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BROADBAND USER DISCRIMINATION AND THE NET NEUTRALITY DEBATE

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ABSTRACT

The net neutrality debate has brought out economic rationale for and against a variety of proposals of the broadband service providers to differentiate between different classes of users. Broadband users are characterized by the differing amounts of content they request online, as well as their valuation for such content. A broadband service provider (BSP) has two potential instruments for user discrimination – price discrimination and traffic prioritization (or degradation). We model six different pricing and prioritization options that cover many of the strategies that actual BSPs have adopted in the marketplace. By comparing these options, we find that imposing net neutrality increases the BSP's profit if the BSP price discriminates different consumer groups. If net neutrality is not imposed, however, the BSP might still prefer a net neutrality outcome depending on the various parameter values. These and other results will be useful both for the broadband service providers as they mull over the introduction of the different pricing strategies and for policymakers who are dealing with the net neutrality issue.

Keywords**:** Net neutrality, Internet access pricing, congestion pricing, traffic prioritization, public policy, market regulation

Broadband User Discrimination and the Net Neutrality Debate

1. Introduction

In 2007, it was independently verified that the broadband Internet service provider[2] Comcast was slowing down network traffic within its servers that originated from the popular peer-to-peer (P2P) networks (McCullagh 2007). After initially denying any such behavior, Comcast defended its actions by claiming that the traffic from the P2P networks, which was dominated by just a small fraction of the total number of users, was slowing down the network traffic for the rest of the users. The United States Federal Communications Commission (FCC) later declared Comcast's actions to be illegal, thus providing further fuel to the 'net neutrality' debate that is currently making the rounds in the US Congress and Senate.

The issue of net neutrality received widespread media attention when some broadband service providers like Verizon, Comcast and AT&T (among others) proposed to charge popular online websites for priority delivery of the latter's content to their residential and commercial customers (Helm 2006; Waldmeir 2006). The proposal encountered stiff resistance from those who were supposed to be charged, and thus erstwhile competitors like Google, Yahoo! and Microsoft were soon lobbying before the United States Congress to pass legislation that would prevent the broadband service providers from carrying out their proposed plan (WSJ 2006), and thereby maintain what was termed the 'neutrality' of the Internet (the term 'net neutrality' itself is attributed to the Columbia Law School professor Tim Wu). This would involve the designing of "rules that prevent network operators and ISPs from using their power over the transmission

[2] Here, and in the rest of the article, we have uses the terms broadband internet service provider, broadband service provider (or BSP for short) and internet service provider (ISP) interchangeably.

technology to negatively affect competition in complementary markets for applications, content and portals" (van Schewick 2007).

The supporters of net neutrality believe that a "maximally useful public information network aspires to treat all content, sites, and platforms equally" (Wu 2003), and while a formal definition of the operationalization of the principle does not exist, Hahn and Wallsten (2006) point out that it "usually means that broadband service providers charge consumers only once for Internet access, do not favor one content provider over another, and do not charge content providers for sending information over broadband lines to end users."

Lobbied intensely by both sides of the issue, the United States Congress is currently considering proposals to introduce net neutrality legislation (Dunbar 2006; McCullagh and Broache 2006; Windhausen 2006). The U.S. House of Representatives and the Senate have held several hearings on the subject (Representatives 2005; Senate 2006). The Federal Trade Commission has also chimed in, and has recently published a report that has advised a wait-and-watch approach on the matter (FTC 2007).

As is to be expected in a debate which has implications in many different areas, academicians too can be found on both sides of the debate (for a recent example of such debate, see (van Schewick and Farber 2009)). From a technical standpoint, the issue is as follows: the original design philosophy of the Internet communication protocols abide by the principle that every data packet is treated equally, so that no data packet gets priority over another (leading to the coinage of the term net neutrality – i.e., the net is neutral in its handling of any data packet that passes through it). From a broadband service provider's perspective, however, priority delivery of packets for a fee makes perfect economic sense, if there happen to be interested parties who would pay for the service. So far, the growing literature that has analyzed these economic issues of net neutrality (see for example (Economides and Tag 2007; Hermalin and Katz 2007; Bandyopadhyay et al. 2009; Cheng et al. 2009; Guo et al. 2009)) has modeled that interested party as the content providers who are jockeying for a position in the consumers' minds. However, as the aforementioned Comcast example shows, the interested party might well be some of the consumers themselves who are willing to pay a fee to have their requested packets delivered with priority. In other words, a data packet traveling from its origin to its destination can be made “non-neutral” by the BSP at various stages of its journey – either at the ‘supply’ side, whereby the BSP charges content providers for preferential delivery of their packets, or on the ‘demand’ side, whereby the BSP charges the individual consumers a fee for the priority delivery of their requested content (or equivalently, de-prioritizes the requested content in the absence of the fee). Figure 1 shows a schematic of the different aspects of the net neutrality debate that we just described. It clearly brings out the role of the BSP as the gatekeeper who can charge either the content providers (at the left of the figure) or the consumers (at the right of the figure) for preferential delivery of requested content.

--Insert Figure 1 about here--

In this article, our focus is on the latter aspect of net neutrality, whereby we analyze the economic rationale for and against the proposals put forth by several broadband service providers who intend to differentiate between different classes of users. For example, the cable broadband service provider Time Warner Cable has recently started an experiment in certain markets where they plan to charge Internet customers based on how much Web data they consume. The experiment started in a single market (Beaumont, TX) in the summer of 2008, and the company plans to introduce tiered pricing in several other markets in the near future. By charging a premium to the heaviest broadband users, much the same way cell phone providers collect fees from subscribers who exceed their allotted minutes, Time Warner would upend a longstanding uniform pricing strategy among (fixed-line) Internet service providers in the United States, whereby phone and cable companies have charged flat fees for unlimited access to the Web. AT&T has started a similar experiment with its own customers, also in Beaumont, TX.

As expected, such experiments have reignited the net neutrality debate. Proponents of net neutrality – consumer advocates and online content providers, for example – have opined that that a tiered Web-use pricing would limit customer choice and could stifle innovation by crimping demand for high-bandwidth services such as online video and music (Al-Chalabi 2008). However, cable and phone companies have countered by saying that they need the flexibility in setting prices for use of large, expensive, heavily used broadband networks, so as to effectively serve the majority of their customers and encourage greater efficiency in the way customers use capacity (Tweney 2008).

As consumers spend more time online, and also use the Internet to consume various types of data-intensive content (like music and video – a high-definition movie typically consumes around 8 GB of traffic), the decision to charge data consumption by volume can be expected to have profound implications in the way online content is consumed in future. In such scenarios, heavy users can expect to spend much more than what they currently spend on the erstwhile “all you can eat” plans. However, Time Warner has countered that most people are actually not downloading that much data. The company's trial in Beaumont, TX, lasted several months: of the 10,000 broadband customers enrolled – which represented about 25% of the company's total number of consumers in Beaumont – about 14% exceeded their cap and had to pay additional fees that averaged about $19 a month. Time Warner Cable also discovered that the top 25% of users consumed 100 times more data than the bottom 25% of users, suggesting an enormous gap in usage patterns.

Broadband service providers have often mentioned that as more and more people download TV shows and movies, particularly those in high-definition, the broadband network infrastructure faces enormous strain. Time Warner Cable has said its strategy is intended to alleviate some of that strain, with users self-regulating themselves under the new plan. But critics have expressed concerns that the pricing scheme will discourage broadband use and impede new online media businesses before they even have a chance to flourish.

The entire debate has raised a number of unanswered questions that are of interest to researchers and practitioners alike, not to mention the regulatory agencies. While legal scholars might debate whether such pricing plans (as those that Time Warner and AT&T are experimenting with) or prioritization strategies (as Comcast briefly attempted) are fair on the consumers, it is an entirely separate issue whether there are economic incentives for the BSPs to pursue such strategies that go against the net neutrality principle. In other words, facing a highly dynamic and differentiated data usage patterns from different classes of users, would a BSP gain (as compared to the status quo) by employing different pricing and/or packet prioritization strategies? In the first part of our analysis, we explore this issue.

While the BSP might prefer not to adhere to the principles of net neutrality under certain circumstances, such a move might be detrimental to the consumers or the society as a whole. Thus, from a social planner's perspective, the issue is somewhat different: would the abolishment of net neutrality on the 'demand' side result in lower consumer surplus or social welfare? Depending on that answer, the social planner might wish to regulate on the issue.

In this paper, we explore these issues and model them in an analytical framework and examine the economic impacts of user discrimination and net neutrality from the perspectives of both the BSP and the social planner. We characterize the dynamic and differentiated data demand of the end consumers by their valuations for data consumption and their usage patterns. Specifically, we consider a stylized model that segments the consumers into two types, H (for heavy) and L (light), with the H-type consumers constituting a (relatively small) fraction of the entire consumer base (for example, as we point out later, AT&T characterized their heavy users constituting about 5% of the total consumer base). These two types of consumers are characterized by their valuations for data consumption (V_H and V_L where $V_H > V_L$) and their usage patterns (λ_H and λ_L where $\lambda_H > \lambda_L$). We will discuss these user characteristics in greater detail in next section. Under the current scenario (which can be thought of as the net neutrality model with a uniform fixed fee pricing strategy), all users are charged the same fixed price for accessing broadband content. Both types of users face similar delays while accessing their desired content – the delay arises from the fact that the users' packets are serviced by the broadband service provider who has a fixed capacity. Facing this heterogeneous user data demand, broadband service providers have two potential instruments for user discrimination – price discrimination and traffic prioritization. If the BSP is allowed to differentially charge its users and/or prioritize their requested content, we explore six different strategies that it might employ:

1. Broadband user traffic from different user types face the same delay, and all users are charged the same fixed fee (i.e., the status quo).
2. Broadband user traffic from different user types face the same delay, and different types of users are charged different fixed fees.
3. Broadband user traffic from different user types face the same delay, and different types of users are charged a two-part tariff.
4. Broadband user traffic from different user types face different delays, and all users are charged the same fixed fee.
5. Broadband user traffic from different user types face different delays, and different types of users are charged different fixed fees.
6. Broadband user traffic from different user types face different delays, and different types of users are charged a two-part tariff.

The first three options (where all the broadband users face the same delay for their packets) cover different pricing strategies under net neutrality (or NN for short), while the last three options cover the different pricing strategies under no net neutrality (NNN). Another way to look at these options would be to think of the first three as representing the strategies that the BSP can adopt if it is allowed to use only price discrimination, while the last three would represent strategies where the BSP is allowed to use both price and traffic prioritization as discriminating tools. These six different options help us model a broad swath of strategies that a BSP might employ under and in the absence of net neutrality. Depending on the characteristics of users' valuations for content and their usage patterns, different types of pricing and traffic prioritization regimes yield different profits for the BSP. However the optimal choice for the BSP might not coincide with that of a policymaker who intends to maximize the total social surplus. The results of the analysis should therefore be useful both for the broadband service providers as they mull over the introduction of the different pricing/prioritization strategies in an age where consumers increasingly get their information and entertainment online, and for policymakers who might wish to regulate the BSPs' practice of user discrimination in order to maximize social surplus.

We find that with net neutrality in place, the BSP would prefer to charge a two-part tariff for Internet access, but without net neutrality, a BSP may choose to charge a uniform price and degrade heavy users or else charge a higher price to high type users for preferential delivery of their data packets, depending on the characteristics of users' valuations for content and their usage patterns. Without net neutrality in place, we find that degrading the experience of the heavy users increases social welfare. Finally, we also identify conditions under which the BSP's user discrimination choice deviate from the social optimum. The last result helps establish the criteria under which the social planner might wish to regulate the BSP's actions in order to maximize the social surplus.

The remainder of the paper is organized as follows: In next section, we propose a stylized model of the BSP's pricing mechanisms in the context of net neutrality. We then analyze the BSP's pricing options under net neutrality (Section 3), followed by a similar analysis of the BSP's pricing options in the absence of net neutrality (Section 4). This enables us to compare the different alternatives and examine the joint impact of pricing and traffic prioritization mechanisms from the perspectives of the BSP (Section 5) and the social planner (Section 6) respectively. Section 7 concludes with a summary of our findings and some directions for future research.

2. The Model

We assume a monopolist BSP who provides Internet access to the end consumers. While the monopoly assumption is a simplification in some geographies, it is to be noted that unlike many other countries, the extent of competition in the local broadband services market is very limited in the United States, so much so that in many places, a single broadband service provider is often a de facto monopolist (Hausman et al. 2001; Economides 2008). Some of the factors leading to this scenario are the high switching costs induced by long-term service contracts and by incompatible broadband technologies between cable and phone companies. Further, many customers are not qualified for DSL broadband services from phone companies because they exceed the maximal distance limit from the phone company's nearest switching office, making the cable operators the only feasible broadband service providers in several local markets (Turner 2007). Thus, in addition to providing the benefit of making the analysis tractable, the assumption closely reflects the reality of local broadband services in the U.S. market.

To model the demand for broadband Internet access service, we consider a unit mass of end consumers. As mentioned earlier, we assume that there are two types of users: a fraction α of H-type consumers and $1-\alpha$ fraction of L-type consumers. High-type users request more content (the requested rate of data packets by the two user types are given by λ_H and λ_L respectively, where $\lambda_H > \lambda_L$) and have higher valuation for that content ($V_H > V_L$) than the Low-type users. Considering the consumers' heterogeneous demand patterns, the BSP may charge a uniform fixed fee (F) per unit time to all consumers; different fixed fees (F_H and F_L) per unit time to different types of consumers; or a usage-based fee (p) per packet to consumers for Internet access, a pricing strategy that has been already employed in some Scandinavian countries (Economist 2003; Bandyopadhyay and Cheng 2006). Since the consumers are serviced by the

BSP which has a fixed network infrastructure capacity, the former encounter a disutility while they wait for the packets to arrive. The consumers' utility function thus takes the following form:

$$u_i = \begin{cases} V_i - w_i - F, & \text{if the BSP charges a uniform fixed fee} \\ V_i - w_i - F_i, & \text{if the BSP charges differential fixed fee} \\ V_i - w_i - F - \lambda_i p, & \text{if the BSP charges two-part tariff} \end{cases} \tag{1}$$

where $i = H$ or L and w_i is the delay cost for type i consumers.

Consumers request data from various websites and the requested data packets are transmitted through the BSP's network. We model the congestion in the network after (Mendelson 1985; Bandyopadhyay and Cheng 2006), and accordingly, consumers' request for data packets follows a Poisson process with arrival rate λ_H and λ_L for H-type and L-type consumers respectively. The gross valuations the two types of consumers receive are denoted by V_H and V_L. Consumers face a delay cost due to network congestion during the data transmission process. The BSP's capacity is fixed and denoted by μ. As noted in the afore-mentioned literature, we assume an M/M/1 queue to model the data transmission service provided by the BSP under net neutrality. Then the time that a data packet spent in the system is $\frac{1}{\mu - \lambda}$ (when net neutrality is enforced, i.e., when no packet has priority over another) and the corresponding delay cost is $\frac{d}{\mu - \lambda}$ where d is the delay parameter that captures the unit cost of delay for consumers waiting for the content to arrive from the websites. We summarize all the notations in Table 1.

--Insert Table 1 about here--

The delay cost for the consumers under net neutrality is:

$$w_i = \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}, \ i = H \text{ or } L \tag{2}$$

In the absence of net neutrality, the BSP may prioritize data traffic based on user types. In this context, we note that the technology to discriminate packets and streamline Internet traffic has been available at minimal cost, and we therefore assume that there is no additional expense incurred by the BSP to implement a mechanism that enables preferential delivery of content (Cheng et al. 2009). We use a two-class priority queue to model the BSP's data transmission service. If both H-type and L-type consumers receive the same priority for their traffic, then the congestion cost and the corresponding utility function would remain the same as in equation (2). However, if H-type consumers receive higher priority while L-type consumers receive lower priority, then the delay costs for the two types are as follows:

$$w_H = \frac{d}{\mu - \alpha\lambda_H},\ w_L = \frac{d\mu}{(\mu - \alpha\lambda_H)\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} \tag{3}$$

On the other hand, if L-type consumers receive higher priority while H-type consumers receive lower priority, then the delay costs for the two types are given by the following expressions:

$$w_H = \frac{d\mu}{\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]},\ w_L = \frac{d}{\mu - (1-\alpha)\lambda_L} \tag{4}$$

In terms of pricing, the BSP may charge a uniform fixed fee to all consumers or charge different fixed fees to different types of consumers for Internet access. The potential regulation of net neutrality limits the BSP from selectively prioritizing the Internet traffic. In the absence of net neutrality, the BSP can also discriminate against different types of consumers through traffic prioritization. In the next two sections, we model these scenarios.

3. Net Neutrality

In this section, we analyze three potential pricing structures for the BSP under net neutrality – uniform fixed fee, differential fixed fees and charging a two-part tariff.

Option NN1: Uniform fixed fee under net neutrality

Under net neutrality all consumers receive the same priority and therefore face the same congestion for data transmission. The most simple and common pricing mechanism for the BSP is to charge a uniform fixed fee for all consumers. The BSP's profit maximization problem is formulated as follows:

$$\begin{aligned}&\max_{F_{\text{NN1}}} \pi_{\text{NN1}} = F_{\text{NN1}} \\ &\text{s.t.} \quad V_H - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - F_{\text{NN1}} \geq 0 \quad (i) \\ &\qquad\; V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - F_{\text{NN1}} \geq 0 \quad (ii)\end{aligned} \tag{5}$$

Constraint (*i*) is the participation constraint for H-type consumers and constraint (*ii*) is the participation constraint for L-type consumers. Since $V_H > V_L$, the BSP will charge a fixed access fee that is high enough to just keep the L-type consumers to participate, i.e.,

$F^*_{\text{NN1}} = V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$, and the BSP then receives a corresponding profit of

$\pi^*_{\text{NN1}} = F^*_{\text{NN1}} = V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$.

The corresponding consumer surplus, defined as the sum of the utility of all consumers, is given by

$$\text{CS}_{\text{NN1}} = \alpha\left(V_H - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - F_{\text{NN1}}\right) + (1-\alpha)\left(V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - F_{\text{NN1}}\right)$$

$= \alpha(V_H - V_L)$, and the social welfare, defined as the sum of both the BSP's profit and consumer surplus, is $\text{SW}_{\text{NN1}} = \pi^*_{\text{NN1}} + \text{CS}_{\text{NN1}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$.

Option NN2: Differential fixed fees under net neutrality

It is easy to see that this option reduces to the option NN1 above. This is because the BSP has just one service offering at its disposal, and therefore will not be able to differentiate between the two classes of users by using different prices (if the two user types are offered two different price points, the H-type users will always choose the lower price, as would the L-type users). The formal statement of the BSP's profit maximization problem is as follows:

$$\max_{F_{\mathrm{NN2\_H}},F_{\mathrm{NN2\_L}}} \pi_{\mathrm{NN2}} = \alpha F_{\mathrm{NN2\_H}} + (1-\alpha) F_{\mathrm{NN2\_L}}$$

$$\begin{aligned}
\text{s.t.}\quad & V_H - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L} - F_{\mathrm{NN2_H}} \ge 0 && (i) \\
& V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L} - F_{\mathrm{NN2_L}} \ge 0 && (ii) \\
& V_H - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L} - F_{\mathrm{NN2_H}} \ge V_H - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L} - F_{\mathrm{NN2_L}} && (iii) \\
& V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L} - F_{\mathrm{NN2_L}} \ge V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L} - F_{\mathrm{NN2_H}} && (iv)
\end{aligned} \tag{6}$$

Constraints (*i*) and (*ii*) are participation constraints for H-type and L-type consumers respectively. Constraints (*iii*) and (*iv*) are incentive compatibility constraints for H-type and L-type consumers respectively. Constraint (*iii*) can be reduced to $F_{\mathrm{NN2\_H}} \le F_{\mathrm{NN2\_L}}$ and Constraint (*iv*) can be reduced to $F_{\mathrm{NN2\_H}} \ge F_{\mathrm{NN2\_L}}$. So $F_{\mathrm{NN2\_H}} = F_{\mathrm{NN2\_L}}$. As a result, under net neutrality Option NN2 can be reduced to Option NN1 with $\pi^*_{\mathrm{NN2}} = F^*_{\mathrm{NN2\_H}} = F^*_{\mathrm{NN2\_L}} = V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}$.

The corresponding consumer surplus will still be $\mathrm{CS}_{\mathrm{NN2}} = \alpha(V_H - V_L)$, and the social welfare will be given by $\mathrm{SW}_{\mathrm{NN2}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}$.

Option NN3: Two-part tariff under net neutrality

Under this option, the BSP charges a two-part tariff for Internet access – a lump-sum fee F and a per-unit charge p. Under net neutrality, the BSP cannot prioritize any user's requested content. The BSP's profit maximization problem is:

$$\max_{F_{\text{NN3}},\, p_{\text{NN3}}} \pi_{\text{NN3}} = F_{\text{NN3}} + \left[\alpha\lambda_H + (1-\alpha)\lambda_L\right] p_{\text{NN3}}$$
$$\text{s.t.} \quad V_H - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - F_{\text{NN3}} - \lambda_H p_{\text{NN3}} \geq 0 \quad (i)$$
$$V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - F_{\text{NN3}} - \lambda_L p_{\text{NN3}} \geq 0 \quad (ii) \tag{7}$$

Constraint (i) is the participation constraint for H-type consumers and constraint (ii) is the participation constraint for L-type consumers. By solving the BSP's problem (see Appendix A for derivation details), we find when the two types of consumers' valuations for data consumption are comparable (we denote this as Case NN3_1, with the exact criterion being $V_H \leq \frac{\lambda_H V_L}{\lambda_L} - \frac{d(\lambda_H - \lambda_L)}{\lambda_L\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$), the BSP will charge a positive lump-sum fee $F^*_{\text{NN3\_1}} = \frac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$ and a positive usage-based fee $p^*_{\text{NN3\_1}} = \frac{V_H - V_L}{\lambda_H - \lambda_L}$; however, if the two types of consumers differ significantly in their valuations for their requested content (or more precisely, if $V_H > \frac{\lambda_H V_L}{\lambda_L} - \frac{d(\lambda_H - \lambda_L)}{\lambda_L\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$, which we denote as Case NN3_2), the BSP will charge a *zero* lump-sum fee and rely only on usage-based fee: $F^*_{\text{NN3\_2}} = 0$ and $p^*_{\text{NN3\_2}} = \frac{1}{\lambda_L}\left[V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right]$. The corresponding consumer surpluses are $\text{CS}_{\text{NN3\_1}} = 0$ and $\text{CS}_{\text{NN3\_2}} = \alpha\left\{\left[\frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right]\left(\frac{\lambda_H - \lambda_L}{\lambda_L}\right) - \left(\frac{\lambda_H V_L - \lambda_L V_H}{\lambda_L}\right)\right\}$. The resulting social welfare is $\text{SW}_{\text{NN3\_1}} = \text{SW}_{\text{NN3\_2}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$. Note that under Case NN3_1, the entire consumer surplus is extracted away completely by the BSP.

4. No Net Neutrality (NNN)

In this section, we consider the BSP's three pricing options (uniform fixed fee, differential fixed fees and two-part tariff) under NNN. In the absence of any net neutrality regulation, broadband service providers have one extra set of instruments to discriminate between end users: the BSP may assign different priorities to different types of traffic. Technically, BSPs first identify the data destination by inspecting data packets transmitted through the network. The BSPs then either charge the same access fee for both two types and downgrade data transmission for heavy users (H-type consumers in our model) or charge a higher access fee and then assign a higher priority for the data packets requested by H-type consumers. Just as we analyzed the pricing strategies under NN, we now look into the three analogous pricing regimes under NNN.

Option NNN1: Uniform fixed fee under no net neutrality

When the BSP charge a uniform price to both types of the consumers, it has the incentive to assign a lower priority to data packets from H-type users because of their heavy use of the shared bandwidth. The BSP's decision problem can be formulated as:

$$\begin{aligned}
&\max_{F_{\text{NNN1}}} \pi_{\text{NNN1}} = F_{\text{NNN1}} \\
&\text{s.t.} \quad V_H - \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - F_{\text{NNN1}} \geq 0 \quad (i) \\
&\qquad\; V_L - \frac{d}{\mu-(1-\alpha)\lambda_L} - F_{\text{NNN1}} \geq 0 \quad (ii)
\end{aligned} \tag{8}$$

Constraint (*i*) is the participation constraint for H-type consumers (reflecting their higher wait times in the prioritized queue) and constraint (*ii*) is the participation constraint for L-type consumers. Notice that we assume $V_H \geq \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$ to ensure that this scenario is feasible. Both constraints give upper bounds for the access fee F_{NNN1}. We can derive the equilibrium by comparing the two upper bounds.

Case NNN1_1: If $V_L - \frac{d}{\mu-(1-\alpha)\lambda_L} \le V_H - \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, i.e.,

$V_H - V_L \ge \frac{d\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, then

$\pi^*_{\text{NNN1\_1}} = F^*_{\text{NNN1\_1}} = V_L - \frac{d}{\mu-(1-\alpha)\lambda_L}$. The corresponding consumer surplus is

$$\begin{aligned}
\text{CS}_{\text{NNN1_1}} &= \alpha\left(V_H - \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - F_{\text{NNN1_1}}\right) \\
&+(1-\alpha)\left(V_L - \frac{d}{\mu-(1-\alpha)\lambda_L} - F_{\text{NNN1_1}}\right) \\
&= \alpha\left[V_H - V_L - \frac{d}{\mu-(1-\alpha)\lambda_L}\cdot\frac{\alpha\lambda_H+(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right].
\end{aligned}$$

The expression for social welfare is

$$\begin{aligned}
\text{SW}_{\text{NNN1_1}} &= \pi^*_{\text{NNN1_1}} + \text{CS}_{\text{NNN1_1}} \\
&= \alpha\left(V_H - \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right) + (1-\alpha)\left(V_L - \frac{d}{\mu-(1-\alpha)\lambda_L}\right).
\end{aligned}$$

Case NNN1_2: If $V_H - V_L < \frac{d\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, then

$$\pi^*_{\text{NNN1\_2}} = F^*_{\text{NNN1\_2}} = V_H - \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}.$$

The corresponding consumer surplus is

$$\begin{aligned}
\text{CS}_{\text{NNN1_2}} &= \alpha\left(V_H - \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - F_{\text{NNN1_2}}\right) \\
&+(1-\alpha)\left(V_L - \frac{d}{\mu-(1-\alpha)\lambda_L} - F_{\text{NNN1_2}}\right)
\end{aligned}$$

$$=(1-\alpha)\left\{-V_H+V_L+\frac{d}{\mu-(1-\alpha)\lambda_L}\cdot\frac{\alpha\lambda_H+(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right\},$$

and the corresponding social welfare is given by the following expression:

$$\begin{aligned}&\mathrm{SW}_{\mathrm{NNN1\_2}}=\pi^*_{\mathrm{NNN1\_2}}+\mathrm{CS}_{\mathrm{NNN1\_2}}\\&=\alpha\left(V_H-\frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right)+(1-\alpha)\left(V_L-\frac{d}{\mu-(1-\alpha)\lambda_L}\right)\cdot\end{aligned}$$

Option NNN2: Differential fixed fees under no net neutrality

Under this option, the BSP charges a higher price for higher quality of the data transmission service through the Internet. Specifically, the BSP would offer the Internet access service with congestion cost $\frac{d}{\mu-\alpha\lambda_H}$ at a fixed price $F_{\mathrm{NNN2\_H}}$ to H-type consumers and the Internet access service with congestion cost $\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$ at a fixed price $F_{\mathrm{NNN2\_L}}$ to L-type consumers. The BSP's profit maximization problem is then as follows:

$$\begin{aligned}&\max_{F_{\mathrm{NNN2\_H}},F_{\mathrm{NNN2\_L}}}\ \pi_{\mathrm{NNN2}}=\alpha F_{\mathrm{NNN2\_H}}+(1-\alpha)F_{\mathrm{NNN2\_L}}\\&\text{s.t.}\quad V_H-\frac{d}{\mu-\alpha\lambda_H}-F_{\mathrm{NNN2\_H}}\ge 0 &(i)\\&\qquad V_L-\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}-F_{\mathrm{NNN2\_L}}\ge 0 &(ii)\\&\qquad V_H-\frac{d}{\mu-\alpha\lambda_H}-F_{\mathrm{NNN2\_H}}\ge V_H-\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}-F_{\mathrm{NNN2\_L}} &(iii)\\&\qquad V_L-\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}-F_{\mathrm{NNN2\_L}}\ge V_L-\frac{d}{\mu-\alpha\lambda_H}-F_{\mathrm{NNN2\_H}} &(iv)\end{aligned}\tag{9}$$

Constraint (*i*) is the participation constraint for H-type consumers and constraint (*ii*) is the participation constraint for L-type consumers. Notice that we assume

$V_L \geq \dfrac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$ to ensure the feasibility of this outcome. Constraints (*iii*) and (*iv*) are incentive compatibility constraints for H-type and L-type consumers respectively. Constraint (*iii*) can be reduced to

$$F_{\mathrm{NNN2\_H}} - F_{\mathrm{NNN2\_L}} \leq \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - \frac{d}{\mu-\alpha\lambda_H}.$$

Constraint (*iv*) can be reduced to

$$F_{\mathrm{NNN2\_H}} - F_{\mathrm{NNN2\_L}} \geq \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - \frac{d}{\mu-\alpha\lambda_H}.$$

Therefore, $F_{\mathrm{NNN2\_H}} - F_{\mathrm{NNN2\_L}} = \dfrac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - \dfrac{d}{\mu-\alpha\lambda_H}$.

From constraint (*i*), we get $F_{\mathrm{NNN2\_H}} \leq V_H - \dfrac{d}{\mu-\alpha\lambda_H}$.

From constraint (*ii*), we get $F_{\mathrm{NNN2\_L}} \leq V_L - \dfrac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$.

Since $\left\{V_H - \dfrac{d}{\mu-\alpha\lambda_H}\right\} - \left\{V_L - \dfrac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right\}$

$> \dfrac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - \dfrac{d}{\mu-\alpha\lambda_H}$, $F^*_{\mathrm{NNN2\_H}} = V_L - \dfrac{d}{\mu-\alpha\lambda_H}$,

$F^*_{\mathrm{NNN2\_L}} = V_L - \dfrac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, and

$$\pi^*_{\mathrm{NNN2}} = \alpha F^*_{\mathrm{NNN2\_H}} + (1-\alpha)F^*_{\mathrm{NNN2\_L}} = V_L - \frac{d}{\mu-\alpha\lambda_H}\left[\frac{\mu-\alpha^2\lambda_H-\alpha(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right].$$

The corresponding consumer surplus is

$$\mathrm{CS}_{\mathrm{NNN2}} = \alpha\left(V_H - \frac{d}{\mu-\alpha\lambda_H} - F_{\mathrm{NNN2\_H}}\right) + (1-\alpha)\left(V_L - \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - F_{\mathrm{NNN2\_L}}\right) = \alpha(V_H - V_L)$$

, and the social welfare is given by

$$\mathrm{SW}_{\mathrm{NNN2}} = \pi^*_{\mathrm{NNN2}} + \mathrm{CS}_{\mathrm{NNN2}} = \alpha\left(V_H - \frac{d}{\mu-\alpha\lambda_H}\right) + (1-\alpha)\left(V_L - \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right).$$

Option NNN3: Two-part tariff under no net neutrality

Under this scenario, the BSP charges the H-type consumers a two-part tariff to ensure a preferential delivery of their data packets, while the L-type consumers are charged only a lump-sum fee for their data delivery (which involves a higher delay). The BSP's decision problem can be formulated as:

$$\max_{F_{\mathrm{NNN3}},\,p_{\mathrm{NNN3}}} \pi_{\mathrm{NNN3}} = F_{\mathrm{NNN3}} + \alpha\lambda_{\mathrm{H}}\, p_{\mathrm{NNN3}}$$

$$\text{s.t.}\quad V_H - \frac{d}{\mu-\alpha\lambda_H} - F_{\mathrm{NNN3}} - \lambda_{\mathrm{H}}\, p_{\mathrm{NNN3}} \geq 0 \qquad (i)$$

$$V_L - \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - F_{\mathrm{NNN3}} \geq 0 \qquad (ii)$$

$$V_H - \frac{d}{\mu-\alpha\lambda_H} - F_{\mathrm{NNN3}} - \lambda_{\mathrm{H}}\, p_{\mathrm{NNN3}} \geq V_H - \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - F_{\mathrm{NNN3}} \qquad (iii)$$

$$V_L - \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - F_{\mathrm{NNN3}} \geq V_L - \frac{d}{\mu-\alpha\lambda_H} - F_{\mathrm{NNN3}} - \lambda_{\mathrm{H}}\, p_{\mathrm{NNN3}} \qquad (iv)$$

(10)

Constraint (*i*) is the participation constraint for H-type consumers and constraint (*ii*) is the participation constraint for L-type consumers. Constraints (*iii*) and (*iv*) are incentive compatibility constraints for H-type and L-type consumers respectively. Constraint (*iii*) can be reduced to

$$p_{\text{NNN3}} \le \frac{1}{\lambda_{\text{H}}}\left\{\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}-\frac{d}{\mu-\alpha\lambda_H}\right\}$$

Constraint (*iv*) can be reduced to

$$p_{\text{NNN3}} \ge \frac{1}{\lambda_{\text{H}}}\left\{\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}-\frac{d}{\mu-\alpha\lambda_H}\right\}.$$

So $p^*_{\text{NNN3}} = \frac{1}{\lambda_{\text{H}}}\left\{\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_{\text{H}}-(1-\alpha)\lambda_{\text{L}}\right]}-\frac{d}{\mu-\alpha\lambda_H}\right\}.$

Substituting back to constraint (*i*) gives

$$F_{\text{NNN3}} \le V_H - -\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}.$$

Constraint (*ii*) implies $F_{\text{NNN3}} \le V_L - \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$.

So $F^*_{\text{NNN3}} = V_L - \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$ and

$$\pi^*_{\text{NNN3}} = F^*_{\text{NNN3}} + \alpha\lambda_{\text{H}}\, p^*_{\text{NNN3}} = V_L - \frac{d}{\mu-\alpha\lambda_H}\left[\frac{\mu-\alpha^2\lambda_H-\alpha(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right].$$

The corresponding consumer surplus is

$$\begin{aligned}\text{CS}_{\text{NNN3}} &= \alpha\left(V_H-\frac{d}{\mu-\alpha\lambda_H}-F_{\text{NNN3}}-\lambda_{\text{H}}\, p_{\text{NNN3}}\right)\\ &+(1-\alpha)\left(V_L-\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}-F_{\text{NNN3}}\right)=\alpha\left(V_H-V_L\right)\end{aligned}.$$

Therefore the social welfare is $\text{SW}_{\text{NNN3}} = \pi^*_{\text{NNN3}} + \text{CS}_{\text{NNN3}}$

$$=\alpha\left(V_H-\frac{d}{\mu-\alpha\lambda_H}\right)+(1-\alpha)\left(V_L-\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right).$$

Based on the BSP's pricing and traffic prioritization strategies, the BSP has six options and we summarize these six options in the Table 2.

--Insert Table 2 about here--

In the previous two sections, we have analyzed the BSP's six options involving pricing and (under NNN) different priorities for different user classes. In the next section, we compare these different options, and thus explore the conditions under which the BSP might choose any one of them.

5. The BSP's Choices

In this section we study the effects of pricing structure and traffic prioritization on the BSP's profit.

The BSP's preference for pricing structure under net neutrality (choice between three options NN1, NN2, NN3)

Under net neutrality, the BSP is limited to just the pricing mechanisms to discriminate between the different user types. Comparing the BSP's three pricing options (NN1, NN2 and NN3) under net neutrality yields $\pi^*_{\mathrm{NN3\_1}} > \pi^*_{\mathrm{NN1}} = \pi^*_{\mathrm{NN2}}$ and $\pi^*_{\mathrm{NN3\_2}} > \pi^*_{\mathrm{NN1}} = \pi^*_{\mathrm{NN2}}$. This result is summarized in the following proposition.

Proposition 1: (BSP's preferred pricing structure under net neutrality)

Under net neutrality, the BSP prefers a two-part tariff.

Proof: See Appendix B.

The BSP's preference for pricing structure under no net neutrality (choice between three options NNN1, NNN2, NNN3)

In the absence of net neutrality, the BSP may either charge the same price to both types of consumers and set a lower priority to data packets from H-type consumers (NNN1), or charge a higher price and set a higher priority to H-type consumers (NNN2), or charge H-type consumers a usage-based fee to get a higher priority (NNN3). The first option yields profit levels

$$\pi^*_{\text{NNN1\_1}} = V_L - \frac{d}{\mu-(1-\alpha)\lambda_L} \text{ if } V_H - V_L \geq \frac{d\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} \text{ or}$$

$$\pi^*_{\text{NNN1\_2}} = V_H - \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} \text{ if}$$

$V_H - V_L < \frac{d\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$. The second and third option generates the same profit level for the BSP, i.e., $\pi^*_{\text{NNN2}} = \pi^*_{\text{NNN3}} = V_L - \frac{d\left[\mu-\alpha^2\lambda_H - \alpha(1-\alpha)\lambda_L\right]}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$.

Comparing the three options, we find that if $V_H - V_L \geq \frac{d\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$ then $\pi^*_{\text{NNN1\_1}} > \pi^*_{\text{NNN2}} = \pi^*_{\text{NNN3}}$ i.e., when H-type consumers value their requested content more than the L-type consumers beyond a threshold, the BSP benefits from charging the same price to both types and assigning a lower priority to traffic from H-type consumers. If on the other hand $V_H - V_L < \frac{d\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, then $\pi^*_{\text{NNN1\_2}} < \pi^*_{\text{NNN2}} = \pi^*_{\text{NNN3}}$., i.e., when H-type consumers and L-type consumers have similar valuation for content, the BSP prefers to charge a higher price and in return offer preferential delivery to the data packets from the H-type consumers. This leads to our next proposition.

Proposition 2: (BSP's preferred pricing structure under no net neutrality)

(*i*) If $V_H - V_L \geq \frac{d\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, $\pi^*_{\text{NNN1}} = \pi^*_{\text{NNN1\_1}} > \pi^*_{\text{NNN2}} = \pi^*_{\text{NNN3}}$;

(*ii*) If

$$\frac{d(1-\alpha)\left\{(\lambda_L - \alpha\lambda_H)\mu + \alpha\lambda_L\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]\right\}}{(\mu-\alpha\lambda_H)\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} \leq V_H - V_L < \frac{d\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]},$$

$\pi^*_{\text{NNN1}} = \pi^*_{\text{NNN1\_2}} > \pi^*_{\text{NNN2}} = \pi^*_{\text{NNN3}}$;

(*iii*) If $V_H - V_L < \dfrac{d(1-\alpha)\left\{(\lambda_L - \alpha\lambda_H)\mu + \alpha\lambda_L\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]\right\}}{(\mu - \alpha\lambda_H)\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$,

$\pi^*_{\text{NNN1}} = \pi^*_{\text{NNN1\_2}} < \pi^*_{\text{NNN2}} = \pi^*_{\text{NNN3}}$.

Proof: See Appendix C.

The BSP's overall preference for pricing structure (choice between the six options NN1, NN2, NN3, NNN1, NNN2, NNN3)

In this subsection we address the question of what would be the equilibrium outcome if the BSP is given all six user discrimination options. Proposition 3 summarizes the comparison result of all six options.

Proposition 3: (BSP's overall preferred pricing structure)

There are two potential preferred pricing structures for the BSP: NN3 or NNN1, depending on the parameter values.

Proof: See Appendix D.

We illustrate these results by adopting some real-life parameter values. AT&T has recently estimated that their top 5% of users (in terms of usage) account for about 40% of the total traffic, i.e., $\alpha = 0.05$ and $\dfrac{\alpha\lambda_H}{\alpha\lambda_H + (1-\alpha)\lambda_L} = 0.4$ (Tweney 2008). Using these parameter values, Figure 2 depicts the BSP's overall preferred pricing/prioritization strategy for such a traffic pattern in the $V_H - V_L$ space. The BSP prefers an NN3 outcome (two-part tariff with equal priority) in the shaded area and it prefers an NNN1 outcome (uniform fixed fee with low priority for heavy users) in the un-shaded area. The area marked by the bold lines represents the feasible parameter space. The different intercepts C_0, C_1, etc. on the two axes (the precise values of these intercepts have been defined at the beginning of the Appendices) and the straight lines emanating from them represent the different regions (marked by numbers 1 through 7) in the parameter space within which we have to consider the optimal regime choice for the BSP.

--Insert Figure 2 about here—

A different traffic pattern would change the slope of the line that has the intercept of $-C_0$, but would not materially change the nature of the outcome – there would still be some regions where the BSP would opt for the NN3 outcome and the rest of the feasible region where the BSP would opt for the NNN1 outcome.

6. The Social Planner's Preference for Pricing Structure

As outlined before, the choice of the social planner with regards to the pricing/prioritization regime might be at odds with that of the BSP, since social welfare is the sum of the BSP's profit and the consumers' surplus. Note that since the consumers' payments for the broadband services are effectively internal transfers as far as the calculation of the social welfare is concerned, the only measurable effect of the consumers on the social welfare comes from their valuation and the disutility that they attribute towards the congestion.

The social planner's preference for pricing structure under net neutrality (NN1, NN2, NN3)

In this subsection, we examine the social planner's preference for different pricing structures under net neutrality by comparing the social welfare levels when the BSP adopts the three pricing structures. The following proposition summarizes the analysis.

Proposition 4: (Social planner's preferred pricing structure under net neutrality)

When net neutrality is in place, social welfare is the same for one-level fixed fee, two-level fixed fee, and two-part tariff, i.e., $\mathrm{SW}_{\mathrm{NN1}} = \mathrm{SW}_{\mathrm{NN2}} = \mathrm{SW}_{\mathrm{NN3}}$. This is expected, since the effect of pricing is internalized, and there are no other effects to consider, as traffic prioritization is not allowed under net neutrality.

The social planner's preference for pricing structure under no net neutrality (NNN1, NNN2, NNN3)

In this subsection, we examine the social planner's preference for different pricing structures under no net neutrality by comparing the social welfare levels when the BSP adopts the three pricing structures. Propositions 5 and 6 summarize the results.

Proposition 5: (Social planner's preferred pricing structure under no net neutrality)

Without net neutrality, the social planner always prefers the BSP charging a uniform fixed fee while downgrading heavy users, i.e., $\mathrm{SW}_{\mathrm{NNN1}} > \mathrm{SW}_{\mathrm{NNN2}} = \mathrm{SW}_{\mathrm{NNN3}}$.

Proof: See Appendix E.

The social planner's overall preference for pricing structure (NN1, NN2, NN3, NNN1, NNN2, NNN3)

Proposition 6: (Social planner's overall preferred pricing structure)

$\mathrm{SW}_{\mathrm{NNN1}} > \mathrm{SW}_{\mathrm{NN1}} = \mathrm{SW}_{\mathrm{NN2}} = \mathrm{SW}_{\mathrm{NN3}} > \mathrm{SW}_{\mathrm{NNN2}} = \mathrm{SW}_{\mathrm{NNN3}}$

Proof: See Appendix F.

Differences between the BSP's and the social planner's preferences

Based on Proposition 1-6, we can see the BSP has incentive to deviate in its pricing choice from the social optimum. We summarize the differences in Proposition 7.

Proposition 7: (The BSP's deviation from social optimum)

The BSP's preference differs from the social planner's preference under two scenarios:

(1) $V_H > V_L + \dfrac{d\lambda_H}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$ and

$V_L > \dfrac{d\left\{\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]\lambda_L+\mu(\lambda_H-\lambda_L)\right\}}{(\lambda_H-\lambda_L)\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$; and

(2) $V_H \leq \frac{\lambda_H V_L}{\lambda_L} - \frac{d\left(\lambda_H - \lambda_L\right)}{\lambda_L\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$ and

$$V_L < V_H < V_L + \frac{d\lambda_L}{\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}.$$

Proof: See Appendix G.

The above set of results is very interesting in the context of the net neutrality debate. As we mentioned in the introduction, all the extant literature that covers the economic aspects of the net neutrality debate have concentrated on the 'supply' side of the equation (i.e., the issue whether the BSP should charge content providers for the priority delivery of their content), and the results in such analyses have shown that for almost all parameter values, the BSP would prefer an NNN outcome over an NN outcome, even though from a social planner's perspective, an NN outcome would be preferable (see for example (Cheng et al. 2009)). In such situations, it would often make sense for the social planner to regulate net neutrality on the 'supply' side. When we however concentrate on the 'demand' side of the net neutrality debate, we find that while there are once again scenarios under which the social planner would deviate from the BSP's choice, the deviation is towards an *NNN* outcome: the social planner would rather have the BSP choose to degrade the quality of the heavy users (and thereby opt for a *no* net neutrality outcome), but instead the BSP ends up choosing a two-part tariff that falls under the ambit of net neutrality. This represents a dilemma for the social planner: while he can decide between enforcing a net neutrality regime and not enforcing it, he however cannot enforce that the BSP chooses a NNN outcome when it is given the choice.

The results also help illustrate the complexity of the net neutrality debate. While there is growing evidence that a net neutrality regime might be preferable when it comes to charging content providers, the results in this paper illustrate that there are conditions under which NNN might be the preferred outcome when it comes to charging consumers for preferential delivery of their requested packets. As some industry observers have recently commented, the same network neutrality rules that ensure higher social welfare by prohibiting the BSP from charging online content providers might actually protect “bandwidth hogs” at the expense of Internet users with average usage patterns (McDougall 2008).

While the discussion might not be that clear-cut as our stylized model might suggest (for example, some commentators have pointed to the fact that these “bandwidth hogs” often help promote innovation on the Internet – see for example (Al-Chalabi 2008)), but we do hope that our results help promote the richness of the discourse on a very important subject that might well determine how online content is accessed in the future.

7. Conclusion

The debate of net neutrality and the potential regulation of net neutrality may fundamentally change the dynamics of data consumption and transmission through the Internet. In contrast to the extant literature that has looked at the problem from the ‘supply’ perspective, in this paper, we look at the issue from the ‘demand’ perspective. We examine the economic impact of net neutrality on the BSP and the society as a whole, if the former is not allowed to either prioritize or degrade the delivery of content to one class of users. We consider scenarios with and without net neutrality and analyze the problem of the monopoly broadband service provider trying out different pricing and prioritization strategies.

We find that the impact of net neutrality depends on both the characteristics of the Internet data consumption market and the BSP’s pricing strategies. We find that with net neutrality in place, the BSP would prefer to charge a two-part tariff for Internet access, but without net neutrality, a BSP may choose to charge a uniform price and degrade heavy users or else charge a higher price to high type users for preferential delivery of their data packets depending on the characteristics of users’ valuations for content and their usage patterns. Interestingly, we find that without net neutrality in place, degrading the experience of the heavy users increases social welfare, a practice that was recently banned by the FCC. The joint impact of both pricing and net neutrality under the framework of our model has potentially very important policy implications. We identify conditions under which the BSP's user discrimination choices deviate from the social optimum. The last result helps illustrate the social planner's dilemma: even though he might decide not to enforce net neutrality, there will still be scenarios under which the BSP would opt for a net neutrality solution that would be socially sub-optimal.

The involved nature of the problem and the surfeit of relevant parameters meant that we had to consider a stylized model in order to get analytical closure. In particular, we did not consider one issue that has been raised by some commentators – that of the possibility that a select few "power users" within a network have positive externalities that help other users and the BSP in the long run(Al-Chalabi 2008). While the veracity of such a claim can be debated, we think that future research can consider simulating the presence of such users within a network, and thus xamine the fallouts of their presence.

Figures and Tables

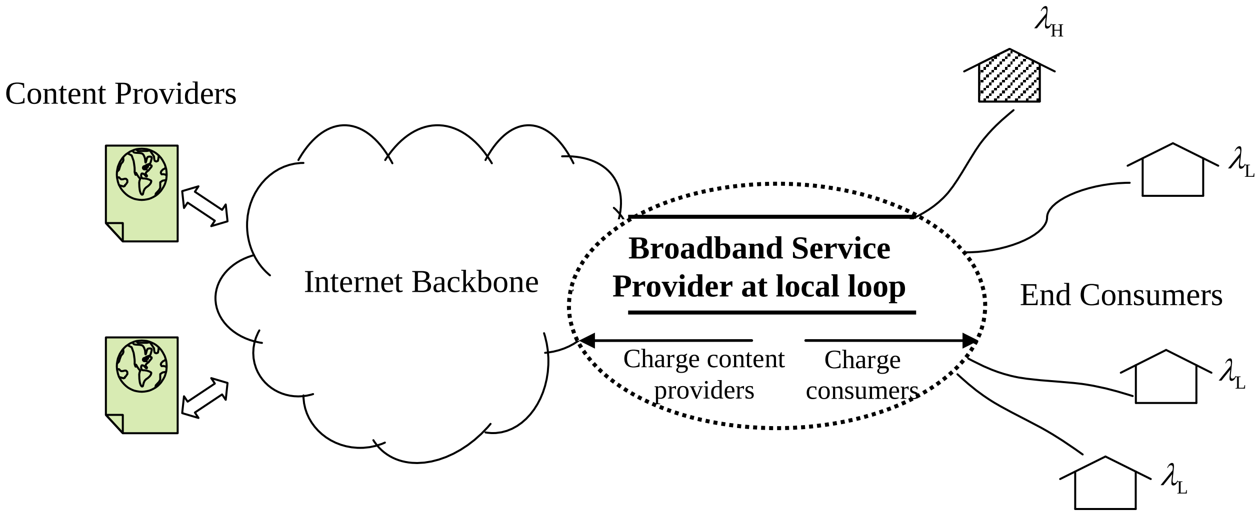
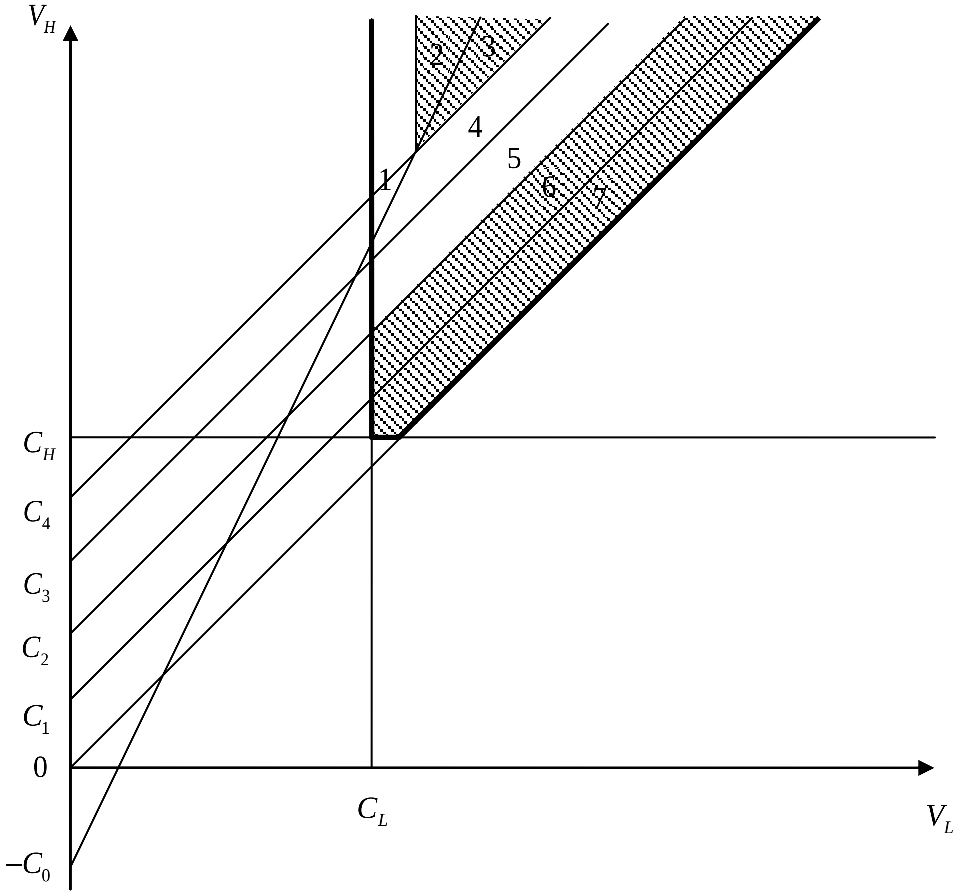


Figure 1: Schematic to show the two different aspects of the net neutrality debate. The heart of the net neutrality debate is at the local loop of the BSP. Here, the BSP can charge either the content providers or the end consumers in order to make a data packet "non-neutral"



Notes: (a) The area marked by the bold lines represents the feasible parameter space ($V_H \geq C_H$, and $V_L \geq C_L$, and $V_H > V_L$ where C_H and C_L are defined in the appendix). (b) The BSP's preferred option is: NNN1_1 for region 1, NN3_2 for region 2, NN3_1 for region 3, NNN1_1 for region 4, NNN1_2 for region 5, NN3_1 for region 6, and NN3_1 for region 7. (c) The shaded areas correspond to the regions where the BSP's preference is different from the social planner's preference.

Figure 2: The BSP's overall preference for pricing structure and how it differs from the social planner's preference

Table 1: List of Notations

Notation	Description
α	Percentage of H-type consumers
λ_H , λ_L	Rate of content requested from H-type and L-type consumers in packets per unit of time
V_H , V_L	The gross value function of retrieving content for H-type and L-type consumers respectively
F	A uniform fixed fee per unit of time charged by the BSP to end consumers
F_H , F_L	Fixed fees charged to H-type and L-type consumers respectively
p	Unit price per packet for data packet transmission
w_H , w_L	Consumers' delay cost (congestion cost) for H-type and L-type consumers respectively
μ	Capacity of the BSP in packets per unit of time
d	Consumers' delay parameter that converts the delay for consumers waiting for the content to arrive from the websites to the unit cost of delay per unit of time
u_H , u_L	The utility function for H-type and L-type consumers respectively
π_i	The BSP's profit, $i =$ NN1, NN2, NN3, NNN1, NNN2, NNN3
CS_i	Consumer surplus, $i =$ NN1, NN2, NN3, NNN1, NNN2, NNN3
SW_i	Social Welfare, $i =$ NN1, NN2, NN3, NNN1, NNN2, NNN3

Table 2: The BSP's Six Options

Options		Results
Net Neutrality	NN1	$\pi^*_{\text{NN1}} = F^*_{\text{NN1}} = V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$ $\text{CS}_{\text{NN1}} = \alpha(V_H - V_L)$ $\text{SW}_{\text{NN1}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$
	NN2	$\pi^*_{\text{NN2}} = F^*_{\text{NN2\_H}} = F^*_{\text{NN2\_L}} = V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$ $\text{CS}_{\text{NN2}} = \alpha(V_H - V_L)$ $\text{SW}_{\text{NN2}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$
	NN3	Case NN3_1: If $\frac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} \geq \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$, $F^*_{\text{NN3\_1}} = \frac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$, $p^*_{\text{NN3\_1}} = \frac{V_H - V_L}{\lambda_H - \lambda_L}$ $\pi^*_{\text{NN3\_1}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$ $\text{CS}_{\text{NN3\_1}} = 0$ $\text{SW}_{\text{NN3\_1}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$ Case NN3_2: If $\frac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} < \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$, $F^*_{\text{NN3\_2}} = 0$, $p^*_{\text{NN3\_2}} = \frac{1}{\lambda_L}\left[V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right]$ $\pi^*_{\text{NN3\_2}} = \left[\frac{\alpha\lambda_H + (1-\alpha)\lambda_L}{\lambda_L}\right]\left[V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right]$ $\text{CS}_{\text{NN3\_2}} == \alpha\left\{\left[\frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right]\left(\frac{\lambda_H - \lambda_L}{\lambda_L}\right) - \left(\frac{\lambda_H V_L - \lambda_L V_H}{\lambda_L}\right)\right\}$ $\text{SW}_{\text{NN3\_2}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$

No Net Neutrality	NNN1	Case NNN1_1: If $V_H - V_L \geq \frac{d\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, $\pi^*_{\text{NNN1\_1}} = F^*_{\text{NNN1\_1}} = V_L - \frac{d}{\mu-(1-\alpha)\lambda_L}$ $\text{CS}_{\text{NNN1\_1}} = \alpha\left[V_H - V_L - \frac{d}{\mu-(1-\alpha)\lambda_L}\cdot\frac{\alpha\lambda_H+(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right]$ $\text{SW}_{\text{NNN1\_1}} = \alpha\left(V_H - \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right) + (1-\alpha)\left(V_L - \frac{d}{\mu-(1-\alpha)\lambda_L}\right)$ Case NNN1_2: If $V_H - V_L < \frac{d\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, $\pi^*_{\text{NNN1\_2}} = F^*_{\text{NNN1\_2}} = V_H - \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$ $\text{CS}_{\text{NNN1\_2}} = (1-\alpha)\left\{-V_H + V_L + \frac{d}{\mu-(1-\alpha)\lambda_L}\cdot\frac{\alpha\lambda_H+(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right\}$ $\text{SW}_{\text{NNN1\_2}} = \alpha\left(V_H - \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right) + (1-\alpha)\left(V_L - \frac{d}{\mu-(1-\alpha)\lambda_L}\right)$
	NNN2	$F^*_{\text{NNN2\_H}} = V_L - \frac{d}{\mu-\alpha\lambda_H}$, $F^*_{\text{NNN2\_L}} = V_L - \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$ $\pi^*_{\text{NNN2}} = \alpha F^*_{\text{NNN2\_H}} + (1-\alpha)F^*_{\text{NNN2\_L}} = V_L - \frac{d}{\mu-\alpha\lambda_H}\left[\frac{\mu-\alpha^2\lambda_H-\alpha(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right]$ $\text{CS}_{\text{NNN2}} = \alpha(V_H - V_L)$ $\text{SW}_{\text{NNN2}} = \alpha\left(V_H - \frac{d}{\mu-\alpha\lambda_H}\right) + (1-\alpha)\left(V_L - \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right)$
	NNN3	$F^*_{\text{NNN3}} = V_L - \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$ $p^*_{\text{NNN3}} = \frac{1}{\lambda_{\text{H}}}\left\{\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_{\text{H}}-(1-\alpha)\lambda_{\text{L}}\right]} - \frac{d}{\mu-\alpha\lambda_H}\right\}$ $\pi^*_{\text{NNN3}} = F^*_{\text{NNN3}} + \alpha\lambda_{\text{H}}p^*_{\text{NNN3}} = V_L - \frac{d}{\mu-\alpha\lambda_H}\left[\frac{\mu-\alpha^2\lambda_H-\alpha(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right]$ $\text{CS}_{\text{NNN3}} = \alpha(V_H - V_L)$ $\text{SW}_{\text{NNN3}} = \alpha\left(V_H - \frac{d}{\mu-\alpha\lambda_H}\right) + (1-\alpha)\left(V_L - \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right)$

Appendices

In order to simplify the proofs, we introduce the following notations.

Define $C_H \equiv \dfrac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$

$$C_L \equiv \frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$$

$$C_0 \equiv \frac{d(\lambda_H-\lambda_L)}{\lambda_L\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$$

$$C_1 \equiv \frac{(1-\alpha)d\left\{(\lambda_L-\alpha\lambda_H)\mu+\alpha\lambda_L\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]\right\}}{(\mu-\alpha\lambda_H)\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$$

$$C_2 \equiv \frac{d\lambda_L}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$$

$$C_3 \equiv \frac{d\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$$

$$C_4 \equiv \frac{d\lambda_H}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$$

We know that $C_2 < C_3 < C_4 < C_H$ since $\mu > \lambda_H > \alpha\lambda_H + (1-\alpha)\lambda_L > \lambda_L$.

Next we show $C_1 < C_2$ as below.

$$\begin{aligned}
C_2 - C_1 &= \frac{d\lambda_L}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - \frac{(1-\alpha)d\left\{(\lambda_L-\alpha\lambda_H)\mu+\alpha\lambda_L\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]\right\}}{(\mu-\alpha\lambda_H)\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} \\
&\geq \frac{(1-\alpha)d\lambda_L}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - \frac{(1-\alpha)d\left\{(\lambda_L-\alpha\lambda_H)\mu+\alpha\lambda_L\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]\right\}}{(\mu-\alpha\lambda_H)\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} \\
&= \frac{\alpha(1-\alpha)d(\lambda_H-\lambda_L)}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} > 0
\end{aligned}$$

The intersection between $V_H = \frac{\lambda_H V_L}{\lambda_L} - \frac{d\left(\lambda_H - \lambda_L\right)}{\lambda_L\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} = \frac{\lambda_H V_L}{\lambda_L} - C_0$ and

$V_H = V_L + \frac{d\lambda_H}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} = V_L + C_4$ is

$$V_L = \frac{d\left\{\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]\lambda_L + \mu\left(\lambda_H - \lambda_L\right)\right\}}{\left(\lambda_H - \lambda_L\right)\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}.$$

The intersection between $V_H = \frac{\lambda_H V_L}{\lambda_L} - \frac{d\left(\lambda_H - \lambda_L\right)}{\lambda_L\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} = \frac{\lambda_H V_L}{\lambda_L} - C_0$ and

$V_H = \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} = C_H$ is

$$V_L = \frac{d\left[\mu\lambda_H - (1-\alpha)\left(\lambda_H - \lambda_L\right)\lambda_L\right]}{\lambda_H\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} < C_H$$

since $\frac{d\left[\mu\lambda_H - (1-\alpha)\left(\lambda_H - \lambda_L\right)\lambda_L\right]}{\lambda_H\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} - C_H$

$$= \frac{d\left[\mu\lambda_H - (1-\alpha)\left(\lambda_H - \lambda_L\right)\lambda_L\right]}{\lambda_H\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} - \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$$

$$= \frac{-(1-\alpha)d\left(\lambda_H - \lambda_L\right)\lambda_L}{\lambda_H\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} < 0$$

Appendix A: Solution of Formulation (7) – Option NN3

In Formulation (7), from (*i*), we get $F_{\mathrm{NN3}} \le V_H - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - \lambda_H p_{\mathrm{NN3}}$. From (*ii*), we get $F_{\mathrm{NN3}} \le V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - \lambda_L p_{\mathrm{NN3}}$. We consider two cases:

Case 1: $p_{\mathrm{NN3}} \ge \frac{V_H - V_L}{\lambda_H - \lambda_L}$. Then

$V_H - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - \lambda_H p_{\mathrm{NN3}} \le V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - \lambda_L p_{\mathrm{NN3}}$. So constraint (*i*) is binding, i.e., $F_{\mathrm{NN3}} = V_H - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - \lambda_H p_{\mathrm{NN3}}$. Substituting into the objective function gives $V_H - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - (1-\alpha)(\lambda_H - \lambda_L) p_{\mathrm{NN3}}$. The optimal solution is

$F^*_{\mathrm{NN3}} = -\frac{\lambda_L V_H}{\lambda_H - \lambda_L} + \frac{\lambda_H V_L}{\lambda_H - \lambda_L} - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$, $p^*_{\mathrm{NN3}} = \frac{V_H - V_L}{\lambda_H - \lambda_L}$, and

$\pi^*_{\mathrm{NN3}} = \alpha V_H + (1-\alpha) V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$.

Case 2: $p_{\mathrm{NN3}} \le \frac{V_H - V_L}{\lambda_H - \lambda_L}$. Then

$V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - \lambda_L p_{\mathrm{NN3}} \le V_H - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - \lambda_H p_{\mathrm{NN3}}$. So constraint (*ii*) is binding, i.e., $F_{\mathrm{NN3}} = V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - \lambda_L p_{\mathrm{NN3}}$. Substituting into the objective function gives $V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} + \alpha(\lambda_H - \lambda_L) p_{\mathrm{NN3}}$.

Case 21: $\dfrac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} \geq \dfrac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$. The optimal solution is

$$F^*_{\text{NN3}} = \frac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L},\ p^*_{\text{NN3}} = \frac{V_H - V_L}{\lambda_H - \lambda_L} \text{, and}$$

$$\pi^*_{\text{NN3}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}.$$

Case 22: $\dfrac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} \leq \dfrac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$. The optimal solution is $F^*_{\text{NN3}} = 0$,

$$p^*_{\text{NN3}} = \frac{1}{\lambda_L}\left[V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right]$$

(Since $\dfrac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} \leq \dfrac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$,

$$p^*_{\text{NN3}} = \frac{1}{\lambda_L}\left[V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right] \leq \frac{1}{\lambda_L}\left(V_L - \frac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L}\right) = \frac{V_H - V_L}{\lambda_H - \lambda_L}.)$$

$$\pi^*_{\text{NN3}} = \left[\frac{\alpha\lambda_H + (1-\alpha)\lambda_L}{\lambda_L}\right]\left[V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right].$$

The above cases can be summarized as:

Case NN3_1: If $\dfrac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} \geq \dfrac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$, i.e.,

$$V_H \leq \frac{\lambda_H V_L}{\lambda_L} - \frac{d(\lambda_H - \lambda_L)}{\lambda_L\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} = \frac{\lambda_H V_L}{\lambda_L} - C_0,$$

$$F^*_{\text{NN3\_1}} = \frac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L},\ p^*_{\text{NN3\_1}} = \frac{V_H - V_L}{\lambda_H - \lambda_L},$$

$\pi^*_{\text{NN3\_1}} = \alpha V_H + (1-\alpha)V_L - \dfrac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$. The corresponding consumer surplus is

$$\mathrm{CS}_{\mathrm{NN3\_1}} = \alpha\left(V_H - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L} - F_{\mathrm{NN3\_1}} - \lambda_H p_{\mathrm{NN3\_1}}\right)$$
$$+(1-\alpha)\left(V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L} - F_{\mathrm{NN3\_1}} - \lambda_L p_{\mathrm{NN3\_1}}\right) = 0.$$

Therefore the social welfare is

$$\mathrm{SW}_{\mathrm{NN3\_1}} = \pi^*_{\mathrm{NN3\_1}} + \mathrm{CS}_{\mathrm{NN3\_1}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}.$$

Case NN3_2: If $\frac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} < \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}$, i.e.,

$$V_H > \frac{\lambda_H V_L}{\lambda_L} - \frac{d(\lambda_H-\lambda_L)}{\lambda_L\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} = \frac{\lambda_H V_L}{\lambda_L} - C_0,\ F^*_{\mathrm{NN3\_2}} = 0,$$

$$p^*_{\mathrm{NN3\_2}} = \frac{1}{\lambda_L}\left[V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right],$$

$$\pi^*_{\mathrm{NN3\_2}} = \left[\frac{\alpha\lambda_H + (1-\alpha)\lambda_L}{\lambda_L}\right]\left[V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right].$$

The corresponding consumer surplus is

$$\mathrm{CS}_{\mathrm{NN3\_2}} = \alpha\left(V_H - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L} - F_{\mathrm{NN3\_2}} - \lambda_H p_{\mathrm{NN3\_2}}\right)$$
$$+(1-\alpha)\left(V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L} - F_{\mathrm{NN3\_2}} - \lambda_L p_{\mathrm{NN3\_2}}\right)$$

$$= \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L} - \left[\frac{\alpha\lambda_H + (1-\alpha)\lambda_L}{\lambda_L}\right]\left[V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right]$$
$$= \alpha\left\{\left[\frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right]\left(\frac{\lambda_H-\lambda_L}{\lambda_L}\right) - \left(\frac{\lambda_H V_L - \lambda_L V_H}{\lambda_L}\right)\right\}.$$

Therefore the social welfare is

$$\mathrm{SW}_{\mathrm{NN3\_2}} = \pi^*_{\mathrm{NN3\_2}} + \mathrm{CS}_{\mathrm{NN3\_2}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}.$$

Appendix B: Proof of Proposition 1

Now we move on proving Proposition 1. Comparing the BSP's three options under net neutrality, we know $\pi^*_{\text{NN1}} = V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} = \pi^*_{\text{NN2}}$. Then we compare π^*_{NN1} and π^*_{NN2} to π^*_{NN3}.

If $\frac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} \geq \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$, i.e.,

$$V_H \leq \frac{\lambda_H V_L}{\lambda_L} - \frac{d(\lambda_H - \lambda_L)}{\lambda_L\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} = \frac{\lambda_H V_L}{\lambda_L} - C_0,$$

$$\pi^*_{\text{NN3}} = \pi^*_{\text{NN3\_1}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}.$$

Since $\alpha V_H + (1-\alpha)V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} > V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$,

$\pi^*_{\text{NN3\_1}} > \pi^*_{\text{NN1}} = \pi^*_{\text{NN2}}$.

If $\frac{\lambda_H V_L - \lambda_L V_H}{\lambda_H - \lambda_L} < \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$, i.e.,

$$V_H > \frac{\lambda_H V_L}{\lambda_L} - \frac{d(\lambda_H - \lambda_L)}{\lambda_L\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} = \frac{\lambda_H V_L}{\lambda_L} - C_0,$$

$$\pi^*_{\text{NN3}} = \pi^*_{\text{NN3\_2}} = \left[\frac{\alpha\lambda_H + (1-\alpha)\lambda_L}{\lambda_L}\right]\left[V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right]$$

$> V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} = \pi^*_{\text{NN1}} = \pi^*_{\text{NN2}}$ since $\frac{\alpha\lambda_H + (1-\alpha)\lambda_L}{\lambda_L} > 1$.

Appendix C: Proof of Proposition 2

Comparing the BSP's three options under no net neutrality, we know

$$\pi^*_{\text{NNN2}} = \pi^*_{\text{NNN3}} = V_L - \frac{d}{\mu-\alpha\lambda_H}\left[\frac{\mu-\alpha^2\lambda_H-\alpha(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right].$$

Then we compare π^*_{NNN2} and π^*_{NNN3} to π^*_{NNN1}.

If $V_H - V_L \geq \frac{d\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, i.e.,

$$V_H \geq V_L + \frac{d\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} = V_L + C_3 \text{, then}$$

$$\pi^*_{\text{NNN2}} - \pi^*_{\text{NNN1\_1}} = V_L - \frac{d}{\mu-\alpha\lambda_H}\left[\frac{\mu-\alpha^2\lambda_H-\alpha(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right] - V_L + \frac{d}{\mu-(1-\alpha)\lambda_L}$$

$$= -\frac{d}{\mu-\alpha\lambda_H}\left[\frac{\mu-\alpha^2\lambda_H-\alpha(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right] + \frac{d}{\mu-(1-\alpha)\lambda_L}$$

$$= \frac{-\alpha d(1-\alpha)(\lambda_H-\lambda_L)\left[\mu-(1-\alpha)\lambda_L\right]-\alpha d\lambda_H(\mu-\alpha\lambda_H)}{(\mu-\alpha\lambda_H)\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} < 0.$$

So $\pi^*_{\text{NNN1\_1}} > \pi^*_{\text{NNN2}} = \pi^*_{\text{NNN3}}$.

If $V_H - V_L < \frac{d\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, i.e.,

$$V_H < V_L + \frac{d\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} = V_L + C_3 \text{, then}$$

$$\pi^*_{\text{NNN2}} - \pi^*_{\text{NNN1\_2}} = V_L - \frac{d\left[\mu-\alpha^2\lambda_H-\alpha(1-\alpha)\lambda_L\right]}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - V_H + \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$$

$$= -(V_H-V_L) + \frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]} - \frac{d\left[\mu-\alpha^2\lambda_H-\alpha(1-\alpha)\lambda_L\right]}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$$

$$= -\left(V_H - V_L\right) + \frac{(1-\alpha)d\left\{(\lambda_L - \alpha\lambda_H)\mu + \alpha\lambda_L\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]\right\}}{(\mu - \alpha\lambda_H)\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} = -\left(V_H - V_L\right) + C_1.$$

Since $C_1 < C_3$, we get if $V_H < V_L + C_1$, $\pi^*_{\mathrm{NNN1\_2}} < \pi^*_{\mathrm{NNN2}} = \pi^*_{\mathrm{NNN3}}$; If $V_L + C_1 \le V_H < V_L + C_3$, $\pi^*_{\mathrm{NNN1\_2}} > \pi^*_{\mathrm{NNN2}} = \pi^*_{\mathrm{NNN3}}$.

Summarizing the results, we have: if $V_H \ge V_L + C_3$, $\pi^*_{\mathrm{NNN1}} = \pi^*_{\mathrm{NNN1\_1}} > \pi^*_{\mathrm{NNN2}} = \pi^*_{\mathrm{NNN3}}$; if $V_L + C_1 \le V_H < V_L + C_3$, $\pi^*_{\mathrm{NNN1}} = \pi^*_{\mathrm{NNN1\_2}} > \pi^*_{\mathrm{NNN2}} = \pi^*_{\mathrm{NNN3}}$; if $V_H < V_L + C_1$, $\pi^*_{\mathrm{NNN1}} = \pi^*_{\mathrm{NNN1\_2}} < \pi^*_{\mathrm{NNN2}} = \pi^*_{\mathrm{NNN3}}$.

Appendix D: Proof of Proposition 3

From the results of Proposition 1 and Proposition 2, we know: under net neutrality,

If $V_H \le \frac{\lambda_H V_L}{\lambda_L} - C_0$, $\pi^*_{\mathrm{NN}} = \pi^*_{\mathrm{NN3\_1}} = \alpha V_H + (1-\alpha)V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$.

If $V_H > \frac{\lambda_H V_L}{\lambda_L} - C_0$, $\pi^*_{\mathrm{NN}} = \pi^*_{\mathrm{NN3\_2}} = \left[\frac{\alpha\lambda_H + (1-\alpha)\lambda_L}{\lambda_L}\right]\left[V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right]$.

Under no net neutrality, If $V_H \ge V_L + C_3$, then $\pi^*_{\mathrm{NNN}} = \pi^*_{\mathrm{NNN1\_1}} = V_L - \frac{d}{\mu - (1-\alpha)\lambda_L}$;

If $V_L + C_1 \le V_H < V_L + C_3$, $\pi^*_{\mathrm{NNN}} = \pi^*_{\mathrm{NNN1\_2}} = V_H - \frac{d\mu}{\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$;

If $V_H < V_L + C_1$, $\pi^*_{\mathrm{NNN}} = \pi^*_{\mathrm{NNN2}} = \pi^*_{\mathrm{NNN3}} = V_L - \frac{d\left[\mu - \alpha^2\lambda_H - \alpha(1-\alpha)\lambda_L\right]}{(\mu - \alpha\lambda_H)\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$.

Considering the BSP's overall preference, there are six cases:

<u>Case (*i*):</u> If $V_H \le \frac{\lambda_H V_L}{\lambda_L} - C_0$ and $V_H \ge V_L + C_3$, then

$$\pi^*_{\mathrm{NNN}} - \pi^*_{\mathrm{NN}} = \pi^*_{\mathrm{NNN1\_1}} - \pi^*_{\mathrm{NN3\_1}} = \left[V_L - \frac{d}{\mu - (1-\alpha)\lambda_L}\right] - \left[\alpha V_H + (1-\alpha)V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right]$$

$$= -\alpha(V_H - V_L) + \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} - \frac{d}{\mu - (1-\alpha)\lambda_L}$$

$$= -\alpha(V_H - V_L) + \frac{\alpha d\lambda_H}{\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$$

If $V_L + C_4 = V_L + \frac{d\lambda_H}{\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} \le V_H \le \frac{\lambda_H V_L}{\lambda_L} - C_0$, then

$\pi^*_{\mathrm{NNN1\_1}} \le \pi^*_{\mathrm{NN3\_1}}$.

If $V_L + C_3 \le V_H < V_L + C_4$ and $V_H \le \frac{\lambda_H V_L}{\lambda_L} - C_0$, then $\pi^*_{\mathrm{NNN1\_1}} > \pi^*_{\mathrm{NN3\_1}}$.

Case (*ii*): If $V_H \le \frac{\lambda_H V_L}{\lambda_L} - C_0$ and $V_L + C_1 \le V_H < V_L + C_3$, then $\pi^*_{\text{NNN}} - \pi^*_{\text{NN}} = \pi^*_{\text{NNN1\_2}} - \pi^*_{\text{NN3\_1}}$

$$= \left[V_H - \frac{d\mu}{\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} \right] - \left[\alpha V_H + (1-\alpha) V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} \right]$$

$$= (1-\alpha)(V_H - V_L) - \frac{d\mu}{\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} + \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$$

$$= (1-\alpha)(V_H - V_L) - \frac{(1-\alpha) d\lambda_L}{\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$$

If $V_L + C_2 = V_L + \frac{d\lambda_L}{\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} \le V_H < V_L + C_3$ and

$V_H \le \frac{\lambda_H V_L}{\lambda_L} - C_0$, then $\pi^*_{\text{NNN1\_2}} \ge \pi^*_{\text{NN3\_1}}$.

If $V_L + C_1 \le V_H < V_L + C_2$ and $V_H \le \frac{\lambda_H V_L}{\lambda_L} - C_0$, then $\pi^*_{\text{NNN1\_2}} < \pi^*_{\text{NN3\_1}}$.

Case (*iii*): If $V_H \le \frac{\lambda_H V_L}{\lambda_L} - C_0$ and $V_H < V_L + C_1$, then $\pi^*_{\text{NNN}} - \pi^*_{\text{NN}} = \pi^*_{\text{NNN2}} - \pi^*_{\text{NN3\_1}}$

$$= \left[V_L - \frac{d\left[\mu - \alpha^2\lambda_H - \alpha(1-\alpha)\lambda_L\right]}{(\mu - \alpha\lambda_H)\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} \right] - \left[\alpha V_H + (1-\alpha) V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L} \right]$$

$$= -\alpha(V_H - V_L) - \frac{d\left[\mu - \alpha^2\lambda_H - \alpha(1-\alpha)\lambda_L\right]}{(\mu - \alpha\lambda_H)\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} + \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}$$

$$= -\alpha(V_H - V_L) - \frac{\alpha(1-\alpha) d(\lambda_H - \lambda_L)}{(\mu - \alpha\lambda_H)\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]} < 0.$$

So $\pi^*_{\text{NN3\_1}} > \pi^*_{\text{NNN2}}$.

Case (*iv*): If $V_H > \frac{\lambda_H V_L}{\lambda_L} - C_0$ and $V_H \ge V_L + C_3$, then $\pi^*_{\text{NNN}} - \pi^*_{\text{NN}} = \pi^*_{\text{NNN1\_1}} - \pi^*_{\text{NN3\_2}}$

$$=\left[V_L-\frac{d}{\mu-(1-\alpha)\lambda_L}\right]-\left[\frac{\alpha\lambda_H+(1-\alpha)\lambda_L}{\lambda_L}\right]\left[V_L-\frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right]$$

$$=\frac{-\alpha(\lambda_H-\lambda_L)V_L}{\lambda_L}+\frac{\alpha d\left\{\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]\lambda_L+\mu(\lambda_H-\lambda_L)\right\}}{\lambda_L\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$$

If $V_H>\frac{\lambda_H V_L}{\lambda_L}-C_0$, $V_H\geq V_L+C_3$, and

$V_L\geq\frac{d\left\{\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]\lambda_L+\mu(\lambda_H-\lambda_L)\right\}}{(\lambda_H-\lambda_L)\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, then $\pi^*_{\text{NNN1\_1}}\leq\pi^*_{\text{NN3\_2}}$. Notice

$V_L=\frac{d\left\{\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]\lambda_L+\mu(\lambda_H-\lambda_L)\right\}}{(\lambda_H-\lambda_L)\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$ is also where the line

$V_H=\frac{\lambda_H V_L}{\lambda_L}-\frac{d(\lambda_H-\lambda_L)}{\lambda_L\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}=\frac{\lambda_H V_L}{\lambda_L}-C_0$ intersects the line

$V_H=V_L+\frac{d\lambda_H}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}=V_L+C_4$.

If $V_H>\frac{\lambda_H V_L}{\lambda_L}-C_0$, $V_H\geq V_L+C_3$, and

$V_L<\frac{d\left\{\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]\lambda_L+\mu(\lambda_H-\lambda_L)\right\}}{(\lambda_H-\lambda_L)\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, then $\pi^*_{\text{NNN1\_1}}>\pi^*_{\text{NN3\_2}}$.

<u>Case (v):</u> If $V_H>\frac{\lambda_H V_L}{\lambda_L}-C_0$ and $V_L+C_1\leq V_H<V_L+C_3$, then $\pi^*_{\text{NNN}}-\pi^*_{\text{NN}}=\pi^*_{\text{NNN1\_2}}-\pi^*_{\text{NN3\_2}}$

$$=\left[V_H-\frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right]-\left[\frac{\alpha\lambda_H+(1-\alpha)\lambda_L}{\lambda_L}\right]\left[V_L-\frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right]$$

$$=\frac{\lambda_L V_H-\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]V_L}{\lambda_L}+\frac{\alpha d\mu(\lambda_H-\lambda_L)-(1-\alpha)d\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]\lambda_L}{\lambda_L\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$$

If $\lambda_L V_H - \left[\alpha\lambda_H + (1-\alpha)\lambda_L\right] V_L \geq \dfrac{\alpha d\mu(\lambda_H - \lambda_L) - (1-\alpha) d\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]\lambda_L}{\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$, i.e.,

$V_H \geq \dfrac{\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right] V_L}{\lambda_L} + \dfrac{\alpha d\mu(\lambda_H - \lambda_L) - (1-\alpha) d\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]\lambda_L}{\lambda_L\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$, then

$\pi^*_{\text{NNN1\_2}} \geq \pi^*_{\text{NN3\_2}}$.

If $\lambda_L V_H - \left[\alpha\lambda_H + (1-\alpha)\lambda_L\right] V_L < \dfrac{\alpha d\mu(\lambda_H - \lambda_L) - (1-\alpha) d\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]\lambda_L}{\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$, i.e.,

$V_H < \dfrac{\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right] V_L}{\lambda_L} + \dfrac{\alpha d\mu(\lambda_H - \lambda_L) - (1-\alpha) d\left[\alpha\lambda_H + (1-\alpha)\lambda_L\right]\lambda_L}{\lambda_L\left[\mu - (1-\alpha)\lambda_L\right]\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}$, then

$\pi^*_{\text{NNN1\_2}} < \pi^*_{\text{NN3\_2}}$.

<u>Case (*vi*):</u> If $V_H > \dfrac{\lambda_H V_L}{\lambda_L} - C_0$ and $V_H < V_L + C_1$, then $\pi^*_{\text{NNN}} - \pi^*_{\text{NN}} = \pi^*_{\text{NNN2}} - \pi^*_{\text{NN3\_2}}$

$$= \left[V_L - \frac{d\left[\mu - \alpha^2\lambda_H - \alpha(1-\alpha)\lambda_L\right]}{(\mu - \alpha\lambda_H)\left[\mu - \alpha\lambda_H - (1-\alpha)\lambda_L\right]}\right] - \left[\frac{\alpha\lambda_H + (1-\alpha)\lambda_L}{\lambda_L}\right]\left[V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right]$$

$$< \left[V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right] - \left[\frac{\alpha\lambda_H + (1-\alpha)\lambda_L}{\lambda_L}\right]\left[V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right]$$

$$< \left[V_L - \frac{d}{\mu - \alpha\lambda_H - (1-\alpha)\lambda_L}\right]\left[1 - \frac{\alpha\lambda_H + (1-\alpha)\lambda_L}{\lambda_L}\right] < 0$$

So $\pi^*_{\text{NN3\_2}} > \pi^*_{\text{NNN2}}$.

Appendix E: Proof of Proposition 5

Comparing social welfare under NNN1, NNN2, and NNN3 gives

$$\mathrm{SW}_{\mathrm{NNN2}}=\mathrm{SW}_{\mathrm{NNN3}}=\alpha\left(V_H-\frac{d}{\mu-\alpha\lambda_H}\right)+(1-\alpha)\left(V_L-\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right).$$

Since

$$\mathrm{SW}_{\mathrm{NNN1\_1}}=\mathrm{SW}_{\mathrm{NNN1\_2}}=\alpha\left(V_H-\frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right)+(1-\alpha)\left(V_L-\frac{d}{\mu-(1-\alpha)\lambda_L}\right)$$

,

$$\mathrm{SW}_{\mathrm{NNN2}}-\mathrm{SW}_{\mathrm{NNN1\_1}}=\alpha\left(\frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}-\frac{d}{\mu-\alpha\lambda_H}\right)$$

$$-(1-\alpha)\left(\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}-\frac{d}{\mu-(1-\alpha)\lambda_L}\right)$$

$$=\frac{d}{\mu-(1-\alpha)\lambda_L}\left[\frac{\mu-\alpha(1-\alpha)\lambda_H-(1-\alpha)^2\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right]-\frac{d}{\mu-\alpha\lambda_H}\left[\frac{\mu-\alpha^2\lambda_H-\alpha(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\right]$$

$$=\frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}\left[\frac{\mu-\alpha(1-\alpha)\lambda_H-(1-\alpha)^2\lambda_L}{\mu-(1-\alpha)\lambda_L}-\frac{\mu-\alpha^2\lambda_H-\alpha(1-\alpha)\lambda_L}{\mu-\alpha\lambda_H}\right]$$

$$=\frac{-\alpha(1-\alpha)d\left(\lambda_H-\lambda_L\right)\left[2\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}{\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H\right]}<0$$

Therefore $\mathrm{SW}_{\mathrm{NNN1}}>\mathrm{SW}_{\mathrm{NNN2}}=\mathrm{SW}_{\mathrm{NNN3}}$.

Appendix F: Proof of Proposition 6

Recall $\mathrm{SW}_{\mathrm{NN1}}=\mathrm{SW}_{\mathrm{NN2}}=\mathrm{SW}_{\mathrm{NN3}}=\alpha V_H+(1-\alpha)V_L-\dfrac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}$ and

$$\mathrm{SW}_{\mathrm{NNN1}}=\alpha\left(V_H-\frac{d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right)+(1-\alpha)\left(V_L-\frac{d}{\mu-(1-\alpha)\lambda_L}\right)$$
$$>\mathrm{SW}_{\mathrm{NNN2}}=\mathrm{SW}_{\mathrm{NNN3}}=\alpha\left(V_H-\frac{d}{\mu-\alpha\lambda_H}\right)+(1-\alpha)\left(V_L-\frac{d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}\right)$$

Since

$$\mathrm{SW}_{\mathrm{NN1}}-\mathrm{SW}_{\mathrm{NNN2}}=\frac{\alpha d}{\mu-\alpha\lambda_H}+\frac{(1-\alpha)d\mu}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}-\frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}$$

$$=\frac{\alpha d}{\mu-\alpha\lambda_H}-\frac{\alpha d(\mu-\lambda_H)}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}=\frac{\alpha(1-\alpha)d(\lambda_H-\lambda_L)}{(\mu-\alpha\lambda_H)\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}>0,$$

$$\mathrm{SW}_{\mathrm{NN1}}-\mathrm{SW}_{\mathrm{NNN1}}=\frac{\alpha d\mu}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}+\frac{(1-\alpha)d}{\mu-(1-\alpha)\lambda_L}-\frac{d}{\mu-\alpha\lambda_H-(1-\alpha)\lambda_L}$$
$$=\frac{(1-\alpha)d}{\mu-(1-\alpha)\lambda_L}-\frac{(1-\alpha)d(\mu-\lambda_L)}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}=\frac{-\alpha(1-\alpha)d(\lambda_H-\lambda_L)}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}<0$$

, $\mathrm{SW}_{\mathrm{NNN1}}>\mathrm{SW}_{\mathrm{NN1}}=\mathrm{SW}_{\mathrm{NN2}}=\mathrm{SW}_{\mathrm{NN3}}>\mathrm{SW}_{\mathrm{NNN2}}=\mathrm{SW}_{\mathrm{NNN3}}$.

Appendix G: Proof of Proposition 7

From Proposition 6, we know that the social planner always prefers NNN1. From Proposition 3, we know that under the following two scenarios: (1)

$V_H > V_L + \frac{d\lambda_H}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$ and

$V_L > \frac{d\left\{\left[\alpha\lambda_H+(1-\alpha)\lambda_L\right]\lambda_L+\mu(\lambda_H-\lambda_L)\right\}}{(\lambda_H-\lambda_L)\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$; (2)

$V_H \le \frac{\lambda_H V_L}{\lambda_L} - \frac{d(\lambda_H-\lambda_L)}{\lambda_L\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$ and

$V_L < V_H < V_L + \frac{d\lambda_L}{\left[\mu-(1-\alpha)\lambda_L\right]\left[\mu-\alpha\lambda_H-(1-\alpha)\lambda_L\right]}$, the BSP prefers NN3 and therefore the BSP would deviate from the social planner's preferred option.

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