs of better serving end users, which effectively lowers end user willingness to pay. We model these congestion costs as congestion on the open Internet relative to congestion on the fast-lane and these congestion costs $K(\theta, X^\theta, X_c^\theta, I) \in \mathbf{R}_{\geq \mathbf{0}}$ depend on the production technology – its bandwidth requirement per unit of output, θ, the aggregate bandwidth use from the open Internet, X^θ, the aggregate bandwidth use from the fast-lane, X_c^θ, and overall investments in capacity of the Internet, $I \in \mathbf{R}_{\geq \mathbf{0}}$. I is the sum of investments made by the broadband provider to maximize profits, I_{bp}, and investments of the broadband provider required by the policy maker to maximize social welfare, I_{pm}, where $I_{bp}, I_{pm} \in \mathbf{R}_{\geq \mathbf{0}}$. We define X^θ and X_c^θ in detail later. Our assumption is that congestion costs are higher for edge providers with greater bandwidth requirements per unit of output, and are increasing and convex in aggregate bandwidth use from the open Internet with the latter due to dynamics of congestion. Both of these assumptions are due to capacity restrictions of the Internet: the more bandwidth of the open Internet is used, the higher are congestion costs per additional unit of output. Our assumption of congestion follows indirectly from the early work on priority pricing in the Internet (e.g., Gupta et al. 1997).

If the capacity of the open and fast-lane Internet together is fixed, then we further assume that congestion costs for edge providers that use the open Internet increase in aggregate bandwidth use from the fast-lane, as increasing bandwidth use in the fast-lane leads to a decrease in aggregate capacity (i.e., bandwidth) of the open Internet. Moreover, we assume that the congestion costs are decreasing in investments in Internet capacity, independent of whether these investments are made by the broadband provider maximizing profit or required by the policy maker.

ASSUMPTION 3 **(Congestion Costs)**.

$$\frac{\partial K(\theta, X^\theta, X_c^\theta, I)}{\partial X^\theta}, \frac{\partial^2 K(\theta, X^\theta, X_c^\theta, I)}{\partial [X^\theta]^2}, \frac{\partial K(\theta, X^\theta, X_c^\theta, I)}{\partial X_c^\theta}, \frac{\partial K(\theta, X^\theta, X_c^\theta, I)}{\partial \theta} > 0$$

$$\text{and} \quad \frac{\partial K(\theta, X^\theta, X_c^\theta, I)}{\partial I} < 0.$$

Cross Effects: Given the nature of edge providers' production technology, there are relationships between the production technology's bandwidth requirement, output, and investment that affect edge providers' profits and congestion costs. These relationships are fundamental to our results, and are: *(a)* marginal profits are weakly decreasing for edge providers that require greater bandwidth per unit of output and *(b)* marginal congestion costs are increasing for edge providers that require greater bandwidth per unit of output, are decreasing in investments in Internet capacity, and are increasing in aggregate bandwidth use of the fast-lane.

ASSUMPTION 4 **(Cross Effects)**.

$$(a): \ \frac{\partial^2 PR(\theta,x)}{\partial\theta\partial x} \leq 0; \ (b): \ \frac{\partial^2 K(\theta,X^\theta,X_c^\theta,I)}{\partial\theta\partial X^\theta} > 0, \frac{\partial^2 K(\theta,X^\theta,X_c^\theta,I)}{\partial I\partial X^\theta} < 0, \frac{\partial^2 K(\theta,X^\theta,X_c^\theta,I)}{\partial X_c^\theta\partial X^\theta} > 0.$$

The assumption on profit reflects that edge providers with greater bandwidth requirements per unit of output have slightly higher marginal costs – if higher at all – from using the Internet and consequently slightly lower profits (cf. Assumption 2 and its explanation in the context of Cournot competition). The assumptions on congestion costs reflect that edge providers with greater bandwidth requirements per unit of output are likely to cause higher marginal congestion costs than edge providers with smaller bandwidth requirements per unit of output. Moreover, in the open Internet, the impact on congestion edge providers face from expanding bandwidth use is lessened with greater investment. Finally, with greater aggregate bandwidth use in the fast-lane there is lower capacity in the open Internet that results in higher congestion costs for edge providers expanding output in the open Internet.

Conversion to fast-Lane Internet: Edge providers can choose to mitigate their congestion costs through a conversion to a fast-lane where their traffic is prioritized so that congestion they face in the fast-lane is eliminated or at least lower relative to the open Internet. We rule out all edge providers converting to the fast-lane as the open Internet has proven to be an important and inexpensive mode of communication and innovation for edge providers that choose not to convert to the fast-lane. Moreover, as the open Internet is now classified as public utility by the FCC, it must remain available with a consistent QoS (EC 2013; EC 2015, FCC 2015; US Court of Appeals 2016). The cost of converting production to use the fast-lane results mostly from internal adaptations of production technology. We assume this cost to be fixed and relatively minor, and we drop it from our analysis without loss of generality. For example, in an edge provider's production there is little difference between the broadband services requested through the fast-lane or open Internet as long as the same communication standards can be used (e.g., the communication protocol SOAP for web services) and no internal adaptations are required.

Social impacts: Edge providers do not only cause congestion costs ($K(\cdot)$) that capture end users' lower willingness to pay for content, applications and services, consumed from edge providers in the open Internet but also cause negative externalities for end users using the Internet more generally, for instance, for social networking using various social media services such as Facebook or for communication using Skype. Negative externalities for end users are denoted by $q(\theta, X^\theta, X_c^\theta, I) \in \mathbf{R}_{\geq \mathbf{0}}$ and depend on the same arguments as congestion costs. For reasons similar to those in the congestion costs above, we assume that negative externalities are increasing in aggregate bandwidth use of the open as well as of the fast-lane, and decreasing in the investments in Internet capacity.

Assumption 5 **(Negative Externalities)**.

$$\frac{\partial q(\theta, X^\theta, X_c^\theta, I)}{\partial X^\theta}, \frac{\partial q(\theta, X^\theta, X_c^\theta, I)}{\partial X_c^\theta} > 0 \quad \textit{and} \quad \frac{\partial q(\theta, X^\theta, X_c^\theta, I)}{\partial I} < 0.$$

The open Internet is used for both commercial and personal purposes, and consequently the negative externalities have social impacts. Defining $Q(\cdot)$ as aggregate negative externalities from use of the open Internet, we can define total social costs from negative externalities as $\omega(Q(\cdot)) \in \mathbf{R}_{\geq \mathbf{0}}$. We take total social costs as increasing in aggregate negative externalities, $d\omega(Q(\cdot))/dQ > 0$.

3.2. Broadband provider

Market power: The two-tier Internet is provided by a monopoly broadband provider that owns the physical last-mile facilities and effectively is the Internet access provider for end users. The FCC finds that in 2009 nearly 70% of households in the U.S. lived in census tracts where only one or two wireline or fixed wireless firms offered broadband service, and that any market power broadband providers have with end users increases their power with edge providers. Moreover, end users are unlikely to know if their broadband provider has agreements with certain edge providers, and it is costly for end users to switch broadband providers: early termination fees, inconvenience of ordering, installation and setup with associated deposit fees, difficulty in returning equipment, cost of incompatible customer-owned equipment, temporary loss of service, learning how to use the new equipment, and loss of broadband provider-specific e-mail or website access (FCC 2010). Consequently, for many end users the broadband provider functions as a "terminating monopolist" (FCC 2010; US Court of Appeals 2014) and hence has monopoly power, and as a consequence this monopoly power extends to edge providers.

Investment and pricing: The broadband provider decides on investments, I_{bp}, and sets a fixed fee, S, and a marginal fee, s, that depends on usage, θx, of the fast-lane Internet and are paid by all converting edge providers. In turn, the broadband provider faces fixed costs of setting up the fast-lane and we represent these costs by T. We take S, s and T as $\mathbf{R}\geq \mathbf{0}$. Although our model does not focus on costs of setting up a fast-lane, the scope of these fixed costs depends on whether the fast-lane is logically or physically separate from the open Internet, or a combination of the two. The difference is fundamental – if it is logically separate, then using the fast-lane can consume capacity that would otherwise be available for the open Internet. Consequently, the fixed costs of the fast-lane are, for example, costs of installing and embedding deep packet inspection appliances that can identify the sender by the IP header and the types of packets to prioritize them accordingly. We assume logically separate tiers for our analyses, recognizing that fixed costs are much more substantial for a physically separate fast-lane; for example, building a separate all fiber-optic-based Internet service through to the last mile.

3.3. End users

As we described in our literature review, due to recent regulatory and legal decisions to classify the Internet as public utility, together with a highly inelastic demand for broadband subscription, we consider the number of end users as fixed. Given that end users consume content, applications, and services from multiple edge providers, some that convert to the fast-lane and some that do not, it is important to explain how end user consumption is considered in our model. From the perspective of end users, the presence of edge providers converting to the fast-lane has two economic effects.

The first effect is that edge providers that convert can offer an enhanced set of content, applications, and services, thereby increasing output. Thus, end users that consume from edge providers that convert to the fast-lane have a higher willingness to pay. Converting edge providers can extract some or all of that additional end user willingness to pay as additional profit. Consequently, profits may differ between the open and the fast-lane Internet. We use $PR(\theta, x)$ defined above for edge providers that do not convert, and $PR_c(\theta, x_c)$ for edge providers that do convert, where the subscript c is used as a label for profits from the fast-lane resulting from an enhanced set of content, applications, and services represented by x_c of a converting edge provider. Assumptions 2 and 4 apply to both $PR(\theta, x)$ and $PR_c(\theta, x_c)$ – the functions differ only in the scale of output x (or x_c) that correspond to the different (but overlapping) sets of content, applications, and services. With the different levels of output in the open and fast-lane Internet, the inverse demand function in the Cournot example described after Assumption 2 can be restated to account for output from non-converting and converting edge providers, $r(X; X_c)$ and $r_c(X_c; X)$. The first and second order conditions for profit maximization are the same in either case.

The second effect is that edge providers that do not convert offer their content, applications, and services with a lower QoS. Thus, end users that consume content, applications, and services from the open Internet have a lower willingness to pay due to additional congestion that is captured in the congestion costs faced by these edge providers, our function $K(\theta, X^\theta, X_c^\theta, I)$.

Recognizing again, end users can use content, applications, and services from multiple edge providers which can make different production and conversion decisions. Our reduced form profit functions together with congestion costs capture the aggregate end user consumption effects faced by individual edge providers.

3.4. Policy maker

To balance openness and prioritization in a two-tier Internet, the policy-maker may require the broadband provider invest an amount of its fast-lane profits in its Internet capacity to maintain the QoS of the open Internet as required by the EC's Net Neutrality rules (EC, 2015). These investments, I_{pm}, directly affect negative externalities, congestion costs, and marginal congestion costs as in Assumptions 3, 4, and 5, as well as indirectly affect edge provider output. We can define the potential range of these investments as

$$I_{pm} \in [0, \int_0^1 [S + s\theta x] f(\theta) d\theta - I_{bp} - [1+\tau]T].$$

The term under integration is the revenue the broadband provider receives from edge providers that convert to the fast-lane, I_{bp} are the investments made by the broadband provider maximize profits, T is the fixed cost of providing the fast-lane, and $\tau \in \mathbf{R}^+$ is a minimum rate of return on the fixed costs of providing the fast-lane. The latter is necessary so that the broadband provider is motivated to offer the fast-lane when facing a mechanism constrained by its profits.

We take as given that the policy-maker knows the distribution of production technology across edge providers, but cannot identify their individual type as per our Assumption 1. However, to the degree that it is useful for instruments, the policy-maker can observe and verify which Internet (open or fast-lane) the edge provider is using, and each edge provider's level of output.

4. Use of a two-tier Internet

Considering a two-tier Internet, a policy-maker first decides on overall investments the broadband provider has to make in Internet capacity. Second, the broadband provider decides on own investments in Internet capacity and whether to charge edge providers a fixed fee, a usage-based fee, or both for prioritization in the fast-lane; based on these fees edge providers decide whether to convert to the fast-lane. The sequence of decisions is shown in Figure 3.

To analyze the economic effects of a two-tier Internet, we work backwards and examine first edge providers' production decisions and their choice of whether to convert to the fast-lane. Then we model the broadband provider's investment and pricing problem, and subsequently the policy-maker's policy mechanism decision.

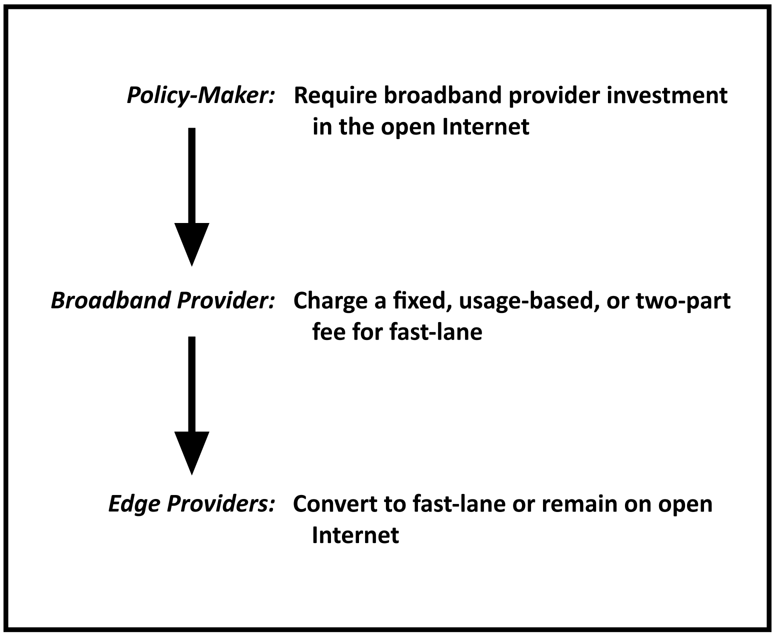

Figure 3: Sequence of Decisions

4.1. Edge Providers' Production Decisions

Edge Providers that Convert to the Fast-lane Internet: For edge providers that convert to the fast-lane, net profits $\Pi_c(x_c;\theta)$ include the fees for using the fast-lane

$$\Pi_c(x_c;\theta) = PR_c(\theta, x_c) - S - s\,\theta\,x_c, \tag{1}$$

where, as we describe in the prior section, we subscript the reduced form profit function and the resulting output with c. As we noted earlier, we abstract from congestion costs in the fast-lane and model them later in the open Internet relative to congestion on the fast-lane. We further drop the broadband access fee of edge providers from our analysis because this fee is inconsequential for edge providers' production decisions and whether to convert to the fast-lane. For converting edge providers, assuming an interior solution, the first-order condition by choice of output is

$$\frac{\partial \Pi_c}{\partial x_c} = \frac{\partial PR_c(\theta, x_c)}{\partial x_c} - s\theta = 0 = \psi_c(\theta, x_c, s), \tag{2}$$

where $\psi_c(\theta, x_c, s)$ implicitly defines the optimal value function $x_c(\theta, s)$. Lemma 1 describes the behaviour of $x_c(\theta, s)$. Proofs of our Lemmas and Theorems are in the Appendix.

Lemma 1. *For edge providers that convert to the fast-lane Internet, output is weakly lower for those edge providers that require greater bandwidth per unit of output, and is decreasing in the usage-based fee.*

Edge Providers that do not Convert to the Fast-lane Internet: For edge providers that do not convert to the fast-lane, net profits $\Pi(x;\theta)$ include congestion costs from using the open Internet,

$$\Pi(x;\theta) = PR(\theta,x) - K(\theta, X^{\theta}, X_c^{\theta}, I).$$

For those non-converting edge providers, assuming an interior solution, the first-order condition by choice of output is

$$\begin{aligned}\frac{\partial \Pi}{\partial x} &= \frac{\partial PR(\theta,x)}{\partial x} - \frac{\partial K(\theta, X^{\theta}, X_c^{\theta}, I)}{\partial X^{\theta}}\frac{\partial X^{\theta}}{\partial x} \\ &= \frac{\partial PR(\theta,x)}{\partial x} - \frac{\partial K(\theta, X^{\theta}, X_c^{\theta}, I)}{\partial X^{\theta}}\theta f(\theta) = 0 = \psi(\theta, x, X_c^{\theta}, I),\end{aligned} \tag{3}$$

where $\partial X^{\theta}/\partial x$ is only for a given θ. $\psi(\theta, x, X_c^{\theta}, I)$ implicitly defines the optimal value function $x(\theta, X_c^{\theta}, I)$. Our next lemma describes the behavior of $x(\theta, X_c^{\theta}, I)$.

Lemma 2. *For edge providers that do not convert, output is lower for those edge providers that require greater bandwidth per unit of output, is increasing in the investments in the Internet, and is decreasing in the aggregate bandwidth use of the fast-lane Internet.*

Interpreting the second and third parts of the lemma, for non-converting edge providers, investments in Internet capacity make the bandwidth use more effective, expanding output. In contrast, increasing aggregate bandwidth use in the fast-lane makes bandwidth use by non-converting edge providers less effective, reducing output.

We can now restate aggregate output in the fast-lane as $X_c(\theta,s) = \int_0^1 x_c(\theta,s) f(\theta) d\theta$ and aggregate output in the open Internet as $X(\theta, X_c, I) = \int_0^1 x(\theta, X_c(\theta,s), I) f(\theta) d\theta$. Similarly, aggregate bandwidth use in the fast-lane and open Internet is $X_c^{\theta}(\theta,s) = \int_0^1 \theta x_c(\theta,s) f(\theta) d\theta$ and $X^{\theta}(\theta, X_c^{\theta}, I) = \int_0^1 \theta x(\theta, X_c^{\theta}(\theta,s), I) f(\theta) d\theta$, respectively.

As we will see shortly, θ will become an active argument in X_c and X because each edge provider θ chooses between $x_c(\theta,s)$ or $x(\theta, X_c^{\theta}(\theta,s), I)$ being positive.

4.2. Industry Response

Each edge provider maximizes net profit by deciding whether to convert. That is

$$\max\{PR_c(\theta, x_c(\theta, s)) - S - s\,\theta\, x_c(\theta, s),$$
$$PR(\theta, x(\theta, X_c^\theta(\theta, s), I)) - K(\theta, X^\theta(\theta, X_c^\theta(\theta, s), I), X_c^\theta(\theta, s), I)\}.$$

We identify the edge provider with the bandwidth requirement per unit of output, $\tilde{\theta}$, that is indifferent between converting and not converting by

$$\begin{aligned} &PR_c(\tilde{\theta}, x_c(\tilde{\theta}, s)) - S - s\,\tilde{\theta}\, x_c(\tilde{\theta}, s) \\ &-PR(\tilde{\theta}, x(\tilde{\theta}, X_c^\theta(\tilde{\theta}, s), I)) + K(\tilde{\theta}, X^\theta(\tilde{\theta}, X_c^\theta(\tilde{\theta}, s), I), X_c^\theta(\tilde{\theta}, s), I) \\ &= 0 = \phi(S, s, I, \tilde{\theta}), \end{aligned} \tag{4}$$

where $\phi(S, s, I, \tilde{\theta})$ implicitly defines the bandwidth requirement per unit of output of the indifferent edge provider $\tilde{\theta}(S, s, I)$. We use $(\cdot)$ for (S, s, I) in the arguments to simplify and shorten our notation, and $K(\tilde{\cdot})$ for the congestion term in (4) in what follows.

Our first theorem has to be defined for two cases:

THEOREM 1. *Case 1: If* $s\, x_c(\tilde{\theta}, s) < \partial K(\tilde{\cdot})/\partial\tilde{\theta}$, *then edge providers with a greater bandwidth requirement per unit of output convert and edge providers with a lesser bandwidth requirement per unit of output do not convert.*

Case 2: If $s\, x_c(\tilde{\theta}, s) > \partial K(\tilde{\cdot})/\partial\tilde{\theta}$, *then edge providers with a lesser bandwidth requirement per unit of output convert and edge providers with a greater bandwidth requirement per unit of output do not convert.*

The condition in Theorem 1 compares the usage-based fee times output for the indifferent edge provider to the effect of the indifferent edge provider on congestion in the open Internet. Interpreting the result of the Theorem, edge providers that have a greater bandwidth requirement per unit of output convert if the usage-based fee edge providers have to pay in the fast-lane are lower than the additional congestion costs they generate in the open Internet. Otherwise, edge providers with a lesser bandwidth requirement per unit convert. It is worth noting that the choice of output levels together with the choice of whether to convert constitutes a Nash equilibrium among edge providers as the strategy sets (i.e., convert and output) are compact and the profit functions are continuous in output. In Theorem 1 we take a given case as holding over all θ as a priori $\tilde{\theta}$ can be any θ in $[0,1]$.

The following lemma determines the effects of the fixed fee, the usage-based fee, and investments in Internet capacity for each of our two cases.

LEMMA 3. *Case 1: the proportion of edge providers converting is decreasing in the fixed fee, the usage-based fee, and investments in Internet capacity.*

Case 2: the proportion of edge providers converting is increasing in the fixed fee, the usage-based fee, and investments in Internet capacity.

From these effects it follows directly that the effect of a change in the usage-based fee is precisely the effect of a change in the fixed fee multiplied by the amount of bandwidth used to generate output,

$$\tilde{\theta}\, x_c(\tilde{\theta}, s)\frac{\partial \tilde{\theta}(\cdot)}{\partial S} = \frac{\partial \tilde{\theta}(\cdot)}{\partial s}. \tag{5}$$

4.3. Broadband Provider's Investment and Pricing Decisions

As described earlier, we take the broadband provider as a monopoly over its end user base that extends to market power over edge providers (FCC, 2010). Furthermore, we consider the number of broadband providers' end users as fixed due to recent regulatory and legal decisions to classify open Internet access as public utility and essential for end users (FCC 2015; US Court of Appeals 2016), together with a highly inelastic demand for broadband subscription (Duffy-Deno 2003; Galperin and Ruzzier 2013). In this case broadband provider subscription revenue from end users is the same regardless of whether there is a fast-lane as the broadband provider can only charge end users for access to overall bandwidth – the broadband provider cannot price discriminate in end user subscription fees based on whether the consumed content, applications and services by end users are from edge providers that convert to the fast-lane. As this subscription revenue from end users is constant, we drop it in order to simplify our analysis. We discuss the issue of broadband provider subscription revenue from end users in our Conclusion.

The monopoly broadband provider chooses own investments, I_{bp}, and sets a two-part price for edge provider use of the fast-lane: a fixed fee, S, and a usage-based fee, s. As we stated earlier, the broadband provider also faces costs of providing a fast-lane. We take these costs as fixed and denote them by T.

As we saw in Theorem 1, there are two separate cases based on the relationship between the usage-based fee times the indifferent edge provider output, $s\, x_c(\tilde{\theta}, s)$, and the additional congestion costs to the open Internet from the indifferent edge provider, $\partial K(\tilde{\cdot})/\partial\tilde{\theta}$.

Case 1: Following Theorem 1, we take that $s\, x_c(\tilde{\theta}, s) \leq \partial K(\tilde{\cdot})/\partial\tilde{\theta}$ so that edge providers with greater bandwidth requirements per unit of output convert to the fast-lane. The broadband provider's profit maximization problem is

$$\max_{I_{bp},S,s} \Lambda_1(I_{bp}, S, s) = \max_{I_{bp},S,s} \{S \int_{\tilde{\theta}(\cdot)}^{1} f(\theta)d\theta + s \int_{\tilde{\theta}(\cdot)}^{1} \theta\, x_c(\theta, s) f(\theta)d\theta - I_{bp} - I_{pm} - T\}$$
$$\ni\; s\, x_c(\tilde{\theta}, s) \leq \frac{\partial K(\tilde{\cdot})}{\partial\tilde{\theta}}, \tag{6}$$

where we consider profits as larger than τT, the required return on fixed costs. The constraint in (6) is the incentive compatibility (IC) condition that determines which edge providers convert. Individual rationality (IR) is implicit in the edge providers' choices of output: *we take profit as positive with positive output.* The three first derivatives are

$$\frac{\partial\Lambda_1(I_{bp}, S, s)}{\partial I_{bp}} = -S\frac{\partial\tilde{\theta}(\cdot)}{\partial I_{bp}} f(\tilde{\theta}) - s\frac{\partial\tilde{\theta}(\cdot)}{\partial I_{bp}}\tilde{\theta} x_c(\tilde{\theta}, s) f(\tilde{\theta}) - 1 \tag{7}$$

$$\frac{\partial\Lambda_1(I_{bp}, S, s)}{\partial S} = \int_{\tilde{\theta}(\cdot)}^{1} f(\theta)d\theta - S\frac{\partial\tilde{\theta}(\cdot)}{\partial S} f(\tilde{\theta}) - s\frac{\partial\tilde{\theta}(\cdot)}{\partial S}\tilde{\theta} x_c(\tilde{\theta}, s) f(\tilde{\theta}) \tag{8}$$

and

$$\frac{\partial\Lambda_1(I_{bp}, S, s)}{\partial s} = \int_{\tilde{\theta}(\cdot)}^{1} \theta x_c(\theta, s) f(\theta)d\theta - S\frac{\partial\tilde{\theta}(\cdot)}{\partial s} f(\tilde{\theta}) - s\frac{\partial\tilde{\theta}(\cdot)}{\partial s}\tilde{\theta} x_c(\tilde{\theta}, s) f(\tilde{\theta}) + s \int_{\tilde{\theta}(\cdot)}^{1} \theta\frac{\partial x_c(\theta, s)}{\partial s} f(\theta)d\theta. \tag{9}$$

THEOREM 2. *Case 1: the broadband provider does not invest in Internet capacity, charges a positive fixed fee and no usage-based fee.*

Case 2: Following Theorem 1, we take that $s\, x_c(\tilde{\theta}, s) > \partial K(\tilde{\cdot})/\partial\tilde{\theta}$ so that edge providers with lesser bandwidth requirements per unit of output convert to the fast-lane. The broadband provider's profit maximization problem is

$$\max_{I_{bp},S,s} \Lambda_2(S,s) = \max_{I_{bp},S,s} \{S \int_0^{\tilde{\theta}(\cdot)} f(\theta) d\theta + s \int_0^{\tilde{\theta}(\cdot)} \theta x_c(\theta, s) f(\theta) d\theta - I_{bp} - I_{pm} - T\}$$
$$\ni\ s x_c(\tilde{\theta}, s) > \frac{\partial K(\tilde{\cdot})}{\partial\tilde{\theta}} \tag{10}$$

where the limits of integration and the constraint are reversed from the optimization in Case 1, (6), and again we take profits as being greater than the required return on fixed costs, τT. As in Case 1, the constraint in (10) is the IC condition that determines which edge providers convert, and IR is implicit in edge providers' choices of output. The three first derivatives are

$$\frac{\partial\Lambda_2(I_{bp}, S, s)}{\partial I_{bp}} = S \frac{\partial\tilde{\theta}(\cdot)}{\partial I_{bp}} f(\tilde{\theta}) + s \frac{\partial\tilde{\theta}(\cdot)}{\partial I_{bp}} \tilde{\theta} x_c(\tilde{\theta}, s) f(\tilde{\theta}) - 1 \tag{11}$$

$$\frac{\partial\Lambda_2(I_{bp}, S, s)}{\partial S} = \int_0^{\tilde{\theta}(\cdot)} f(\theta) d\theta + S \frac{\partial\tilde{\theta}(\cdot)}{\partial S} f(\tilde{\theta}) + s \frac{\partial\tilde{\theta}(\cdot)}{\partial S} \tilde{\theta}\, x_c(\tilde{\theta}, s) f(\tilde{\theta}) \tag{12}$$

and

$$\frac{\partial\Lambda_2(I_{bp}, S, s)}{\partial s} = \int_0^{\tilde{\theta}(\cdot)} \theta\, x_c(\theta, s) f(\theta) d\theta + S \frac{\partial\tilde{\theta}(\cdot)}{\partial s} f(\tilde{\theta}) + s \frac{\partial\tilde{\theta}(\cdot)}{\partial s} \tilde{\theta} x_c(\tilde{\theta}, s) f(\tilde{\theta}) + s \int_0^{\tilde{\theta}(\cdot)} \theta \frac{\partial x_c(\theta, s)}{\partial s} f(\theta) d\theta. \tag{13}$$

THEOREM 3. *Case 2: the broadband provider does not invest in Internet capacity and if the impact of the bandwidth requirement per unit of output on edge provider output is no more than moderate, then Case 2 is infeasible.*

The premise of Theorem 3 is important to the extent that the output of converting edge providers is insensitive to increases in the usage-based fee, ***this needs to be clarified***

$$s \int_0^{\tilde{\theta}(\cdot)} \theta \frac{\partial x_c(\theta, s)}{\partial s} f(\theta) d\theta.$$

Although the difference embedded in $\tilde{\theta}x_c(\tilde{\theta},s) < \theta x_c(\theta,s)$ is small, the difference is increasing in s, and thus the premise is required to ensure that Theorem 3 holds. If the output of converting edge providers is sensitive to increases in the usage-based fee, then the premise of the Theorem is not necessary.

To summarize, Theorem 3 holds because there is neither an interior solution for the fixed fee nor for the usage-based fee that satisfy the constraint in (10). Thus, Case 1 is the only one that remains and edge providers with high bandwidth requirements per unit of output, such as one might expect for Netflix, convert to the fast-lane.

With the results from Theorems 2 and 3 whereby edge providers with greater bandwidth requirements per unit of output convert (i.e., Case 1), the broadband provider does not invest in Internet capacity and only uses a fixed fee, we can now restate the broadband provider's profit maximization problem as

$$\max_S \Lambda(S) = \max_S \{S \int_{\tilde{\theta}(\cdot)}^1 f(\theta)d\theta - I_{pm} - T\}, \tag{14}$$

where $\tilde{\theta}(\cdot)$ represents $\tilde{\theta}(S, s=0, I_{pm})$, that is, the indifferent edge provider when the usage-based fee is zero. Here the IC condition is implicit in the limits of integration. Notice that the broadband provider ignores the congestion effects of the fast-lane on the open Internet. Noting that $\Lambda(S)$ is increasing from $S=0$, the first derivative is

$$\frac{d\Lambda(S)}{dS} = \int_{\tilde{\theta}(\cdot)}^1 f(\theta)d\theta - S\frac{\partial\tilde{\theta}(\cdot)}{\partial S}f(\tilde{\theta}),$$

from which it is clear that $d\Lambda(S)/dS$ becomes negative as S becomes large, establishing that there exists an upper limit to the optimal fixed fee.

4.4. Social Welfare

The objective of the policy-maker is to maximize social welfare, which we denote by $B(\cdot)$, by choice of the level of investment in Internet capacity required from the broadband provider, I_{pm}. As the broadband provider has no incentive to invest Internet capacity (cf., Theorem 2), $I_{pm} = I$.

$$\max_I B(I) = \max_I \{EUS(X_c(\cdot), X(\cdot)) + EPS(\cdot) - \omega(Q(\cdot)) - T\}, \tag{15}$$

where from the prior section the broadband provider does not employ a usage-based fee, $s = 0$. Suppressing the obvious arguments from the functions detailed earlier, social welfare is made up of end user surplus, $EUS(X_c(\cdot), X(\cdot))$, with its arguments being aggregate output of all converting edge providers $X_c(\cdot)$ and aggregate output of all non-converting edge providers $X(\cdot)$, edge provider surplus, $EPS(\cdot)$, the total social value of negative externalities, $\omega(Q(\cdot))$, and the fixed cost of providing the fast-lane Internet from the broadband provider, T. Broadband provider profit does not enter social welfare analysis as it is a transfer between edge providers and the broadband provider. End user surplus is net of what end users pay to edge providers – that is, we implicitly assume that edge providers cannot practice perfect price discrimination and extract all end user surplus. In the following subsections, we analyze the effects of our policy mechanism – requiring the broadband provider to invest a portion of its fast-lane profits in Internet capacity – on the different components of social welfare.

4.4.1. End User Surplus End user surplus is increasing in its arguments $\partial EUS/\partial X_c > 0$ and $\partial EUS/\partial X > 0$. The aggregate outputs of converting and non-converting edge providers are, respectively,

$$X_c(\cdot) = \int_{\tilde{\theta}(\cdot)}^{1} x_c(\theta, 0) f(\theta) d\theta \;\text{ and }\; X(\cdot) = \int_{0}^{\tilde{\theta}(\cdot)} x(\theta, X_c^{\theta}(\cdot), I) f(\theta) d\theta.$$

The following lemma establishes the effects of the investments in Internet capacity on aggregate output:

Lemma 4. *Aggregate output of converting edge providers is decreasing, while aggregate output of non-converting edge providers is increasing, in investments in Internet capacity.*

The first result in Lemma 4 represents the reduction in output that comes from the indifferent edge provider in the fast-lane choosing instead to use the open Internet in response to increased investment in Internet capacity. The first term of the second result in Lemma 4, the complement of the first result, represents the increase in output that comes from the indifferent edge provider choosing to use the open Internet in response to increased investment in Internet capacity. The second term in the second result represents the additional output of all non-converting edge providers in response to increased investment in Internet capacity. The third term in the second result represents the additional output of all non-converting edge providers in response to the decreasing aggregate bandwidth use in the fast-lane (thereby increasing capacity in the open Internet) from increased investment.

4.4.2. Edge Provider Surplus Edge provider surplus is the sum of the net profits (net of the broadband provider fixed fee which is a transfer) of converting and non-converting edge providers:

$$EPS(\cdot) = \int_{\tilde{\theta}(\cdot)}^{1} [PR_c(\theta, x_c(\theta,0))] f(\theta) d\theta + \int_{0}^{\tilde{\theta}(\cdot)} [PR(\theta, x(\theta, X_c^{\theta}(\cdot), I)) - K(\theta, X^{\theta}(\cdot), X_c^{\theta}(\cdot), I)] f(\theta) d\theta.$$

Differentiating edge provider surplus with respect to investments in Internet capacity:

$$\begin{aligned}
&\frac{\partial EPS(\cdot)}{\partial I} = \\
&-[PR_c(\tilde{\theta}, x(\tilde{\theta},0))] f(\tilde{\theta}) \frac{\partial \tilde{\theta}(\cdot)}{\partial I} + [PR(\tilde{\theta}, x(\tilde{\theta}, X_c^{\theta}(\cdot), I)) - K(\tilde{\theta}, X^{\theta}(\cdot), X_c^{\theta}(\cdot), I)] f(\tilde{\theta}) \frac{\partial \tilde{\theta}(\cdot)}{\partial I} \\
&+ \int_0^{\tilde{\theta}(\cdot)} \frac{\partial PR(\theta, x(\theta, X_c^{\theta}(\cdot), I))}{\partial x} \frac{\partial x(\theta, X_c^{\theta}(\cdot), I)}{\partial I} f(\theta) d\theta - \int_0^{\tilde{\theta}(\cdot)} \frac{\partial K(\theta, X^{\theta}(\cdot), X_c^{\theta}(\cdot), I)}{\partial I} f(\theta) d\theta \\
&- \int_0^{\tilde{\theta}(\cdot)} \frac{\partial K(\theta, X^{\theta}(\cdot), X_c^{\theta}(\cdot), I)}{\partial X^{\theta}} \frac{\partial X^{\theta}(\cdot)}{\partial I} f(\theta) d\theta - \int_0^{\tilde{\theta}(\cdot)} \frac{\partial K(\theta, X^{\theta}(\cdot), X_c^{\theta}(\cdot), I)}{\partial X_c^{\theta}} \frac{\partial X_c^{\theta}(\cdot)}{\partial I} f(\theta) d\theta.
\end{aligned}$$

Rearranging terms, using (4), and noting that $s = 0$ we have

$$\begin{aligned}
\frac{\partial EPS(\cdot)}{\partial I} &= -S f(\tilde{\theta}) \frac{\partial \tilde{\theta}(\cdot)}{\partial I} + \int_0^{\tilde{\theta}(\cdot)} \frac{\partial PR(\theta, x(\theta, X_c^{\theta}(\cdot), I))}{\partial x} \frac{\partial x(\theta, X_c^{\theta}(\cdot), I)}{\partial I} f(\theta) d\theta \\
&\quad - \int_0^{\tilde{\theta}(\cdot)} \frac{\partial K(\theta, X^{\theta}(\cdot), X_c^{\theta}(\cdot), I)}{\partial I} f(\theta) d\theta - \int_0^{\tilde{\theta}(\cdot)} \frac{\partial K(\theta, X^{\theta}(\cdot), X_c^{\theta}(\cdot), I)}{\partial X} \frac{\partial X^{\theta}(\cdot)}{\partial I} f(\theta) d\theta \\
&\quad - \int_0^{\tilde{\theta}(\cdot)} \frac{\partial K(\theta, X^{\theta}(\cdot), X_c^{\theta}(\cdot), I)}{\partial X_c^{\theta}} \frac{\partial X_c^{\theta}(\cdot)}{\partial I} f(\theta) d\theta. \qquad (16)
\end{aligned}$$

Using Lemma 3 the first term is negative. Using Assumption 2 and Lemma 2, the second term is positive. From Assumption 3 the third term is positive. Using Assumption 3 as well as Lemma 4, the fourth term is negative and the fifth term is positive.

Consequently, (16) is a balance of different effects. The first term represents the reduction in profits that come as a consequence of the indifferent edge provider choosing the open Internet in response to investment. The second term represents the positive effect of investment on profits through increased output of all non-converting edge providers. The third term represents the reduction in congestion costs due to investment that applies to all edge providers using the open Internet. The fourth term represents the additional congestion costs faced by all non-converting edge providers resulting from higher aggregate bandwidth use in the open Internet and the fifth term represents the reduction of congestion costs resulting from lower aggregate bandwidth use in the fast-lane.

4.4.3. Total Social Value of Negative Externalities The total social value of negative externalities $\omega(Q(\cdot))$ is increasing in its argument $Q(\cdot)$. The aggregate negative externalities of non-converting edge providers are:

$$Q(\cdot) = \int_0^{\tilde{\theta}(\cdot)} q(\theta, X^\theta(\cdot), X_c^\theta(\cdot), I) f(\theta) d\theta.$$

Differentiating the aggregate negative externalities with respect to the investments in Internet capacity:

$$\begin{aligned}
&\frac{\partial Q(\cdot)}{\partial I} = \\
&q(\tilde{\theta}, X^\theta(\cdot), X_c^\theta(\cdot), I) f(\tilde{\theta}) \frac{\partial \tilde{\theta}(\cdot)}{\partial I} + \int_0^{\tilde{\theta}(\cdot)} \frac{\partial q(\theta, X^\theta(\cdot), X_c^\theta(\cdot), I)}{\partial I} f(\theta) d\theta \\
&+ \int_0^{\tilde{\theta}(\cdot)} \frac{\partial q(\theta, X^\theta(\cdot), X_c^\theta(\cdot), I)}{\partial X^\theta} \frac{\partial X^\theta(\cdot)}{\partial I} f(\theta) d\theta \\
&+ \int_0^{\tilde{\theta}(\cdot)} \frac{\partial q(\theta, X^\theta(\cdot), X_c^\theta(\cdot), I)}{\partial X_c^\theta} \frac{\partial X_c^\theta(\cdot)}{\partial I} f(\theta) d\theta.
\end{aligned} \tag{17}$$

Using Lemma 3 the first term is positive. Using Assumption 5 the second term is negative. Using Assumption 5 and Lemma 4, the third term is positive and the fourth term is negative.

The first term represents increased negative externalities from the indifferent edge provider choosing to use the open Internet in response to investment; the second term represents the direct reduction in negative externalities resulting from investment in Internet capacity; the third term represents higher negative externalities generated by the additional bandwidth use of all non-converting edge providers; and the fourth term represents lower negative externalities from the reduced aggregate bandwidth use in the fast-lane.

4.4.4. Maximizing Social Welfare To establish a condition when the policy maker should restrict Internet openness regulation and to ascertain the impact of a fast-lane on the open Internet, we have to analyze the welfare effects of a fast-lane. The following theorem shows the impact of a fast-lane on end users and edge providers of the open Internet and explicates a strict condition under which a fast-lane is beneficial.

THEOREM 4. *If there are no investments in capacity, then (a) all end users and edge providers in the open Internet are worse off; (b) a two-tier Internet is socially beneficial only if the increase of end user surplus and edge provider profits from the fast-lane Internet outweigh the fixed costs of providing a fast-lane Internet as well as the additional congestion costs and negative externalities on the open Internet that result from higher bandwidth use from edge providers that convert to the fast-lane Internet.*

Theorem 4 makes it clear that without establishing a policy mechanism that requires investment in Internet capacity all end users and edge providers of the open Internet are worse off by introducing a fast-lane. As such, a two-tier Internet would not fulfill the EC condition that a fast-lane may not reduce the QoS of the open Internet (EC 2013; EC 2015). Moreover, the condition for a two-tier Internet to be socially beneficial is not straightforward as not only must the positive effects of increased output offset the negative effects, these effects must also offset the costs of providing a fast-lane.

Policy mechanism: As we found that broadband providers have no incentive to invest in Internet capacity (cf., Theorem 2), the policy-maker can require that the broadband provider invests an amount of its fast-lane profits into Internet capacity. This policy mechanism can be used to maintain the QoS of the open Internet and to increase social welfare if the condition expressed in Theorem 4(b) is satisfied or, more critically, to make a two-tier Internet socially beneficial if the condition expressed in Theorem 4(b) is not satisfied. Consequently, we analyze if, and under what condition, such a policy mechanism positively affects the open Internet and increases welfare.

Maximizing social welfare can be written as

$$\max_I B(I) \quad \ni I \in [0, S \int_{\tilde{\theta}(S,0,I)}^{1} f(\theta) d\theta - [1+\tau]T], \tag{18}$$

where investment in the Internet is constrained by revenues from the broadband provider's fixed fee less its fixed costs of providing a fast-lane and its minimum rate of return on these fixed costs.

Combining the results from our analyses of end user surplus, edge provider surplus, and negative externalities, the first derivative of social welfare with respect to investment after grouping like terms is

$$\begin{aligned}
&\frac{dB(I)}{dI} = \\
&f(\tilde{\theta})\frac{\partial\tilde{\theta}(\cdot)}{\partial I}[-\frac{\partial EUS}{\partial X_c}x_c(\tilde{\theta},0) + \frac{\partial EUS}{\partial X}x(\tilde{\theta},X_c^\theta(\cdot),I) - S - \frac{\partial\omega}{\partial Q}q(\tilde{\theta},X^\theta(\cdot),X_c^\theta(\cdot),I)] \\
&+\frac{\partial EUS}{\partial X}\int_0^{\tilde{\theta}(\cdot)}\frac{\partial x(\theta,X_c^\theta(\cdot),I)}{\partial I}f(\theta)d\theta + \frac{\partial EUS}{\partial X}\int_0^{\tilde{\theta}(\cdot)}\frac{\partial x(\theta,X_c^\theta(\cdot),I)}{\partial X_c^\theta}\frac{\partial X_c^\theta(\cdot)}{\partial I}f(\theta)d\theta \\
&+\int_0^{\tilde{\theta}(\cdot)}\frac{\partial PR(\theta,x(\theta,X_c^\theta(\cdot),I))}{\partial x}\frac{\partial x(\theta,X_c^\theta(\cdot),I)}{\partial I}f(\theta)d\theta \\
&-\int_0^{\tilde{\theta}(\cdot)}\frac{\partial K(\theta,X^\theta(\cdot),X_c^\theta(\cdot),I)}{\partial X^\theta}\frac{\partial X^\theta(\cdot)}{\partial I}f(\theta)d\theta - \frac{\partial\omega}{\partial Q}\int_0^{\tilde{\theta}(\cdot)}\frac{\partial q(\theta,X^\theta(\cdot),X_c^\theta(\cdot),I)}{\partial X^\theta}\frac{\partial X^\theta(\cdot)}{\partial I}f(\theta)d\theta \\
&-\int_0^{\tilde{\theta}(\cdot)}\frac{\partial K(\theta,X^\theta(\cdot),X_c^\theta(\cdot),I)}{\partial X_c^\theta}\frac{\partial X_c^\theta(\cdot)}{\partial I}f(\theta)d\theta - \frac{\partial\omega}{\partial Q}\int_0^{\tilde{\theta}(\cdot)}\frac{\partial q(\theta,X^\theta(\cdot),X_c^\theta(\cdot),I)}{\partial X_c^\theta}\frac{\partial X_c^\theta(\cdot)}{\partial I}f(\theta)d\theta \\
&-\int_0^{\tilde{\theta}(\cdot)}\frac{\partial K(\theta,X^\theta(\cdot),X_c^\theta(\cdot),I)}{\partial I}f(\theta)d\theta - \frac{d\omega}{dQ}\int_0^{\tilde{\theta}(\cdot)}\frac{\partial q(\theta,X^\theta(\cdot),X_c^\theta(\cdot),I)}{\partial I}f(\theta)d\theta.
\end{aligned} \tag{19}$$

The first derivative in (19) contains six separate sets of effects, each on a different line on the right hand side.

The first line in (19) is the effect of an increase in investment in Internet capacity that causes the indifferent edge provider to use the open Internet: The first two terms in the squared brackets result in a negative welfare effect since $x_c(\tilde{\theta},0) > x(\tilde{\theta},X_c^\theta(\cdot),I)$. The remaining terms are the forgone fixed fee plus the additional negative externalities from the indifferent edge provider using the open Internet, both of which reduce welfare as well.

The second and third line in (19) are the effects of an increase in investment in Internet capacity on non-converting edge providers producing higher levels of output, increasing end user surplus (second line) and edge provider profit (third line), both of which increase welfare.

The fourth and fifth line in (19) are the effects of an increase in investment in Internet capacity on congestion costs and negative externalities through changes in aggregate bandwidth use in the open Internet which decreases welfare (fourth line) and changes in aggregate bandwidth use in the fast-lane which increases welfare (fifth line).

The sixth line in (19) contains the direct congestion and negative externality relieving effects of additional investment in Internet capacity for non-converting edge providers, both of which increase welfare.

Summarizing the effects in (19) from our policy mechanism we have:

1. Effects of the indifferent edge provider using the open Internet (-)

2. Non-converting edge providers increase output, increasing end user surplus and edge provider profit (+)

3. Effects on congestion costs and negative externalities from changes in aggregate bandwidth use in the fast-lane (+) and open Internet (-)

4. Direct congestion and negative externality relieving effects of investment (+)

The net effect of 3 above is likely to be small as aggregate bandwidth use falls in the fast-lane and rises in the open Internet. The effect of 1 above is also likely to be small as it only applies to tradeoffs faced by the indifferent edge provider. Consequently, the overall sign of (19) is very likely positive. Our theorem and corollary below consider these effects subject to the constraint on investment in (18). The proof is by definition.

Theorem 5. *A sufficient condition for the policy mechanism requiring a portion of broadband provider profits be invested in Internet capacity is that the first dollar of investment increases welfare:*

$$\frac{dB(I)}{dI}|_{I=0} > 0.$$

Corollary 1. *A sufficient condition for the policy mechanism requiring all broadband provider profits (except those from a reasonable rate of return on fixed costs) be invested in Internet capacity is that every dollar of investment increases welfare:*

$$\frac{dB(I)}{dI} > 0 \;\forall\, I \in [0, S\int_{\tilde{\theta}(S,0,I)}^{1} f(\theta)d\theta - [1+\tau]T].$$

The consequence of Theorem 5 and its Corollary is that there is an important role for policy intervention in the form of required investment in Internet capacity. This required investment increases output of non-converting edge providers and relieves congestion and negative externality effects in the open Internet. As long as the positive effects of investment on output (second line of (19)), profits (third line of (19)), and congestion costs and negative externalities (fifth and sixth line of (19)) outweigh the negative effects (first and fourth line of (19)), this policy mechanism can be used to maintain the general QoS of the open Internet (EC 2013; EC 2015).

If the condition in the Corollary to Theorem 5 holds for low but not for all investment levels $I \in [0, S\int_{\tilde{\theta}(S,0,I)}^{1} f(\theta)d\theta - [1+\tau]T]$, then there may be an optimal amount of broadband provider's fast-lane profits to be invested in Internet capacity. Indeed, it is worth noting that as investment in Internet capacity increases, the range of such investment available from broadband provider profits decreases as fewer edge providers convert, $\tilde{\theta}(S,0,I)$ is increasing in I.

However, if the Corollary to Theorem 5 is true, then strict application of policy requires the broadband provider invest all its revenue from the fixed fee for the fast-lane less its fixed costs of providing the fast-lane in Internet capacity and a reasonable rate of return on these fixed costs. In this case, our policy mechanism ensures that the broadband provider covers not only its marginal costs – which are zero in our case – but also its fixed costs F and a rate of return on these fixed costs. This latter situation provides an opportunity to include additional considerations in policy such as how to determine what are reasonable returns to the broadband provider on its investment in the fast-lane, thus investment in Internet capacity would cover fixed costs but also a reasonable level of profit. In this way, such a policy would be equivalent to certain forms of Ramsey-Boiteux pricing (Dierker, 1991).

5. Conclusions

The debate whether to restrict Internet openness regulation and allow broadband providers to prioritize traffic in the Internet started in 2007 with the BitTorrent case where Comcast – the second biggest broadband provider in the U.S. – actively interfered and blocked file sharing traffic from BitTorrent in order to keep it from monopolizing bandwidth. In 2010, the debate was reignited by the joint proposal of Verizon and Google (Verizon and Google 2010) regarding a fast-lane to deal with congestion. In turn the FCC Open Internet Order imposed disclosure, anti-blocking, and anti-discrimination requirements on broadband providers (FCC 2010). Subsequently the Open Internet Order was vacated (see U.S. Court of Appeals 2014). In response the FCC issued a Notice of Proposed Rulemaking (FCC 2014) in May of 2014 that poses the question of whether broadband providers could charge edge providers fees for prioritization of their Internet traffic. In February 2015 the FCC narrowly voted to reclassify broadband providers as common carriers, similar to utilities, reinforcing their prior Open Internet Order, and the reclassification was supported by a recent court ruling (US Appeals Court 2016). At the same time the European parliament enshrined net neutrality rules into E.U. law that opened the door for a two-tier Internet by allowing broadband providers the provision of prioritized services with an enhanced QoS as long as this does not harm the general quality of the open Internet (EC 2013; EC 2015).

This debate extends to the academic literature. Most of the extant literature compares the welfare effects of an Internet openness regime with a non-openness regime, implicitly considering a fast-lane as a substitute for the open Internet, which is not feasible due to recent regulations and legal judgements. Further, existing approaches treat the Internet as a content distribution channel and are usually based on two-sided market models. Our work broadens this focus considering a two-tier Internet where the fast-lane coexists with the open Internet. We develop a new model that takes new regulations and judgments for the Internet into account (e.g., Internet as production factor, open Internet as public utility with inelastic demand, and arbitrary sources of revenue for edge providers). We consider edge providers that differ in their bandwidth requirement for production, a monopolist broadband provider, and a policy-maker and the following decisions: The policy-maker decides whether to apply a policy measure that requires the broadband provider to invest a portion of its fast-lane profits in the open Internet. The broadband provider decides whether to invest in Internet capacity separate from the policy requirement and whether to charge edge providers a fixed, a usage-based, or a two-part fee for the fast-lane. Finally, edge providers decide on whether to convert to a fast-lane and on output levels to maximize their net profits.

Within this model set-up we find that edge providers with greater bandwidth requirements per unit of output convert to the fast-lane and produce an enhanced set of content, applications, and services. The broadband provider has no incentive to invest in Internet capacity and chooses a fixed fee rather than a usage-based or two-part fee for the fast-lane. This result is consistent with a policy-maker that may wish to regulate usage-based prices.

We also find that by establishing a two-tier Internet, end users and edge providers of the open Internet are worse off so long as there are no increases in investments in Internet capacity. To maintain or increase the QoS of the open Internet and social welfare, a two-tier Internet has to be coupled with a policy mechanism whereby a portion of broadband provider profit from the fast-lane is invested in the open Internet. Alternatively, if the policy-maker mandates a minimum QoS from the open Internet such as maintaining the QoS of the current open Internet (EC 2013; EC 2015), so long as the objective of such a policy is to maximize welfare, our analysis is identical: a portion of broadband provider profit from the fast-lane must be invested in Internet capacity to maintain the QoS of the open Internet. Thus, on balance our analysis supports the implementation of a two-tier Internet with the proviso that investment from broadband providers can be required to maintain the viability and contributions to social welfare from the open Internet.

We have chosen a sophisticated new model structure to examine a two-tier Internet that is general enough to capture three major decisions, each made by a different group of participants and that influence each other. However, as with any model, abstraction requires choices of what to include, and inevitably some elements are left out. In formulating our model, we treat the number of end users as fixed and drop the end user subscription fee and end users' subscription decision from our analysis. We made this implicit assumption due to recent regulatory decisions such as classifying the open Internet as public utility with inelastic demand that should be available for all end users such as water, electricity and telephone. Of course, a two-tier Internet may prompt end users to not consume higher priced content, applications, and services provided by edge providers in the fast-lane which we consider in edge provider reduced form profit functions and congestion costs as described in subsection 3.3. This means that the vast majority of end users may change their consumption behavior in a two-tier Internet but they would continue to subscribe to overall bandwidth as they receive economic value from edge providers in the open Internet as well as social value from communication and social networking in the open Internet even if slowed by congestion.

We also note that the congestion effects from the fast-lane on the open Internet may reduce the willingness to pay of some end users to an extent that they drop broadband subscription. However, if the policy-maker establishes our proposed mechanism to maintain the QoS of the open Internet, this effect is reversed.

There is a potential second-order effect whereby the broadband provider may acquire new end users due to the enhanced set of content, applications and services from edge providers that convert to the fast-lane. Enhancements such as remote healthcare monitoring may sufficiently increase end user willingness to pay that new end users may choose to subscribe to Internet service. We capture the additional edge provider revenues from this effect in our reduced form profit function but we do not capture the additional subscription revenues for broadband providers because we believe this effect is relatively minor.

Our results lead to further research closely related to our analysis. Our theoretical model shows that investments in Internet capacity are required to sustain the open Internet, and the degree of investment may depend on the costs of setting up a fast-lane and providing a reasonable return on investment (profit) for broadband providers along the lines of Ramsey-Boiteux pricing. An empirical or numerical model is needed to determine what magnitude of investment in Internet capacity is required to maintain the QoS of the open Internet, while balancing other policy considerations at the same time. A further extension of our model would allow edge providers to make investments in their production technology at some cost which is consistent with investments in content delivery networks (see Choi et al. 2015; Davidson 2015; Peitz and Schuett 2016). Such investments could be considered as further argument in our reduced-form profit function and this is an interesting avenue for extending our model.

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