WP-2024-023

Individuals' Social Concern, Externalities and Voluntary Vaccination: Monopoly and First-Best Public Policy

Sumana Kundu and Rupayan Pal

Indira Gandhi Institute of Development Research, Mumbai
October 2024

Individuals' Social Concern, Externalities and Voluntary Vaccination: Monopoly and First-Best Public Policy

Sumana Kundu and Rupayan Pal

Email(corresponding author): sumana@igidr.ac.in

Abstract

This paper studies the role of individuals' social concern in a monopoly vaccine market characterized by externalities, and the first-best public policy. Considering a voluntary vaccination environment and social concern as private information, we show the following. A `spread-preserving, mean-increasing' shift in distribution of social concern induces the monopolist to curb vaccine coverage, unless there is sufficient heterogeneity in social concern. A `mean-preserving, spread-increasing' shift enhances vaccine coverage if vaccine quality and its marginal direct health benefit are sufficiently large. If net intensity of externality is stronger or vaccine quality is higher, for the monopolist to increase vaccine coverage, it's necessary to have significant heterogeneity in social concern. Monopoly-induced downward distortion in market coverage can be corrected through alternative balanced-budget, profit-neutral policy interventions. Under endogenous vaccine quality, the monopolist provides a partially-effective vaccine. A performance-linked R&D subsidy that achieves socially optimal vaccine quality depends on the distribution of social concern.

Keywords: Heterogeneity in Social Concern; Network Externality; Vaccine Quality; Monopoly Pricing; Social Optimality; Public Policy

JEL Code: D91, D42, D62, I11, I18

Acknowledgements:

We would like to thank Krishnendu Ghosh Dastidar for his comments and suggestions on an earlier darft. Usual disclaimer applies.

Individuals' Social Concern, Externalities and Voluntary Vaccination: Monopoly and First-Best Public Policy

Sumana Kundu[†] and Rupayan Pal[‡]

[†,‡] Indira Gandhi Institute of Development Research (IGIDR), Mumbai, India

Abstract: *This paper studies the role of individuals' social concern in a monopoly vaccine market characterized by externalities, and the first-best public policy. Considering a voluntary vaccination environment and social concern as private information, we show the following. A 'spread-preserving, mean-increasing' shift in distribution of social concern induces the monopolist to curb vaccine coverage, unless there is sufficient heterogeneity in social concern. A 'mean-preserving, spread-increasing' shift enhances vaccine coverage if vaccine quality and its marginal direct health benefit are sufficiently large. If net intensity of externality is stronger or vaccine quality is higher, for the monopolist to increase vaccine coverage, it's necessary to have significant heterogeneity in social concern. Monopoly-induced downward distortion in market coverage can be corrected through alternative balanced-budget, profit-neutral policy interventions. Under endogenous vaccine quality, the monopolist provides a partially-effective vaccine. A performance-linked R&D subsidy that achieves socially optimal vaccine quality depends on the distribution of social concern.*

JEL Codes: D91, D42, D62, I11, I18

Keywords: Heterogeneity in Social Concern; Network Externality; Vaccine Quality; Monopoly Pricing; Social Optimality; Public Policy

---

Conflict of Interests: None

Acknowledgments: We would like to thank Krishnendu Ghosh Dastidar for his comments and suggestions on an earlier darft. Usual disclaimer applies.

Corresponding Author and Address: Sumana Kundu, Indira Gandhi Institute of Development Research (IGIDR), Film City Road, Santosh Nagar, Goregaon (E), Mumbai 400065, India.

E-mails: (Kundu) sumana@igidr.ac.in, sumana.kundu99@gmail.com;

(Pal) rupayan@igidr.ac.in, rupayanpal@gmail.com

1 Introduction

For decades, vaccination has been recognized as an efficient, cost-effective way to prevent and eradicate infectious diseases, saving millions of lives worldwide.[1] Research demonstrates that vaccination against infectious diseases not only provides direct benefits to vaccinated individuals but also generates social benefits by reducing transmission. Consequently, vaccination is widely considered a prosocial act and a moral obligation (Böhm and Betsch, 2022; Korn et al., 2020).

During the COVID-19 pandemic, governments and health officials worldwide launched extensive campaigns to promote public health and encourage vaccination (see, for instance, Hong (2023)).[2] Additionally, recent studies suggest that educating people on the benefits of protecting the community and emphasizing the potential risks they pose to family and community members can significantly increase vaccine uptake (Arnesen et al., 2018; Böhm and Betsch, 2022; Vilar-Lluch et al., 2023).

Several studies, including Lake et al. (2021), Reddinger et al. (2024), and Arnesen et al. (2018), argue that people derive a sense of personal fulfilment or "psychic satisfaction" from vaccination, as it allows them to contribute to the containment of potential health risks they might otherwise pose to vulnerable individuals. This satisfaction, motivated by what we might call "social concern," reflects a willingness to protect others by mitigating public health risks. Consequently, individuals who prioritize social responsibility are more likely to get vaccinated and may even be willing to pay more for the vaccine, especially when a large share of the population remains unprotected. By vaccinating, these individuals reduce the risk of passing on the infection, providing a psychological reward for those motivated by social concern. The more the susceptible individuals there are, the greater this sense of fulfilment, as vaccinated individuals feel they are helping to protect a larger group.[3] Notably, this behaviour contrasts with the common "free-

[1] According to the Center for Disease Control and Prevention, public health experts have nominated vaccination as one of the top 10 worldwide public-health achievements during the years 2001-2010 (Centers for Disease Control (US). (2011). Morbidity and mortality weekly report: MMWR.). Every year, nearly 3.5-5 million deaths are prevented by using vaccines against diseases like polio, measles, rubella, influenza, etc. (World Health Organization, 2023).

[2] Examples of these social media messages include "Break the chain," "Stop the spread," and "Protect yourself, protect others."

[3] We note that individuals' psychological satisfaction from vaccination may stem from intrinsic moral motivation, extrinsic social or material motivation, or a combination of both, as individuals can credibly disclose their vaccination status. It has been argued that, in certain contexts, extrinsic motivation can

riding" mentality, where individuals rely on others to get vaccinated instead of doing so themselves.

A growing empirical literature suggests that individuals' pro-sociality is positively associated with their vaccine uptake decisions. For example, through a survey conducted in Australia, Lake et al. (2021) found that social focus values (e.g., valuing social outcomes concerning others and treating all fairly) are significant positive predictors of willingness to get vaccinated. Based on an experimental study, Reddinger et al. (2024) documents that more pro-social people are more likely to take a voluntary COVID-19 vaccination. Das et al. (2023), using a survey from India conducted before the roll-out of COVID-19 vaccine in India, demonstrate that pro-sociality has a significant positive effect on individuals' likelihood to pay (LTP) as well as willingness to pay (WTP) for different hypothetical vaccine variants against COVID-19. This stream of empirical literature also highlights that individuals differ from each other in terms of their social concern quite significantly.[4] Further, the average level and the extent of within-society heterogeneity in individuals' social concern vary across societies as well.

On the other hand, in modern market driven economies most (if not all) of the vaccines are produced by profit oriented private firms, and these firms enjoy significant market powers in their respective vaccine markets. In fact, it is observed that there are absolute monopolies in many vaccine markets (Arnould and DeBrock, 1996; Scherer, 2007; Danzon and Pereira, 2011). Thus, it is important to understand the implications of individuals' social concern and its distribution on firms' equilibrium business strategies and corresponding public health outcomes in relation to social optimality. However, to the best of our knowledge, this issue remains unattended in the existing literature. In this paper, we make a modest attempt to analyse this issue by developing a theoretical model and offer several interesting new insights.

"crowd out" intrinsic motivation (see, for example, Bénabou and Tirole (2003)), while in others, extrinsic motivation may instead "crowd in" intrinsic motivation Cappelen et al. (2017). In the present analysis, we side-step the issue of extrinsic motivation for simplicity, consistent with the findings of Cappelen et al. (2017) in the context of individuals' sharing behaviour in a modified dictator game. Nonetheless, it is straightforward to observe that including both types of motivation would not alter our results, provided that intrinsic moral motivation dominates extrinsic motivation in cases where the latter has a crowding-out effect, à la Bénabou and Tirole (2003), or where the latter reinforces the former, as suggested by Cappelen et al. (2017).

[4] Murphy et al. (2021) argues that the extent of psychic benefit gained out of vaccination may vary within a society due to individuals' personal characteristics.

We consider that there is a profit maximizing firm, which is the sole producer of the vaccine against an infectious disease, and a continuum of individuals of mass one. Quality of the vaccine is such that it is partially effective in providing immunity against the infection, unlike as in Kessing and Nuscheler (2006), Amir et al. (2023a) and Amir et al. (2023b). In other words, while an individual's probability of getting infected reduces due to vaccination, the vaccine does not provide complete immunity. It implies that vaccinated individuals remain susceptible with some positive probability, which is less than that for unvaccinated individuals. The higher the effectiveness of the vaccine, the lower is the probability of remaining susceptible post vaccination. In our framework, full effectiveness of the vaccine emerges in a limiting case. We first consider that the vaccine quality is exogenously given. Next, we extend the analysis by allowing for endogenous determination of vaccine quality by the monopolist through investment in R&D for vaccine development.

Individuals are assumed to be heterogeneous in terms of their social concern. An individual's social concern is her private information. The distribution of individuals' levels of social concern, the monopolist's cost parameter(s), and the vaccine quality are common knowledge. Each individual buys at most one unit of the vaccine.[5] An individual's WTP for the vaccine depends on (a) the direct health benefit derived from vaccination, which arises because vaccination reduces the chance of getting infected, (b) the level of her social concern, and (c) the externality effect. The externality effect is present due to the following reason. An individual's probability of getting infected from others is less in case the share of susceptible mass is less, and the share of susceptible mass is less when more people are vaccinated, ceteris paribus. Note that the existing literature has considered the first and the third effects only, and exclusively focused on perfectly effective vaccines. A more effective vaccine results in higher direct benefit from vaccination. On the other hand, an increase in vaccine effectiveness reduces the expected share of the susceptible mass, for any given expected share of vaccinated individuals, and thus, reduces an individual's willingness to pay for the vaccine through two channels. First, a lower expected share of the susceptible mass reduces the chance of getting infected from

[5]To keep the analysis tractable and focused, we consider a static one-shot game, individuals are heterogeneous in one dimension, per person only one dose of the vaccine is necessary, individuals take their respective vaccination decisions simultaneously and independently, the vaccine is free from side effects, and none is vaccine hesitant, as in Kessing and Nuscheler (2006), Amir et al. (2023a) and Amir et al. (2023b).

others (externality channel). Second, given the extent of an individual's social concern, a lower expected share of the susceptible mass results in a lower psychic satisfaction from getting vaccinated (social concern channel).

We begin the analysis by considering a sequential move game; wherein, first, the monopolist commits to supply the vaccine for a particular share of the population and quotes a single price. The quality of the vaccine is exogenously determined and is common knowledge. Subsequently, individuals form expectations, simultaneously and independently, regarding the share of the population to be vaccinated in the equilibrium. Finally, transactions take place and payoffs are realized. We characterize the fulfilled expectations subgame perfect Nash equilibrium (SPNE) of the game, a la Katz and Shapiro (1985).[6] Next, we consider an extended game to examine the implications of public policy intervention(s) in the vaccine market, vaccine R&D and quality choice of the monopolist, and R&D subsidy policy.

Preview of Results and Intuitions:

We show that, in absence of any government intervention, it is optimal for the monopolist to *partially* cover the vaccine market, while full market coverage is socially optimal. This is true, regardless of quality of the vaccine and the extent of heterogeneity in social concern. The reason is, an increase in the share of unvaccinated individuals in the population increases the risk of infection transmission and thereby increases individuals' WTP and (aggregate) vaccine demand, through two channels – externality and social concern. Thus, by under-supplying the vaccine the monopolist can charge a disproportionately higher price, which overcompensates it for corresponding loss due to lower sales. On the other hand, unlike the monopolist, the benevolent social planner takes into account each agent's payoff as well as social damage due to infection transmission.

Interestingly, a 'mean-increasing spread-preserving' shift in the distribution of social concern induces the monopolist to increase (decrease) market coverage in the equilibrium, if the extent of heterogeneity in social concern is more (less) than a critical level. That is, in the equilibrium, a greater (smaller) share of the population gets vaccinated in case

[6] Kessing and Nuscheler (2006), in the context of monopoly vaccine market, and Amir et al. (2023a) and Amir et al. (2023b), in the context of oligopoly vaccine market, have also relied upon this equilibrium concept.

individuals' have higher social concern on an average, provided that they are also (are not) sufficiently heterogeneous in terms of social concern. On the other hand, a 'mean-preserving spread-increasing' shift in the distribution of social concern results in a higher equilibrium vaccine coverage, if the vaccine quality and its marginal direct health benefit are sufficiently large. The intuition behind these results is as follows.

Prevalence elasticity of demand, i.e., proportionate change in vaccine demand due to proportionate change in the share of susceptible mass, is higher (lower), if the average social concern (the extent of heterogeneity in social concern) is higher. Now, if the extent of heterogeneity is sufficiently large, the negative effect of heterogeneity on prevalence elasticity of demand dominates the positive effect of an increase in average social concern on prevalence elasticity of demand. Therefore, when there is an increase in average social concern, for the market coverage contraction effect of susceptibility to be sufficiently low so that it gets dominated by the market coverage expansion effect of direct health benefit of the vaccine, the extent of heterogeneity must be sufficiently large.

Next, an increase in the extent of heterogeneity reduces the prevalence elasticity of demand, implying that the monopolist gains less from market coverage contraction. Further, higher vaccine quality and higher marginal direct health benefit of vaccine quality results in higher direct health benefit, implying the monopolist's gain from market coverage expansion is more. Moreover, given the market coverage, higher vaccine quality results in lower susceptibility. Thus, when the vaccine quality and its marginal direct health benefit are sufficiently large, a 'mean-preserving spread-increasing' shift in the distribution of social concern leads to an expansion of market coverage in the equilibrium.

Comparative statics of the monopoly equilibrium also shows that the net intensity of externality has a positive effect on the equilibrium market coverage in case the extent of heterogeneity in social concern is more than a threshold level, where the threshold level is positively associated with vaccine quality and direct health benefit of the vaccine. Implying that an increase in net intensity of network externality is more likely to increase the equilibrium market coverage, if the vaccine is of poorer quality or individuals derive a lower direct health benefit from the vaccine. In contrast, when individuals are homogeneous in terms of social concern, net intensity of network externality always dampens the equilibrium vaccine coverage, regardless of vaccine quality and its direct health benefit.

Considering perfectly effective vaccine and purely selfish individuals, Kessing and Nuscheler (2006) and Amir et al. (2023a,b) argue that network externality has a negative effect on the equilibrium vaccine coverage under imperfect competition, but in the context of perfectly effective vaccine. Clearly, the result of Kessing and Nuscheler (2006) and Amir et al. (2023a,b) emerges in a special case of the present analysis. We also demonstrate that their result holds true in the case of partially effective vaccine as well. However, this result gets reversed when individuals are sufficiently heterogeneous in terms of social concern. The reason, in brief, is as follows. Higher net intensity of externality implies that the positive effect of susceptibility on WTP is larger and, thus, the monopolist can charge a higher price and gain more by contracting market coverage. Presence of individuals' social concern also provides an incentive to the monopolist for supply contraction. However, heterogeneity in social concern increases the elasticity of demand and thereby results in coverage expansion, which dominates the coverage contraction effect of externality in case heterogeneity is sufficiently large.

We also show that the equilibrium market coverage is greater if the vaccine is of better quality, if both marginal direct health benefit of vaccine quality and the extent of heterogeneity in social concern are sufficiently large. Otherwise, vaccine quality adversely affects the equilibrium market coverage. The intuition behind this result is as follows. Quality of the vaccine impacts its demand through two channels. First, it enhances direct health benefit of the vaccine and thereby increases demand, the extent of such increase in demand is more in case marginal direct health benefit of vaccine quality is higher. Second, for any given market coverage, better quality vaccine results in lower susceptibility. And, greater heterogeneity in social concern results in lower prevalence elasticity of demand. Thus, if both marginal direct health benefit of vaccine quality and the extent of heterogeneity in social concern are sufficiently large, better quality vaccine results in greater market coverage. Otherwise, if marginal direct health benefit of vaccine quality is low or heterogeneity in social concern is not sufficiently large, the negative effect of vaccine quality, via its susceptibility reducing effect, on demand dominates its positive effect, via its positive effect on direct health benefit. As a result, in the latter scenario, vaccine quality adversely affects the equilibrium market coverage.

Since the equilibrium market coverage under uniform pricing is socially inefficient, implications of alternative pricing rule, e.g. perfect price discrimination (ppd), assumes importance. However, in the present context ppd is feasible only if the monopolist can access data on each individual's level of social concern, which does not appear to be realistic. Nonetheless, for the sake of argument, if we assume that nuanced data on social concern is accessible by the monopolist, perhaps, due to availability of modern sophisticated technologies, such as AI-ML techniques, and the monopolist can price discriminate, then also the equilibrium market coverage falls short of the socially optimal level unless the vaccine quality is very poor or the vaccine is of moderate quality and marginal direct health benefit of vaccine quality is sufficiently large. It follows that ppd is socially inefficient if the vaccine provides complete immunity against the infection a la Kessing and Nuscheler (2006). However, unlike as in Kessing and Nuscheler (2006), ppd is socially efficient under some conditions in the present context. Nevertheless, in reality, the appeal of ppd in vaccine market within a political territory is rather limited, if not non-existent.

We show that the government can implement the first-best market coverage, given the vaccine quality, in the equilibrium through alternative balanced-budget public policy interventions. In particular, we show that, given the vaccine quality, the socially optimal full market coverage can be ensured in the equilibrium through any of the following three public policies. First, the government may commit to full market coverage, procure required vaccine dosages from the monopolist at an agreeable price, cease the monopolist's right to sale in open market, offer the vaccine to individuals at a price equal to the least socially concerned individual's WTP, and impose a per unit profit tax to recover the net government expenditure from the monopolist (PP1: Government procurement coupled with per unit profit tax). Second, the government may subsidize vaccine price, which incentive the monopolist to fully cover the market, and impose a per unit profit tax (PP2: Price subsidy coupled with per unit profit tax). Third, the government may mandate the monopolist to cover the market fully and impose a short-fall tax as a disciplining instrument (PP3: Mandated full coverage coupled with a short-fall tax). Interestingly, the monopolist retains the same level of profit in the equilibrium under each of these three alternative public policy interventions. Under PP2, the optimal price subsidy is less in case the vaccine is more effective, unless the marginal effect of vaccine quality on direct health benefit is low. If the vaccine quality is higher than a threshold level, optimal price subsidy increases (decreases) in net intensity of network externality and the average level of social concern (heterogeneity in social concern).

Next, we consider an extended game in which first the monopolist invests in R&D for vaccine development, vaccine quality gets determined and becomes common knowledge . Next, the government announces public policy intervention with the objective of achieving full market coverage in a balanced budget manner. Subsequently, vaccine production takes place, and the monopolist either sells its entire produce to the government or it commits to a particular output and quotes a single price, depending on the public policy in place. Finally, individuals form expectations regrading market coverage and take vaccination decisions. We show that, in the equilibrium, the monopolist under invests in R&D, which results in partially effective vaccine. Interestingly, the monopolist is more likely to develop a better quality vaccine in case the extent of heterogeneity in social concern is higher or the average level of social concern prevailing the the society is lower. It implies that nudging individuals to be more concerned about others' well-being may incentivize the monopolist to develop better quality vaccine. We also show that quality-linked R&D subsidy is an useful policy instrument to incentivize the monopolist to develop vaccine of socially optimal quality.

Highlights of Our Contributions:

We contribute to the extant literature on equilibrium behaviour under imperfect competition in market for vaccines against infectious disease and government regulation in the following way. First, to the best of our knowledge, this is the first theoretical study that examines the implications of individuals' non-standard preferences on equilibrium vaccination behaviour, in a voluntary vaccination environment, under imperfect competition in the vaccine market. To be specific, based on the findings of empirical and experimental studies, we consider that individuals may have social concerns and they may also differ from each other in terms of level of social concern. Second, we offer fresh insights on the role of the distribution of individual's social concern on the equilibrium public health outcomes. Third, we examine the implication of partial effectiveness of the vaccine on the equilibrium coverage of the vaccine market under imperfect competition, unlike Kessing and Nuscheler (2006) and Amir et al. (2023a,b). Further, we re-examine the implications of network effect on the equilibrium market coverage and demonstrate that the validity of existing results crucially depends on the distribution of social concern and vaccine quality. Fourth, we design a set of profit-neutral and balanced-budget public policy interventions that can implement the socially optimal vaccination behaviour in the equilibrium, and highlight the implications of individuals' social concern to policy instruments. Fifth, we present an integrated analysis of vaccine development and the equilibrium vaccination behaviour under imperfect competition, unlike existing studies, and demonstrate the importance of designing appropriate performance-linked R&D subsidy policy. Finally, analysis of this paper offer useful insights to understand the equilibrium behaviour of agents in imperfectly competitive markets, characterized by consumption externalities, in general.

The rest of the paper is organised as follows. In Section 2, we discuss the related theoretical literature. Section 3 presents the setup of our model and the analysis of a benchmark case involving homogeneous individuals (Section 3.1). Section 4 considers heterogeneity in social concern and analyses its impact on changes in market coverage with respect to vaccine effectiveness, shifts in the distribution of social concern, and the intensity of externalities in the case of exogenous vaccine quality. Sections 5 and 6, respectively, present the analysis of socially optimal vaccine coverage and alternative public policy interventions to achieve social optimality for any given vaccine quality. Section 7 considers the endogenous determination of vaccine quality through investment in R&D for vaccine development and analyses the monopolist's choice of quality under market coverage regulation. It also discusses the role of a performance-linked R&D subsidy policy in implementing the first-best vaccine quality in equilibrium. Section 8 concludes.

2 Related Theoretical Literature: A Brief Review

Most of the existing theoretical literature related to the vaccine market focuses on building models of individuals' vaccination decision-making based on free-riding behaviour. Brito et al. (1991), Xu (1999), Heal and Kunreuther (2005) and Sorensen (2023) primarily exploits the idea that consumers' utility from getting vaccinated is negatively related to the size of the network i.e., the share of the vaccinated population. On one hand, there are costs associated with vaccination (both monetary and non-monetary, e.g., time, and discomfort), and on the other hand, with the increasing share of vaccinated population, an unvaccinated individual is less likely to contract the infection through transmission. These result in a low willingness to take vaccine due to the free-riding intention. Brito et al. (1991) builds upon such a model which postulates that when vaccines are fully effective, a voluntary vaccination program is always better than compulsory vaccination in terms of social welfare[7]. This proposition has subsequently been supported by Heal and Kunreuther (2005) and Sorensen (2023). The reason behind such an unconventional outcome is that when vaccines are fully effective, a vaccinated individual doesn't care about others' vaccination status. Thus in a compulsory vaccination, the people who would have chosen to get vaccinated in free choice are unaffected but who would not have earlier chosen to get vaccinated are worse off due to the implicit costs(time, pain) involved with vaccination. However, this may not be the case for a less effective vaccine, since the people who choose to get vaccinated under free choice may be better off in case of a compulsory vaccination due to the potential reduction in negative externality i.e., the transmission risk from the susceptible mass. Heal and Kunreuther (2005) presents a vaccination game where in the equilibria, the number of vaccinated population may range from zero to the entire population at risk depending on parameters like the probabilities of infection, the cost of vaccination, and the cost of illness. Moreover, the number of vaccinated individuals in equilibrium goes down as the probability of catching the disease from the unvaccinated mass reduces. Xu (1999) introduced a model where the probability of a susceptible individual getting infected goes down with increasing probability of others' vaccination. According to their study, the increase in vaccine efficacy has an ambiguous effect on an individual's incentive to vaccinate. When there is an improvement in vaccine efficacy, an individual gets a higher expected utility when vaccinated (termed as direct effect). On the other hand, an increased efficacy also reduces the chances of infection of a susceptible individual, resulting in a higher expected utility when unvaccinated (termed as indirect effect). Sorensen (2023) introduced an individual decision-making model where vaccination generates a positive externality for the unvaccinated mass. According to their study, an increase in effectiveness may lead to a decrease or increase in equilibrium vaccination but the welfare is higher when the vaccination increases with effectiveness since the probability of transmission risk i.e., the negative externality reduces with increasing vaccination. Geoffard and Philipson (1997)

[7] Although both of them are inferior to the socially optimal level of vaccination.

introduced the idea of a "prevalence-dependent demand" where demand for vaccines vanishes when prevalence of the disease is low enough since the benefit of vaccination is not large enough with low prevalence levels. However, with zero vaccination, an infection can regenerate itself and the prevalence starts increasing again, making disease eradication infeasible. Moreover, a "prevalence-responsive demand" may limit the negative impact of increasing prices on demand. As increasing price decreases demand, causing a rise in prevalence; a prevalence-responsive demand makes the demand increase again. Thus a high prevalence-responsive demand makes the demand highly price-inelastic and a profit-maximizing monopolist never finds it profitable to eradicate the disease.

Although the notion of individual vaccine decision-making has been substantially studied in the literature, there are very few studies that pay attention to vaccine providers' markets and the impact of their strategic behaviour on the vaccination coverage of a society. Kessing and Nuscheler (2006) analyse the strategy of a monopolist vaccine producer in a market characterized by negative network effect i.e., decreasing consumers' willingness to pay with increasing vaccination which emerges from their free-riding intention and consumer heterogeneity with respect to income. Later Amir et al. (2023a,b) introduced this free-riding effect in an oligopoly vaccine market. Amir et al. (2023a,b) portray the external effect as a benefit accrued to an unvaccinated individual due to the vaccinated share of the population and as the benefit increases with increasing share of vaccinated population i.e., increasing network size, it consequently reduces an unvaccinated individual's willingness to pay due to free-riding intention. A common finding of Kessing and Nuscheler (2006), Amir et al. (2023a,b) is that with increasing strength of the external effect, the vaccine producers have the incentive to reduce the vaccine supply. The reason for this is profit-maximizing providers' incentive to exploit individuals through their high willingness to pay when there is an increased fear of transmission due to low vaccine coverage. A standard consideration of these models on vaccination is that individuals do not have any social concern and the vaccine provides 100% immunity against the infection.

The framework of our analysis allows for (a) partially effective vaccine and (b) consumer heterogeneity in terms of their social concerns. It also examines implications of different types of changes in the distribution of social concern on monopolist's optimal strategy, both under exogenous and endogenous vaccine effectiveness. Further, we compare and contrast the equilibrium market coverage under monopoly with the socially optimal level, and design balanced-budget profit-neutral public policies to implement the first-best market coverage. We also demonstrate that the monopolist can be induced to develop the vaccine of socially optimal quality, through an appropriately designed performance-linked R&D subsidy policy.

3 The Model

Consider a society with continuum of individuals of mass one and a profit maximizing vaccine manufacturing firm. Each individual is at a complete risk of contracting an infectious disease in absence of vaccination. The firm produces a vaccine against the infectious disease. The vaccine is of quality, measured in terms of effectiveness of the vaccine in preventing infection, $\varepsilon \in (0, 1]$, which is common knowledge. That is, vaccination reduces the risk of getting infected by ε. In other words, if an individual gets vaccinated, that individual's probability of getting infected reduces from 1 to $(1-\varepsilon) \in [0, 1)$.[8] Individuals are assumed to be uniformly distributed over the interval $[\psi_l, \psi_h] \subset \mathbb{R}^+$ in terms of their social concern (Ψ); where ψ_l and ψ_h denote, respectively, the lowest and the highest levels of social concern prevailing in the society. Social concern of an individual is her private information. However, the distribution of social concern is common knowledge. The firm and individuals are assumed to be risk neutral.

Let $\theta^e \in [0, 1]$ be the expected share of individuals who get vaccinated. Then, given the vaccine quality (ε), the expected share of susceptible mass (s^e) can be written as $s^e = s^e(\theta^e, \varepsilon) = \theta^e(1-\varepsilon) + (1-\theta^e) = (1-\theta^e\varepsilon) \in [0, 1]$, since vaccinated (unvaccinated) individuals contract the disease with probability $1-\varepsilon$ (one): $\frac{\partial s^e(\cdot)}{\partial \theta^e} < 0$ and $\frac{\partial s^e(\cdot)}{\partial \varepsilon} < 0$. By getting vaccinated, an individual derives utility due to direct health benefits of the vaccine, $u_{hb} = \beta\varepsilon$, where $\beta > 0$ is the marginal direct health benefit of vaccine quality.[9] Moreover, a vaccinated individual can potentially avoid the cost imposed by her on the susceptible mass $s^e(\cdot)$, by reducing the possibility of transmission of the infection from her to susceptible others. Higher the $s^e(\cdot)$, higher is the scope of such cost avoidance.

[8] Note that the present framework encompasses the scenario of fully effective vaccine a la Kessing and Nuscheler (2006), Phelan and Toda (2022), Amir et al. (2023a) and Amir et al. (2023b), wherein the vaccine provides complete immunity against the infection, as a special case corresponding to $\varepsilon = 1$. We consider, if a person gets infected, that person suffers from the same cost, due to loss in health and associated monetary and non-monetary loss, regardless of whether that person was vaccinated or not.

[9] In case the vaccine has any side effect, β can be interpreted as net marginal direct health benefit.

Thus, individual i's derived psychic benefit from getting vaccinated due to her social concern ψ_i, $u_{sc,i}(\psi_i, s^e(\cdot))$, increases with $s^e(\cdot)$. We consider that $u_{sc,i}(\psi_i, s^e(\cdot)) = \psi_i s^e(\cdot)$, for simplicity. On the other hand, a high $s^e(\cdot)$ is associated with a high expected risk of infection due to transmission. That is, an individual's probability of getting the infection from others increases with $s^e(\cdot)$. In other words, higher $s^e(\cdot)$ generates more negative externalities from the susceptible mass to the society. Let $ud_{ne,k} = m_k s^e(\cdot)$ be the disutility, due to negative externalities from the susceptible mass, of an individual of type $k \in \{0, 1\}$, where $k = 1$ ($k = 0$) indicates that the individual is vaccinated (unvaccinated). The parameter m_k can be interpreted as a type k individual's perceived intensity of negative externalities from susceptible others. Since a vaccinated individual's risk of getting infected is less than that of an unvaccinated individual, we have $0 \leq m_1 < m_0$, i.e., a vaccinated individual's perceived intensity of negative externalities from susceptible others is less than that of an unvaccinated individual; where $m_1 \begin{cases} = 0, if \varepsilon = 1 \\ > 0, if \varepsilon \in (0, 1) \end{cases}$.[10]
It follows that, for any given price (p) of the vaccine, the payoff of individual i (a) in case she gets vaccinated, $u_i(\theta^e, \varepsilon)|_{k=1}$, and (b) in case she remains unvaccinated, $u_i(\theta^e, \varepsilon)|_{k=0}$, respectively, can be written as follows.[11]

$$u_i(\theta^e, \varepsilon)|_{k=1} = u_{hb} + u_{sc,i} - ud_{ne,1} - p = \beta\varepsilon + \psi_i(1 - \theta^e\varepsilon) - m_1(1 - \theta^e\varepsilon) - p \quad (1)$$
$$u_i(\theta^e, \varepsilon)|_{k=0} = -ud_{ne,0} = -m_0(1 - \theta^e\varepsilon) \quad (2)$$

Therefore, the incentive compatibility condition of individual i for getting vaccinated is as follows.

$$u_i(\theta^e, \varepsilon)|_{k=1} \geq u_i(\theta^e, \varepsilon)|_{k=0} \quad (3)$$
$$\Rightarrow \quad p \leq \beta\varepsilon + \psi_i(1 - \theta^e\varepsilon) + (m_0 - m_1)(1 - \theta^e\varepsilon) = \bar{p_i} \quad (4)$$
$$\Rightarrow \quad \psi_i \geq \frac{p - \beta\varepsilon}{(1 - \theta^e\varepsilon)} - m, \quad (5)$$

[10] We note here that individuals in a society differ from each other in several dimensions, e.g., health conditions, income, education, occupation, risk aversion, etc., other than social concern, and thus their perceptions regarding vaccine quality, health benefits of vaccination, intensity of negative externality, risk of getting infected, etc. may also differ. However, to keep the analysis tractable we have considered one dimensional heterogeneity only. Such a consideration also helps us to alienate the implications of individual's social concern and of its heterogeneity in clearer terms and keep the analysis focused.

[11] It is assumed that individuals do not incur any cost over and above the price of the vaccine to get vaccinated.

where $m = m_0 - m_1 (> 0)$ is the vaccination induced reduction in perceived intensity of negative externalities generated by susceptible others. $\bar{p}_i = \beta\varepsilon + \psi_i(1-\theta^e\varepsilon) + m(1-\theta^e\varepsilon)$ is individual i's maximum willingness to pay (WTP) for the vaccine. Clearly, m may be interpreted as the 'net intensity of externality effect' on an individual's WTP, which is positive. From (4) it is easy to observe that an increase in susceptibility s^e $(= 1 - \theta^e\varepsilon)$ enhances WTP through two channels: (a) it enhances the extent of perceived reduction in negative externality effect due to vaccination and (b) it increases psychic benefit arising from individual's social concern. Note that, for any given expected share of vaccinated individuals (θ^e), vaccine quality (ε) has two opposing effects on WTP. First, it has a positive effect on WTP, through its direct health benefit enhancing effect ($\frac{\partial u_{hb}}{\partial \varepsilon} = \beta > 0$). Second, it has negative effect on WTP, via its negative effects on psychic benefits ($\frac{\partial u_{sc,i}}{\partial \varepsilon} = -\psi_i\theta^e < 0$) and reduction in externality effect ($\frac{\partial [ud_{ne,0} - ud_{ne,1}]}{\partial \varepsilon} = -m\theta^e < 0$). However, as we explain shortly, individuals' expectation formation is responsive to vaccine quality and its price, and thus the equilibrium θ^e will also depend on ε. It implies that it is not straightforward to assert the sign of the net effect of vaccine quality on WTP.

Condition (5) implies that, for any given vaccine price p, all those individuals whose social concern is no less than $\hat{\psi} = \frac{p-\beta\varepsilon}{(1-\theta^e\varepsilon)} - m$ will choose to get vaccinated; while others will prefer to remain unvaccinated. Therefore, the firm faces the following demand function for its vaccine.

$$\theta = \frac{\psi_h - \hat{\psi}}{\delta} = \frac{1}{\delta}(\psi_h - \frac{p - \beta\varepsilon}{1 - \theta^e\varepsilon} + m), \tag{6}$$

where $\delta = \psi_h - \psi_l$ is the range of individuals' social concern Ψ in the society. Note that δ can be considered as a measure of the extent of heterogeneity in social concern prevailing in the society. Rearranging the terms of equation (6), we get the inverse demand function as follows.

$$p(\theta, \varepsilon) = \underbrace{\beta\varepsilon}_{\textit{First term}} + \underbrace{(\psi_h + m - \delta\theta)(1 - \theta^e\varepsilon)}_{\textit{Second term}} \tag{7}$$

Let $C(\varepsilon)$ be the total cost of the firm, where $C'(\varepsilon), C''(\varepsilon) > 0$ for all $\varepsilon \in [0, 1]$ and $C(0) = 0$. That is, given the vaccine quality ε, marginal cost of vaccine production is assumed to be zero.[12] The cost $C(\varepsilon)$ can be interpreted as the R&D cost for developing

[12]This is consistent with the fact that, while vaccine development is costly and it is likely to be necessary to incur a larger cost to improve the vaccine quality at the margin, incremental cost involved

the vaccine of quality ε. Alternatively, $C(\varepsilon)$ may also be interpreted as the fixed royalty fee paid by the firm to an outsider vaccine developer to obtain the exclusive license to manufacture and sale the vaccine, in case the vaccine quality is considered to be exogenously determined. Thus, the objective function of the firm can be written as follows.

$$\Pi(\theta,\varepsilon) = p(\theta,\varepsilon)\theta - C(\varepsilon) = [\beta\varepsilon + (\psi_h + m - \delta\theta)(1-\theta^e\varepsilon)]\theta - C(\varepsilon) \tag{8}$$

We first consider the following sequential move game with observable actions, which is in the spirit of Kessing and Nuscheler (2006).

Stage 0: The nature decides the vaccine quality $\epsilon \in (0,1]$.

Stage 1: The monopolist perfectly commits to a particular level of output θ and quotes a single price p for the vaccine.

Stage 2: Individuals form expectation regarding the vaccine coverage (θ^e) and take vaccination decisions, simultaneously and independently. Transactions take place and payoffs are realized.

Note that, since in Stage 1 the monopolist can commit to a θ perfectly, individuals correctly anticipate it and set $\theta^e = \theta$ in Stage 2. That is, individuals form rational expectations and in the equilibrium, expectations are fulfilled a la Katz and Shapiro (1985).[13] We extend the analysis, in Section 7, by allowing for endogenous determination of vaccine quality by the monopolist.

Now, note that the first term on the right hand side of the inverse demand function (7) is arising due to direct health benefits of the vaccine, while the second term is due to the presence of negative externalities and individuals social concerns. If the intensity of

in producing an additional unit of the vaccine of given quality is often negligible.

[13]The equilibrium of this game is the same as the equilibrium of an alternative sequential move game, in which the monopolist sets the price in Stage 1 and individuals form expectations about vaccine coverage in Stage 2 when individuals are heterogeneous (Kessing and Nuscheler, 2006, 2003). The idea behind this equilibrium concept is that the consumers are aware of the distribution of social concern. Therefore, after observing the price, a rational consumer can correctly anticipate the demand for vaccination. Therefore individuals' vaccination decision is influenced by their rational expectation of the share of the susceptible mass. This implies that by setting the price for a given quality of the vaccine, the monopolist makes people realize the vaccine coverage in the population and hence their decision to get vaccinated. This suggests that the monopolist's profit-maximization with respect to price p is equivalent to deciding on a profit-maximizing supply θ.

net externality effect and individuals' social concerns are arbitrarily small ($m \to 0$ and $\psi_i \to 0\,\forall\, i$), then at a given price either each individual will choose to get vaccinated ($\theta = 1$) or none will opt for vaccination ($\theta = 0$). In particular, in such a scenario, if $p \leq (>)\beta\varepsilon$, each individual (none) will demand the vaccine. Therefore, for any given ε, it is optimal for the firm to set $p = \beta\varepsilon$ and cover the market fully. The optimality of full market coverage will hold true even in the presence of social concern and externalities, if direct health benefit is sufficiently large. However, full market coverage by a monopolist, under uniform pricing, in unregulated market is a rare phenomenon. Further, in case of vaccines, it is well documented that significantly large part of the market often remains uncovered. Thus, to keep the analysis close to the reality and to focus on more interesting scenarios, we impose certain restrictions on model parameters.

Assumption 1. $0 < \beta < \bar{\beta} = \frac{(\psi_h+m)(1-\varepsilon)+(\psi_l+m)(3\varepsilon-2)}{\varepsilon}$

Assumption 1 ensures that, when expected share of vaccinated individuals is equal to the actual market coverage ($\theta^e = \theta$), the monopolist will find it optimal not to serve the entire population: $\frac{\partial \Pi(\theta,\varepsilon|\theta^e=\theta)}{\partial \theta}|_{\theta=1} < 0$. Note that $\bar{\beta} > 0$ holds true for all $\varepsilon \in (0,1]$, unless $\psi_h < m + 2\psi_l$. In the later case, i.e., when $\psi_h < m + 2\psi_l$, we need to have $\varepsilon > \frac{m-(\psi_h-2\psi_l)}{2m-(\psi_h-3\psi_l)} (< 1)$ for $\bar{\beta} > 0$ to be satisfied. Thus, Assumption 1 states that the marginal effect of vaccine quality on utility from direct health benefit is less than a critical level, which is plausible if the extent of heterogeneity in social concern is sufficiently large or the vaccine quality is greater than a threshold or both.

Assumption 2. $\Pi(\theta = 1, \varepsilon) > 0$ for all $\varepsilon \in (0, 1]$, $\psi_h \geq \psi_l \geq 0$, $\beta > 0$ and $m > 0$.

Assumption 2 states that the monopolist earns positive profit even in case it serves the entire population, i.e., even in case it sets $\theta = 1$. Implicitly, it states that $0 < c < \frac{2}{\varepsilon^2}[\beta\varepsilon + (\psi_l + m)(1 - \varepsilon)]$.

3.1 The Benchmark: Homogeneous Population

To better understand the implications of heterogeneity in social concern, we first consider the benchmark scenario in which each individual has the same level of social concern ($\psi = \psi_h = \psi_l = \psi_i, \forall i$), ceteris paribus. In this case, Assumption 1 is satisfied if and only if $\varepsilon > \frac{1}{2}$ and $0 < \beta < \bar{\beta}|_{\psi_h=\psi_l=\psi} = \frac{(\psi+m)(2\varepsilon-1)}{\varepsilon}$. Now, since $\delta = \psi_h - \psi_l = 0$, $\psi_h = \psi$ and in stage 1 the monopolist correctly anticipates that $\theta^e = \theta$, the problem of the monopolist can be wriiten as follows.

$$\max_{\theta\in[0,1]} \Pi(\theta,\varepsilon|\psi_i=\psi) = [(\psi+m)(1-\theta\varepsilon)+\beta\varepsilon]\theta - C(\varepsilon) \tag{9}$$

Solving problem (9), by ignoring the constraint $0 \leq \theta \leq 1$, we get $\theta = \frac{\beta\varepsilon+\psi+m}{2(\psi+m)\varepsilon}$. It is easy to check that, under Assumption 1, $0 < \frac{\beta\varepsilon+\psi+m}{2(\psi+m)\varepsilon} < 1$. Thus, under Assumption 1, the unique fulfilled expectations subgame perfect Nash equilibrium (SPNE) vaccine coverage, $\theta^*|_{\psi_i=\psi}$, is as follows.

$$\theta^*|_{\psi_i=\psi} = \frac{\beta\varepsilon+\psi+m}{2(\psi+m)\varepsilon} \tag{10}$$

Note that, for any given vaccine coverage (θ), if the vaccine quality (ε) is lower, (a) individuals' direct health benefit is lower, which reduces their WTP, but (b) susceptibility is higher, which increases WTP in the presence of social concern and the externality effect. Note that, for any given ε, the effect of vaccine coverage (θ) on the monopolist's payoff can be decomposed into three parts.

$$\begin{aligned}\frac{\partial\Pi(\theta,\varepsilon|\psi_i=\psi)}{\partial\theta} &= \underbrace{\frac{\partial[p(\theta,\varepsilon|\psi_i=\psi)\theta]}{\partial\theta}}_{Marginal Revenue(MR)} = \underbrace{\frac{\partial[(\psi+m)(1-\theta\varepsilon)\theta]}{\partial\theta}}_{\substack{MR\,due\,to\,the\,presence\,of\\ social\,concern\,and\,externality\,effect}} + \underbrace{\frac{\partial[\beta\varepsilon\theta]}{\partial\theta}}_{MR\,due\,to\,direct\,health\,benefit}\\ &= \underbrace{\theta\underbrace{\frac{\partial}{\partial\theta}[(\psi+m)(1-\theta\varepsilon)]}_{\substack{\text{WTP reducing effect due to}\\ \text{social concern and externalities}\\ (-)ve}} + \underbrace{[(\psi+m)(1-\theta\varepsilon)]}_{\substack{\text{Scale effect due to}\\ \text{social concern and externalities}\\ (+)ve}}}_{(+)ve\,\forall\theta\in[0,1],\,if\,\varepsilon<\frac{1}{2}} + \underbrace{[\beta\varepsilon]}_{\substack{\text{Scale effect due to}\\ \text{direct health benefit}\\ (+)ve}}\end{aligned}$$

An increase in θ (i) has a negative effect, through reducing the share of the susceptible mass, on the part of WTP that arises due to the presence of individuals' social concern and externalities (WTP reducing effect), (ii) results in higher revenue as it can extract the social concern and externality induced part of the WTP from more number of individuals (positive scale effect arising due to the presence of social concern and externalities), and (iii) results in higher revenue as it can extract the direct health benefit induced part of the WTP from more number of individuals (positive scale effect due to direct health benefit). Now, when $\varepsilon < 1/2$, share of the susceptible mass remains sufficiently large even when the market is fully covered. As a result, the second effect dominates the first effect, implying that the part of the monopolists' marginal revenue due to the presence of social concern and externality effect remains positive for all $\theta \in [0,1]$. Therefore, if $\varepsilon < 1/2$, it is optimal for the monopolist to cover the market fully regardless of the magnitude of the third effect, since marginal cost of vaccine production is zero. Alternatively, if $\varepsilon > 1/2$, the first two effects together can be negative for higher values of $\theta(> \frac{1}{2\epsilon})$. In such a scenario, unless the magnitude of the third effect is sufficiently low (i.e., unless $\beta < \bar{\beta}|_{\psi_h=\psi_l=\psi}$), the third effect dominates the first two effects together and the monopolist's marginal revenue remains positive for all $\theta \in [0,1]$; so full market coverage remains optimal for the monopolist. However, if the vaccine quality and its marginal direct health benefit are such that both $\varepsilon > \frac{1}{2}$ and $0 < \beta < \bar{\beta}|_{\psi_h=\psi_l=\psi}$ hold true, i.e., if Assumption 1 is satisfied, as vaccine coverage increases beyond a certain level, $\theta = \theta^*|_{\psi_i=\psi}$, the negative effect of vaccine coverage on monopolist's payoff, due to its WTP reducing effect (the first effect), starts dominating the overall scale effect (the second and the third effects together). As a result, in the later case, it is optimal for the monopolist to cover the market only partially.

Proposition 1. *Suppose that each individual has the same level of social concern ($\psi = \psi_l = \psi_h > 0$) and Assumption 1 is satisfied. Then the following is true.*

(i) It is optimal for the monopolist not to vaccinate each and every individual in the society. That is, in the equilibrium, the monopolist does not cover the market fully: $\theta^*|_{\psi_i=\psi} < 1$.

(ii) The equilibrium share of vaccinated individuals is lower, if (a) the vaccine is of better quality, and/or (b) individuals have a higher level of social concern, and/or (c) individuals perceive that the net intensity of externality effect is higher: $\frac{\partial\theta^*|_{\psi_i=\psi}}{\partial\varepsilon} < 0$, $\frac{\partial\theta^*|_{\psi_i=\psi}}{\partial\psi} < 0$ and $\frac{\partial\theta^*|_{\psi_i=\psi}}{\partial m} < 0$.

Proof: Immediate from Equation (10).

Proposition 1(i) is clear from the earlier discussion. Now, an increase in the quality of the vaccine results in increase in magnitudes of each of these two effects, but the magnitude of the first effect increases more than proportionately than that of the second effect. As a result, the equilibrium vaccine coverage reduces due to increase in vaccine quality. Intuitively, an increase in vaccine quality leads to a reduction in the share of the susceptible mass and that in turn induces a reduction in WTP, for any given vaccine coverage. The monopolist can restrict such a reduction in WTP by reducing the vaccine coverage, and that is optimal for the monopolist to do so long as the incremental effect of susceptibility on revenues is larger than that of direct health benefit. Next, when individual's social concern is higher or their perceived net intensity of externality effect is higher, the positive effect of susceptibility on WTP is stronger. In such a situation, by setting a lower level of vaccine coverage the monopolist can gain more, as that keeps the share of susceptible mass at a higher level, compared to the associated loss in revenues due to reduced scale of operation.

We note here that Kessing and Nuscheler (2006) and Amir et al. (2023a,b) also show that the the equilibrium vaccine coverage is lower in case the net intensity of externality effect is higher, since in that case an increase in the share of susceptible mass has a larger positive effect on individuals' WTP. Kessing and Nuscheler (2006) demonstrates this result considering a monopoly vaccine supplier, while Amir et al. (2023a,b) show the same in case of oligopoly. The present analysis shows that the effect of susceptibility on WTP gets further amplified in the presence of individuals' social concerns, which results in a further decrease in the equilibrium vaccine coverage.

4 Heterogeneity in Social Concern

Suppose that individuals differ from each other in terms of their social concern, as described in Section 3. In this scenario, the problem of the monopolist can be written as follows.

$$\max_{\theta\in[0,1]} \Pi(\theta,\varepsilon) = p(\theta,\varepsilon)\theta - C(\varepsilon) = [\beta\varepsilon + (\psi_h + m - \delta\theta)(1-\theta\varepsilon)]\theta - C(\varepsilon) \tag{11}$$

Solving the above problem, we get the fulfilled expectations SPNE vaccine coverage θ^* as follows

$$\theta^* = \frac{\psi_h - \psi_l + (\psi_h + m)\varepsilon - \sqrt{(\psi_h - \psi_l + (\psi_h + m)\varepsilon)^2 - 3(\psi_h - \psi_l)\varepsilon(\psi_h + m + \beta\varepsilon)}}{3(\psi_h - \psi_l)\varepsilon} \in (0,1) \tag{12}$$

It can be checked that $\theta^* \in (0,1)$ for all $\beta \in (0,\bar{\beta})$ (Assumption 1). Note that $\frac{\partial \Pi(\cdot)}{\partial \theta} = \underbrace{p(\cdot)}_{+ve} + \theta \underbrace{\frac{\partial p(\cdot)}{\partial \theta}}_{(-)ve}$. That is, by increasing vaccine coverage marginally, the monopolist gains from the price received from the marginal consumer, while at the same time it suffers a loss in revenue due to the corresponding reduction in price for all supra-marginal consumers. In the equilibrium, the monopolist balances these two opposing effects by setting $\theta = \theta^*$ such that its gain from the marginal consumer exactly offsets its loss from supra-marginal consumers: $p(\theta^*) = -\theta^* \frac{\partial p(\theta)}{\partial \theta}|_{\theta=\theta^*}$.

Proposition 2. *Suppose that individuals are heterogeneous in terms of their social concern, and Assumption 1 is satisfied. It is optimal for the monopolist not to supply the vaccine to each and every individual, ceteris paribus:* $\theta^* < 1$.

Proof: Follows immediately from the discussion above.

Proposition 1(i) and Proposition 2 together imply that, regardless of whether individuals are homogeneous or heterogeneous, the monopolist does not find it optimal to cover the market fully. However, the question is, does the monopolist find it optimal to leave a greater share of the population as unvaccinated in case the net intensity of externality effect is higher or the vaccine is of higher quality, as in Proposition 1(ii), even when individuals have heterogeneous social preferences? Further, does heterogeneity in social concern affect the monopolist's equilibrium behaviour? If yes, how?

Lemma 1. *Suppose that Assumption 1 holds true and* $0 \leq \psi_l < \psi_h$. *Then, a higher* ψ_h *leads to a lower* θ^*, *ceteris paribus.*

Proof: See Appendix.

Lemma 1 states that, if in society A the most socially concerned individual's level of social concern is higher, while the least socially concerned individual's level of social concern is the same, compared to those in society B, society A will experience a lower vaccine coverage compared to society B. In other words, if a society is more unequal in terms of individuals' social concern, but has a higher average level of social concern, it is optimal for the monopolist to vaccinate a lower share of population of that society. This is because, keeping ψ_l constant, a higher ψ_h implies a higher variance $Var(\Psi)$ $(=\frac{\delta^2}{12})$ and a higher mean $E(\Psi)$ $(=\frac{\psi_l+\psi_h}{2})$. The intuition is as follows. Given ψ_l, if ψ_h is higher, we are likely to find more individuals with higher levels of social concern than before. Thus, the positive marginal effect of susceptibility on social concern-induced WTP of an average individual as well as of the marginal individual are higher. In such a scenario, it is optimal for monopolist to keep susceptibility at a higher level by vaccinating a lower segment of the population from the upper end of the distribution. Since by doing so the monopolist can charge a higher price from individuals with relatively higher social concern, which over compensates the loss in profit due to reduction in volume of sales.

Note that from Lemma 1 it is not possible to identify the implications of (a) the average level of social concern and (b) heterogeneity in social concern on the equilibrium vaccine coverage, separately. Before we address this issue, let us examine the effects of externalities and vaccine quality on the equilibrium vaccine coverage.

Effect of Net Intensity of Externality on the Equilibrium Vaccine Coverage:

Proposition 3. *Suppose that individuals are heterogeneous in terms of social concern ($\delta = \psi_h - \psi_l > 0$) and Assumption 1 is satisfied. Then, the effect of net intensity of externality on the optimal vaccine coverage is as follows:* $\frac{\partial \theta^*}{\partial m} \begin{cases} > 0, \ if \ \delta > 4\beta\epsilon^2 \\ < (=)0, \ if \ \delta < (=)4\beta\epsilon^2 \end{cases}$.

Proof: See Appendix.

To understand Proposition 3 intuitively, consider a changed scenario in which ψ_h is higher, while everything else including ψ_l remains unaltered, compared to that in the initial state. Then, in the changed scenario δ is higher than that in the initial state, i.e., in the changed scenario, the society is more unequal in terms of individuals' social concern and the average level of social concern is also higher. In that case it is optimal for the monopolist to serve a lesser share of the total population, and serve only those who has relatively higher levels of social concern (by Lemma 1). By doing so the monopolist can charge a higher price, as higher susceptibility in the society enhances WTP of individuals with higher social concern by a greater extent, which over compensates the monopolist for its loss due to a lower volume of sales. Similar argument is also true in case ψ_l goes down, while ψ_h remains the same.[14] Now, if δ is sufficiently high, a higher net intensity of externality induces the monopolist to increase supply, since in that case the marginal consumers' WTP becomes larger than the reduction in revenue from supra-marginal consumers. Needless to mention here that such possibility ceases to exist in

[14]Suppose that when Ψ is distributed over $[\psi_l, \psi_h]$, in the equilibrium the marginal consumers social concern in ψ_0. Now, if ψ_l decreases to $\psi_l' \in [0, \psi_l)$, while the marginal consumer remains the same, the equilibrium vaccine coverage reduces from $\frac{\psi_h - \psi_0}{\psi_h - \psi_l}$ to $\frac{\psi_h - \psi_0}{\psi_h - \psi_l'}$ and the monopolist is able to charge a higher price, due to increased susceptibility. However, the monopolist can charge the higher price to a lesser share of the population, which might induce the monopolist to serve all those whose social concern is at least $\psi_0'(< \psi_0)$. However, it may not be optimal for the monopolist to set ψ_0' such that $\frac{\psi_h - \psi_0'}{\psi_h - \psi_l} > \frac{\psi_h - \psi_0}{\psi_h - \psi_l}$, unless $\beta\epsilon$ is sufficiently large such that $\delta < (=)4\beta\epsilon^2$ holds true.

case each individual has the same level of social concern. This result is in sharp contrast to Kessing and Nuscheler (2006) and Amir et al. (2023a,b).

Impact of Vaccine Quality on the Equilibrium Vaccine Coverage:

Proposition 4. *Suppose that individuals are heterogeneous in terms of social concern ($\delta = \psi_h - \psi_l > 0$) and Assumption 1 is satisfied. Then, it is optimal for the monopolist to immunize a larger share of the population in case the vaccine is of better quality, provided that (a) there is sufficient heterogeneity in individuals' social concerns and (b) the marginal direct health benefit of vaccine quality is greater than a critical level. Otherwise, a higher vaccine quality results in lower vaccine coverage in the equilibrium.*

Proof: See Appendix.

The intuition behind Proposition 4 is as follows. Individuals derive higher direct health benefit from a higher quality vaccine, which results in higher WTP for higher vaccine quality. The extent of such increase in WTP is higher in case the marginal direct health benefit of vaccine quality is higher. On the other hand, a higher quality of the vaccine leads to a reduction in susceptibility, for any given vaccine coverage. This negative effect of vaccine quality on susceptibility results in a lower WTP for better quality vaccine. However, if the society is more heterogeneous in terms social concern, the negative effect of decreased susceptibility is lower (see equation (7)). As a result, in the presence of sufficient heterogeneity, higher vaccine quality results in greater vaccine coverage in the equilibrium, if the marginal direct health benefit of vaccine quality is sufficiently large.

Also note that (a) $m+\psi_l \leq \frac{(m+\psi_h)^2}{4(\psi_h-\psi_l)}$, and (b) when $\psi_h-\psi_l > m+\psi_l$, $m+\psi_h > \frac{(m+\psi_h)^2}{4(\psi_h-\psi_l)}$. Therefore, from the above discussion, it is evident that (a) if $\beta < m+\psi_l$, $\frac{\partial \theta^*}{\partial \varepsilon} < 0$, and (b) if $\psi_h - \psi_l > m + \psi_l$ and $m + \psi_h < \beta < \bar{\beta}$, $\frac{\partial \theta^*}{\partial \varepsilon} > 0$. That is, if the marginal direct health benefit of vaccine quality is very low (less than the total marginal effect of susceptibility on WTP of the least socially concerned individual), an increase in vaccine quality results in lower coverage in the equilibrium. This is because, in such a scenario, the monopolist's pricing strategy relies primarily on exploiting individuals' perceived externality effect and their social concern. On the other hand, if there is sufficient heterogeneity in social concern and the marginal direct health benefit of vaccine quality is very large (more than the total marginal effect of susceptibility on WTP of the most socially concerned individual), it is optimal for the monopolist to focus more on extracting the direct health benefit of the vaccine.

4.1 Distribution of Social Concern and Vaccine Coverage

We now attempt to examine the implications of the average level and the spread of social concern on the optimal choice of a monopoly vaccine supplier. In particular, we attempt to answer the following two questions. Will the monopolist immunize a larger share of the population in case individuals have higher level of social concern on an average? If individuals are more heterogeneous in terms of social concern, i.e., if inequality in social concern is higher, is it optimal for the monopolist to lower the vaccine coverage?

First, note that, from equation (12), the optimal vaccine coverage can be written as

$\theta^* = \frac{1}{6\Delta\epsilon}[2\Delta + (\Delta + m + \bar{\psi})\varepsilon - \sqrt{(2\Delta + (\Delta + m + \bar{\psi})\varepsilon)^2 - 6\Delta\varepsilon(\Delta + m + \bar{\psi} + \beta\varepsilon)}]$, where $\bar{\psi} = E(\Psi)$ and $\Delta = \frac{\delta}{2} = \sqrt{3E(\Psi - \bar{\psi})^2}$.

From the above expression, it is evident that $\frac{\partial\theta^*}{\partial\bar{\psi}} = \frac{\partial\theta^*}{\partial m}$. The reason is as follows. Marginal effects of net intensity of externality (m) and average social concern ($\bar{\psi}$) on any individual i's WTP ($\bar{p_i}$) are equal: $\frac{\partial\bar{p_i}}{\partial\bar{\psi}} = \frac{\partial\bar{p_i}}{\partial m} = (1 - \theta^e\varepsilon)$; since, from (4), $\bar{p_i}$ can be written as $\bar{p_i} = \beta\varepsilon + (\bar{\psi} + \tilde{\Delta_i} + m)(1 - \theta^e\varepsilon)$, where $\tilde{\Delta_i} = \psi_i - \bar{\psi} \gtreqless 0$. Therefore, $\frac{\partial\theta^*}{\partial\bar{\psi}} \begin{cases} > 0, \ if \ \Delta > 2\beta\epsilon^2 \\ < (=)0, \ if \ \Delta < (=)2\beta\epsilon^2 \end{cases}$.

Proposition 5. *Suppose that Assumption 1 is satisfied. Then, a 'mean-increasing spread-preserving' shift in the distribution of social concern leads to an increase (decrease) in the equilibrium vaccine coverage, if the extent of heterogeneity in social concern is more (less) than a critical level.*

Proof: Follows immediately from the above discussion.

Note that, if the marginal effect of vaccine quality on direct health benefit (β) is higher, the condition $\Delta > 2\beta\epsilon^2$ is less likely to be true. That is, a 'mean-increasing spread-preserving' shift in the distribution of social concern is less likely to result in a higher vaccine coverage in the equilibrium in case the marginal effect of vaccine quality on direct health benefit is higher. The underlying mechanism is a follows. Suppose that $E(\Psi)$ increases from $\bar{\psi}$ to $\bar{\psi}+\delta_{\psi}$, but Δ remains unchanged. Then, (i) each individual's WTP and hence, the price, increases by $\delta_{\psi}(1-\theta\varepsilon)$, when θ proportion of individuals are expected to be vaccinated, and (ii) total loss in revenue, due to marginal increase in vaccine coverage, from supra-marginal consumers increases by $\theta\delta_{\psi}\varepsilon$. Accordingly, the monopolist's marginal profitability increases by $\delta_{\psi}(1-2\theta\varepsilon)$. It implies that, when there is a 'mean-increasing spread-preserving' rightward shift in the distribution of social concern, it is optimal for the monopolist to immunize a greater proportion of individuals provided that the initial (i.e., prior to the shift in distribution) equilibrium vaccine coverage is less than the critical level $\frac{1}{2\varepsilon}$. Now, if the marginal effect of vaccine quality on direct health benefit is higher, the equilibrium vaccine coverage is higher. Therefore, the higher the marginal effect of vaccine quality on direct health benefit, lower is the possibility of having a positive effect of 'mean-increasing spread-preserving' shift in the distribution on the equilibrium vaccine coverage, ceteris paribus.

Now, consider an alternative scenario where in there is 'mean-preserving spread-increasing' shift of the distribution of social concern. That is, due to the shift in the distribution, extent of heterogeneity in social concern (Δ) becomes higher, while the average level of social concern ($\bar{\psi}$) remain the same. The direction of the effect of such a change in the distribution on the equilibrium vaccine coverage can be assessed by examining the sign of $\frac{\partial\theta^*}{\partial\Delta}$.

Proposition 6. *Suppose that Assumption 1 is satisfied. Then, an increase in mean-preserving spread of the distribution of social concern enhances the equilibrium vaccine coverage, if the vaccine quality and its marginal effect on direct health benefit are sufficiently large. In all other cases, mean-preserving spread has a negative impact on the equilibrium vaccine coverage.*

Proof: See Appendix.

When both ε and β are higher, direct health benefit is higher and, given the market coverage, the share of the susceptible mass is lower. Implying that individuals' WTP on account of susceptibility, due to externality and social concern, is lower; while WTP on account of direct health benefit is larger. This induces the monopolist to focus more on exploiting direct health benefit, compared to focusing on the incremental effect of susceptibility on WTP. As a result, when both ε and β are sufficiently high, the equilibrium market coverage is sufficiently high. In such a scenario, reduction in market coverage, from its high level, results in a small increase in price, which becomes smaller in case there is an increase in heterogeneity. On the other hand, by reducing market coverage, the monopolist forgoes extracting high direct health benefit induced WTP from those whom the monopolist no longer serves. Thus, in case both ε and β are high, the equilibrium market coverage expands due to increase in heterogeneity.

5 Social Optimality

An increase in the proportion of susceptible individuals in a society, through its positive effect on possible infection transmission from infected individuals to others, enhances public health risk. Thus, higher the proportion of susceptible individuals, higher is the expected social damage due to public health risk and associated repercussion effects on the economy and society. Following Amir et al. (2023b), let $D = d(1-\theta\varepsilon)$ be the social damage, due to infection transmission, when $\theta \in [0,1]$ proportion of individuals are vaccinated with the vaccine of quality $\varepsilon \in (0,1]$. The parameter $d(\geq 0)$ measures the marginal effect of the susceptible mass on social damage. The firm and individuals do not take social damage D into account in their respective decision making process. Then, total surplus ($W(\theta)$), which is the sum of consumers' surplus and the monopolist's profit net of social damage, can be be expressed as follows.

$$\begin{aligned} W(\theta) &= \int_0^\theta [\beta\varepsilon + (m+\psi_h - \delta\theta)(1-\theta\varepsilon)]d\theta - C(\varepsilon) - d(1-\theta\varepsilon) \\ \Rightarrow \quad W(\theta) &= (m+\psi_h+\beta\varepsilon)\theta - (\delta + (m+\psi_h)\varepsilon)\frac{\theta^2}{2} + \frac{\delta\varepsilon\theta^3}{3} - C(\varepsilon) - d(1-\theta\varepsilon) \quad (13) \end{aligned}$$

Solving the benevolent social planner's problem, $\underset{\theta\in[0,1]}{Max}\, W(\theta)$, we obtain the following.

Proposition 7. *The socially optimal vaccine coverage (θ^{FB}), for any given vaccine quality, is given by $\theta^{FB} = 1$.*

Proof: See Appendix.

Proposition 7 states that it is socially optimal to vaccinate each and every individual, i.e., to cover the market fully. In contrast, under Assumption 1, it is optimal to cover the market only partially (Lemma 1). In other words, the monopolist under supplies vaccine in the equilibrium. This is true regardless of whether social damage D is included in the social planner's objective function or not. The reason is, the monopolist does not care about consumers' surplus, which is the standard argument for dead-weight loss due to firms' market power under uniform pricing.

Perfect Price Discrimination and Social Optimality

Note that an individual's social concern is her private information. It is generally hard for the monopolist and the social planner to elicit individuals' levels of social concern, as social concern is a latent characteristic, unlike obtaining information on other characteristics such as income, education, ethnicity, etc. Thus, in the present context, it appears to be rather unrealistic to consider alternative pricing, such as perfect price discrimination, by the monopolist.

Nonetheless, for the sake of argument, if we assume that it is possible for the monopolist to learn each individual's level of social concern, perhaps due to availability of 'Big Data' consisting of nuance information on consumers' preferences and sophisticated methods to analyze such data, the following question arises. Will the monopolist supply the vaccine at the socially optimal level, in case it can engage in perfect price discrimination (ppd)? In a similar context, considering income heterogeneity across consumers and fully effective vaccine ($\epsilon = 1$), Kessing and Nuscheler (2006) show that perfect price discriminating monopolist is socially inefficient, in the presence of sufficiently strong externality effect. However, in the present context, where individuals are heterogeneous in terms of social concern and the vaccine is not fully effective, we show the following.

Proposition 8. *Suppose that Assumption 1 holds true, and the monopolist can access information on individuals' social concern. A perfect price discriminating monopolist is socially efficient, if (a) the vaccine quality is sufficiently low or (b) the vaccine is of moderate quality and its marginal effect on direct health benefit is greater than a critical level. In all other cases, a perfect price discriminating monopolist is socially inefficient.*

Proof: See Appendix.

From Proposition 8 it follows that, if the vaccine is fully effective, the perfect price discriminating monopolist is socially inefficient, as in Kessing and Nuscheler (2006). The result of social inefficiency of ppd under monopoly hold true even when the vaccine is not perfectly effective, unless 'the vaccine quality is very low' or 'the vaccine quality is moderate and the marginal effect of vaccine quality on direct health benefit is more than a threshold level'. In later scenarios, perfect price discriminating monopolist turns out to be socially efficient. The reason for the reversal to social efficiency of perfect price discrimination in case of moderate to low vaccine quality is as follows. If the vaccine quality is sufficiently low, individuals remains susceptible to a large extent even after getting vaccinated. As a result, the susceptibility reducing effect of vaccine coverage is very low and thus, an increase in vaccine coverage reduces individuals' WTP, on accounts of externality and social concern effects, less than proportionately compared to the corresponding increase in revenue due to higher sales. Thus, in the case of very poor quality vaccine the perfect price discriminating monopolist finds it optimal to cover the market fully, regardless of the extent of direct health benefit of the vaccine. In case the vaccine is of moderate quality, the WTP reducing effect of vaccine coverage, via its negative effect on susceptibility, is relatively large. So, in case the vaccine is of moderate quality, it is necessary to have direct health benefit to be greater than a threshold level for full market coverage to be optimal for the monopolist.

Further, we note here that Proposition 8 and its underlying mechanism remain qualitatively similar in case the net intensity of externality effect is arbitrarily small, unlike as in Kessing and Nuscheler (2006). This is because, in the present analysis, the share of susceptible mass affects WTP through two reinforcing channels: (i) externality channel and (ii) social concern channel.

6 Public Policy

We now turn to examine the possibilities of implementation of the socially optimal outcome (full coverage of the vaccine market, $\theta = \theta^{FB} = 1$), given that there is only one vaccine manufacturer, through public policy intervention.

6.1 Government Procurement

Suppose that the government aims to procure the vaccine from the monopolist by paying $p_{procure}(> 0)$ per unit and vaccinate the entire population of mass 1. The government makes a 'take it or leave it' offer (price, quantity)=($p_{procure}$, 1) to the monopolist. If the monopolist accepts the offer, it can sale the vaccine only to the government. On the other hand, if the monopolist rejects the offer, it directly vaccinates individuals, as in absence of any intervention. Now, the monopolist accepts the offer, if its payoff from accepting the offer is at least as much as that in case it rejects the offer, i.e., if $p_{procure} - C(\varepsilon) \geq \Pi(\theta^*) \Leftrightarrow p_{procure} \geq R(\theta^*)$; where θ^* is monopoly equilibrium vaccine coverage in absence of intervention and $R(\theta^*) = p(\theta^*)\theta^*$ is the sales revenue of the monopolist when it vaccinates θ^* proportion of the population.[15] Thus, it is optimal for the government to offer the price $p_{procure} = R(\theta^*)$.

Let p_G be the price charged to individuals by the government for each unit of the vaccine. Then, at price p_G each individual gets vaccinated if any only if $p_G = \bar{p}_l = \beta\varepsilon + (\psi_l + m)(1 - \varepsilon)$. Therefore, the total cost of the government's full vaccine coverage drive through procurement is $C_{Pro} = R(\theta^*) - [\beta\varepsilon + (\psi_l + m)(1 - \varepsilon)]$.

Governments across the world often procure and distribute vaccines, to meet targets of their respective national immunization drives. [16] We show that it is possible for a government to achieve the socially optimal vaccine coverage through the procure and distribute mechanism, but it puts an extra financial burden on the government exchequer. However, at least some of the expenditure may be financed through a per unit profit tax $t(> 0)$. Since a per unit profit tax does not distort the market equilibrium outcome, in the present context fulfilment of the balanced-budget criteria calls for the profit tax rate $t = t_{Pro} = \frac{R(\theta^*) - [\beta\varepsilon + (\psi_l + m)(1-\varepsilon)]}{\Pi(\theta^*)} \in (0, 1)$. That is, the policy "procure at price $p_{procure} = R(\theta^*)$ and distribute at price $\bar{p}_l$, coupled with per unit profit tax $t = t_{Pro}$" is an effective means to ensure complete market coverage without imposing any financial burden on government's exchequer. In the later case, the equilibrium retained profit (i.e, post tax profit) of the monopolist is $\Pi^*_{Pro} = (1 - t_{Pro})[R(\theta^*) - C(\varepsilon)] = (1 - t_{Pro})\Pi(\theta^*) = [\beta\varepsilon + (\psi_l + m)(1 - \varepsilon)] - C(\varepsilon)$, which is positive by Assumption 2.

[15] Note that the mass of population is normalized to be one.

[16] For example, the Indian government's routine immunization program against polio for which all inactivated polio virus vaccines used in India is paid for by the government (Haldar et al., 2019).

6.2 Price Subsidy

Consider that the government offers a subsidy s per unit of the vaccine to individuals, before stage 1 of the game. Then, the vaccine demand function and the monopolist's profit expression, respectively, can be written as $p(\theta|s) = s + \beta\varepsilon + (\psi_h + m - \delta\theta)(1 - \theta^e\epsilon)$ and $\Pi(\theta|s) = [s + \beta\varepsilon + (\psi_h + m - \delta\theta)(1 - \theta^e\epsilon)]\theta - C(\varepsilon)$. Solving the monopolist's profit maximization problem, $\underset{\theta\in[0,1]}{Max}\,\Pi(\theta|s)$, we get the equilibrium vaccine coverage under price subsidy policy θ^{*s} as follows.

$$\theta^{*s} = \frac{1}{6\Delta\epsilon}[2\Delta + (\Delta + m + \bar{\psi})\varepsilon - \sqrt{(2\Delta + (\Delta + m + \bar{\psi})\varepsilon)^2 - 6\Delta\varepsilon(s + \Delta + m + \bar{\psi} + \beta\varepsilon)}],$$

where $\bar{\psi} = E(\Psi)$ and $\Delta = \frac{\delta}{2} = \sqrt{3E(\Psi - \bar{\psi})^2}$.

It follows that $\theta^{*s} = 1 \Leftrightarrow s = s^* = \varepsilon(2m + 2\bar{\psi} - 4\Delta - \beta) - m - \bar{\psi} + 3\Delta (> 0)$. [17] That is, price subsidy $s = s^*$ induces the monopolist to vaccinate everyone. Note that $\frac{\partial s^*}{\partial m} = \frac{\partial s^*}{\partial \bar{\psi}} = 2\varepsilon - 1 \begin{cases} > 0, \text{ if } \varepsilon > \frac{1}{2} \\ < 0, \text{ if } \varepsilon < \frac{1}{2} \end{cases}$, $\frac{\partial s^*}{\partial \Delta} = 3 - 4\varepsilon \begin{cases} > 0, \text{ if } \varepsilon < \frac{3}{4} \\ < 0, \text{ if } \varepsilon > \frac{3}{4} \end{cases}$, and $\frac{\partial s^*}{\partial \epsilon} = [2(m + \bar{\psi} - 2\Delta) - \beta] \begin{cases} > 0, \text{ if } 0 < \beta < 2(m + \bar{\psi} - 2\Delta) \\ < 0, \text{ if } 2(m + \bar{\psi} - 2\Delta) < \beta < \bar{\beta} \end{cases}$. As in Kessing and Nuscheler (2006), price subsidy has two opposing effects on vaccine demand. First, price subsidy reduces effective price for individuals, which increases demand. Second, higher demand reduces expected susceptibility $(1 - \theta^e\varepsilon)$, and thus WTP and demand. Now, reduction in expected susceptibility, due to higher demand, is more when the vaccine quality (ε) is higher. Further, the marginal effect of susceptibility on WTP is higher in case (a) the net intensity of externality (m) is higher and/or (b) the average social concern ($\bar{\psi}$) is higher and/or (c) unless vaccine coverage is less than $\frac{1}{2}$ of the population, heterogeneity in social concern (Δ) is lower.[18] Thus, when ε is sufficiently high, a higher m (or $\bar{\psi}$) calls for higher per unit subsidy, while a higher Δ calls for a lower per unit subsidy. Further, since a higher ε also results in a higher direct health benefit of the vaccine, which is increasing in marginal direct health benefit of the vaccine, ε also has a positive effect on demand. Therefore, a higher ε calls for a lower per unit subsidy, unless marginal effect of ε on direct health benefit is less than a threshold.

Required government expenditure to implement the price subsidy scheme may be fully

[17] It can be checked that $s^* > 0$ for all $\beta \in (0, \bar{\beta})$, i.e., whenever Assumption 1 is satisfied.
[18] See equation (7).

financed by imposing a per unit profit tax $t_{subsidy} = \frac{s^*}{\Pi(\theta=1|s=s^*)}$. That is, the government can ensure that the monopolist vaccinates the entire population and at the same time the government's budget is balanced by the policy "offer subsidy $s = s^*$ per unit of vaccination, and impose tax $t = t_{subsidy}$ per unit of the monopolist's profit". In this case, the monopolist's retained profit in the equilibrium is $\Pi^*_{subsidy} = (1 - t_{subsidy})\Pi(\theta = 1|s = s^*) = \Pi(\theta = 1|s = s^*) - s^* = [\beta\varepsilon + (\psi_l + m)(1 - \varepsilon)] - C(\varepsilon)$, which is positive by Assumption 2.

6.3 Short-fall Tax

Suppose that the government mandates the monopolist to vaccinate all (i.e., to set $\theta = \theta_{mandate} = 1$). Since the monopolist does not have any incentive to comply with the given mandate in absence of any penalty for non-compliance, the government imposes a tax t per unit of short-fall in vaccination rate from the mandated level $\theta_{mandate} = 1$. That is, if the monopolist chooses to vaccinate $\theta \in [0, 1)$ proportion of the population, it will end up paying tax $t(1 - \theta) > 0$ for all $\theta \in [0, 1)$. In this scenario, the profit expression of the monopolist can be written as $\Pi(\theta|\theta_{mandate} = 1) = \Pi(\theta) - t(1 - \theta)$. Now, the short-fall tax will ensure that the monopolist fully complies with the mandate, if and only if $\frac{\partial\Pi(\theta|\theta_{mandate}=1)}{\partial\theta}|_{\theta=1} = 0 \Rightarrow t = t_{mandate} = -\frac{\partial\Pi(\theta)}{\partial\theta}|_{\theta=1} > 0$, by Assumption 1. Therefore, under the policy intervention, which mandates the monopolist to fully cover the market and imposes tax $t = t_{mandate}$ per unit of short fall, it is optimal for the monopolist to ensure full coverage. In the equilibrium, the monopolist sets $\theta = 1$, does not pay any tax, and earn profit $\Pi_{mandate} = [\beta\varepsilon + (\psi_l + m)(1 - \varepsilon)] - C(\varepsilon) > 0$, where the last inequality follows from Assumption 2.

Clearly, the monopolist is indifferent between the three alternative policy interventions, (i) government procurement coupled with per unit profit tax – "procure at price $F = R(\theta^*)$ and distribute at price $\bar{p}_l$, coupled with per unit profit tax $t = t_{Pro}$", (ii) price subsidy coupled with per unit profit tax –"offer subsidy $s = s^*$ per unit of vaccination, and impose tax $t = t_{subsidy}$ per unit of the monopolist's profit", and (iii) "mandate full coverage of the market and impose a per unit short-fall tax $t = t_{mandate}$". Each of these public policy interventions is feasible and ensures the socially optimal outcome. Further, none of these proposed policy interventions impose any burden on the government exchequer. Thus, from the government's perspective also these three alternative policy interventions are equivalent, unless there is implementation cost and these policy measures differ in terms of implementation cost.

Proposition 9. *Suppose that Assumptions 1 and 2 hold true. Then, the following public policies are equivalent: in the equilibrium under each of these policies, the entire population gets vaccinated, the monopolist's payoff remains the same, and the balanced-budget criterion is satisfied.*

$PP1$: *Government procurement coupled with per unit profit tax – "procure at price* $p_{procure} = R(\theta^*)$ *and distribute at price* $\bar{p_l}$*, coupled with per unit profit tax* $t = t_{Pro}$*"; where* θ^* *is the unregulated monopoly equilibrium share of vaccinated individuals,* $R(\theta^*) = p(\theta^*)\theta^*$, $\bar{p_l} = \beta\varepsilon + (m + \psi_l)(1 - \varepsilon)$ *and* $t_{Pro} = \frac{R(\theta^*)-[\beta\varepsilon+(\psi_l+m)(1-\varepsilon)]}{\Pi(\theta^*)} \in (0, 1)$.

$PP2$: *Price subsidy coupled with per unit profit tax –"offer subsidy* $s = s^*$ *per unit of vaccination, and impose tax* $t = t_{subsidy}$ *per unit of the monopolist's profit"; where* $s^* = \varepsilon(2m + 2\bar{\psi} - 4\Delta - \beta) - m - \bar{\psi} + 3\Delta(> 0)$ *and* $t_{subsidy} = \frac{s^*}{\Pi(\theta=1|s=s^*)}$.

$PP3$: *Mandated full coverage and short-fall tax –"mandate full coverage of the market and impose a per unit short-fall tax* $t = t_{mandate}$*"; where* $t_{mandate} = -\frac{\partial\Pi(\theta)}{\partial\theta}|_{\theta=1}(>)0$.

Proof: Follows immediately from the above discussions.

7 Quality Choice under Regulation

So far we have assumed that the quality ε of the vaccine is exogenously given. In this section, we relax this assumption. Suppose that the monopolist undertakes R&D activity to develop the vaccine. The R&D outcome is non-stochastic, and a higher R&D expenditure results in better quality of the vaccine. To develop a vaccine of quality $\varepsilon \in (0, 1]$, the monopolist needs to incur the R&D expenditure $C(\varepsilon)$; where $C'(\varepsilon), C''(\varepsilon) > 0$ for all ε, and $C(0) = 0$, as stated before.[19]

We have shown that, for any given vaccine quality ε, it is optimal for the monopolist to cover the market only partially ($\theta^* < 1$) (Proposition 2). However, full market cover-

[19]Following d'Aspremont and Jacquemin (1988), $C(\varepsilon) = \frac{c\varepsilon^2}{2}$, where $c(> 0)$, form of the R&D cost function is considered widely in the literature (see, for example, (Yang et al., 2024; Buccella et al., 2023; Hafezi et al., 2023; Llanes, 2024; Meickmann, 2023; Amir, 2000)).

age ($\theta^{FB} = 1$) is always socially optimal (Proposition 7). Further, the government can ensure that each individual is vaccinated ($\theta = \theta^{FB} = 1$) in the equilibrium by intervening in the market through alternative balanced-budget profit-neutral public policies (Proposition 9). It, therefore, seems to be meaningful to consider the scenario in which the monopolist correctly anticipates that the socially optimal level of vaccine converge will be implemented through public policy interventions, while the monopolist decides on the level of R&D expenditure to be incurred. To be specific, we now consider an 'extended sequential move game', wherein the stages are as follows.

Stage 1: The monopolist decides the level of its R&D expenditure, and the vaccine quality (ε) is determined accordingly.

Stage 2: The government announces policy $g \in \{PP1, PP2, PP3\}$ with the objective to implement the socially optimal vaccine coverage in the equilibrium in a balanced-budget manner, given the quality of the vaccine (ε); where $PP1$, $PP2$ and $PP3$ are as in Proposition 9.

Stage 3: The monopolist undertakes production. It sales the entire produce to the government, in case $PP1$ is in place. Otherwise, it perfectly commits to a particular level of output θ and quotes a single price p for the vaccine.

Stage 4: Individuals form expectation regarding the vaccine coverage (θ^e) and take vaccination decisions, simultaneously and independently. Transactions take place and payoffs are realized.

From the discussion in Section 6, it follows that in the Stage 3 equilibrium of the 'extended game' $\theta = \theta^{FB} = 1$ occurs, for any given vaccine quality (ε) and regardless of which public policy $g \in \{PP1, PP2, PP3\}$ is in place. In Stage 2, the objective of the government is to vaccinate all in a balanced-budget manner. Since each of the three public policies satisfies these criteria, these are equally preferred by the government. Therefore, in Stage 1, the monopolist's profit expression is given by

$$\Pi(\theta = 1, \varepsilon) = [\beta\varepsilon + (\bar{\psi} + m - \Delta)(1 - \varepsilon)] - C(\varepsilon) \tag{14}$$

Solving the monopolist's profit maximization problem with respect to the vaccine quality ε, we obtain the following result.

Proposition 10. *Suppose that Assumptions 1 and 2 hold true. In the fulfilled expectations SPNE of the 'extended game' the monopolist develops a partially effective vaccine, i.e.,* $\varepsilon^* < 1$.

Proof: See Appendix.

The intuition of this result is simple. By providing a partially effective vaccine the monopolist can keep individuals susceptible to infection. Now, when there are susceptible individuals in the society, individuals are willing to pay more for the vaccine due to their social concern and the presence of externality effect, compared to the scenario in which none is susceptible, i.e., when everyone is vaccinated and the vaccine is fully effective. The monopolist's gain from keeping individuals susceptible together with the gain due to a lower R&D cost for a lower quality vaccine outweighs the associated loss due to a reduction in WTP on account of a lower direct health benefit of a less effective vaccine, whenever the marginal direct health benefit of vaccine quality is relatively less.

Proposition 11. *Suppose that Assumptions 1 and 2 hold true. In the fulfilled expectations SPNE of the 'extended game', the monopolist is more likely to serve the society with a better quality vaccine, if there is higher heterogeneity in social concern or individuals have less social concern on an average.*

Proof: See Appendix.

Intuitively, under full market coverage, (i) a higher price of the vaccine always results in higher profit and (ii) the maximum price that the monopolist can charge is given by the least socially concerned individual's WTP. These are true for any given vaccine quality. Now, vaccine quality has two opposite effects on WTP. First, a higher quality vaccine offers more direct health benefit, which has a positive effect on WTP. Second, a higher vaccine quality results in lower susceptibility and that in turn leads to a lower WTP. The extent of such reduction in WTP is lower if social concern is less, and the lowest level of social concern ($\psi_l = \bar{\psi} - \Delta$) is lower in case the the average level of social concern ($\bar{\psi}$) is lower or the extent of heterogeneity (Δ) is higher. It implies that, under full market coverage, the negative effect of vaccine quality on the equilibrium price of the vaccine is less, if the average level of social concern is less or the extent of heterogeneity is high.

On the other hand, the positive effect of vaccine quality on the equilibrium price does not depend on social concern. Therefore, it is more likely for the monopolist to develop a better quality vaccine, when there is greater heterogeneity in social concern or a lower average level of social concern.

Socially Optimal Vaccine Quality and R&D Subsidy:

When the vaccine market is fully covered (i.e., $\theta = 1$), from equation (13), total surplus $W(\varepsilon|\theta = 1)$ can be written as follows.

$$W(\varepsilon|\theta = 1) = (m + \bar{\psi} + \Delta + \beta\varepsilon) - \frac{2\Delta + (m + \bar{\psi} + \Delta)\varepsilon}{2} + \frac{2\Delta\varepsilon}{3} - C(\varepsilon) - d(1 - \varepsilon). \quad (15)$$

Comparing the social planner's optimal level of vaccine coverage with the monopolist's profit-maximizing level of coverage, we get the following.

Proposition 12. *Suppose that Assumptions 1 and 2 hold true. In the fulfilled expectations SPNE of the 'extended game', the monopolist under supplies vaccine quality compared to the socially optimal level, i.e., $\varepsilon^* < \varepsilon^{FB} = 1$, whenever the marginal effect of susceptibility on social damage is greater than the threshold $\underline{d}$; where $\underline{d} = C'(\varepsilon) - \beta + \frac{3m+3\bar{\psi}-\Delta}{6}$.*

Proof: See Appendix.

The reason behind the shortfall of the monopolist's optimal quality choice from the socially optimal level are (a) unlike the benevolent social planner, the monopolist does not take into account the social damage caused due to the presence of susceptibility, and (b) the monopolist considers only the marginal consumers' payoff , while the benevolent social planner cares about payoffs of the marginal as well as each supra-marginal consumers.

Now, suppose that $d > \underline{d}$ holds true and the government aims to induce the monopolist to develop the perfectly effective vaccine, i.e., to set $\varepsilon = \varepsilon^{FB} = 1$. For this purpose the government announces an output linked R&D subsidy scheme, which offers subsidy $s_{r\&d}$ per unit of quality of the vaccine, at the beginning of Stage 1 of the 'extended game', i.e., before the monopolist undertakes R&D investment for vaccine development, so that the total R&D subsidy expenditure is at the lowest possible level and at the same time the monopolist sets $\varepsilon = 1$. — We refer to this as *modified-'extended game'*. Then,

$\frac{\partial\Pi(\theta=1,\varepsilon)}{\partial\varepsilon} = [\beta - (\bar{\psi} + m - \Delta)] - C'(\varepsilon) + s_{r\&d}$, which implies that $\frac{\partial\Pi(\theta=1,\varepsilon)}{\partial\varepsilon}|_{\varepsilon=1} \geq 0$ if $s_{r\&d} \geq C'(1) - [\beta - (\bar{\psi} + m - \Delta)]$. Clearly, $s^*_{r\&d} = C'(1) - [\beta - (\bar{\psi} + m - \Delta)]$ is the lowest possible amount of subsidy per unit of quality, which induces the monopolist to develop the most effective vaccine $\varepsilon = \varepsilon^{FB} = 1$, under full market coverage.

Lemma 2. *Suppose that Assumptions 1 and 2 hold true. By offering subsidy* $s^*_{r\&d} = C'(1) - [\beta - (\bar{\psi} + m - \Delta)]$ *per unit of vaccine quality before the monopolist invests in R&D, the government can implement the socially optimal vaccine quality* $\varepsilon^{FB} = 1$ *in the equilibrium at the least cost.*

Proof: Follows immediately from the above discussion.

It is evident from Lemma 2 that $\frac{\partial s^*_{r\&d}}{\partial\Delta} < 0$ and $\frac{\partial s^*_{r\&d}}{\partial\bar{\psi}} > 0$. The reason is, a higher heterogeneity in (lower average) social concern results in a higher (lower) marginal profitability of vaccine quality: $\frac{\partial}{\partial\Delta}[\frac{\partial\Pi(\theta=1,\varepsilon)}{\partial\varepsilon}] > 0$ and $\frac{\partial}{\partial\bar{\psi}}[\frac{\partial\Pi(\theta=1,\varepsilon)}{\partial\varepsilon}] < 0$, from equation (14).

Now, consider the *modified-'extended game'*. Then, from Proposition 7, Proposition 9, Proposition 12 and Lemma 2, it follows that in the fulfilled expectations SPNE of the modified-'extended game' (a) the monopolist develops the vaccine of socially optimal quality ($\varepsilon^{**} = 1$), (b) each individual of the society gets vaccinated ($\theta^{**} = 1$) by paying price $p^{**} = \beta (> 0)$, and (c) the monopolist earns profit $\Pi^{**} = \beta - C(1) + s^*_{r\&d} = C'(1) - C(1) + \bar{\psi} + m - \Delta (> 0)$. [20]

Note that the government's expenditure on R&D subsidy for vaccine development can be financed through the tax $t_{r\&d} = \frac{s^*_{r\&d}}{\Pi^{**}} = \frac{C'(1)-\beta+\bar{\psi}+m-\Delta}{C'(1)-C(1)+\bar{\psi}+m-\Delta} \in (0,1)$ per unit of profit of the monopolist.[21] Since profit tax in non-distortionary, the tax $t_{r\&d}$ per unit of profit of the the monopolist will not alter the equilibrium outcomes, except that the monopolist's net profit will reduce to $\beta - C(1) (> 0$, by Assumption 2). Also, note that, if the government opted for the policy '$PP1$: Government procurement coupled with per unit profit tax' in stage 2 of the *modified-'extended game'* , then in the equilibrium, the government will procure vaccine at price β from the monopolist and also sell at the same

[20]Note that $\bar{\psi} - \Delta = \psi_l \geq 0$ (by supposition), and $C'(1) - C(1) > 0$, since $C'(\cdot) > 0$ and $C''(\cdot) > 0 \, \forall \varepsilon \in (0,1]$.

[21]By Assumption 2, $\Pi(\theta = 1, \varepsilon) > 0 \, \forall \varepsilon \in (0,1]$. Now, $\Pi(\theta = 1, \varepsilon = 1) = \beta - C(1)$, from equation (8). Therefore, $\beta > C(1)$ (by Assumption 2). It is evident that $\beta > C(1) \Rightarrow t_{r\&d} < 1$. Next, as we have seen, under Assumption 1, $\frac{\partial\Pi(\theta=1,\varepsilon)}{\partial\varepsilon}|_{\varepsilon=1} = \beta - (\bar{\psi} + m - \Delta) - C'(1) < 0$, which together with $C'(1) > C(1)$ and $\psi_l \geq 0$ imply that $t_{r\&d} > 0$.

price β to each individual, the government recovers the total cost of procurement and, so, does not impose any tax on monopolist's profit, in the equilibrium of the *modified-'extended game'*. Alternatively, if the government opted for the policy '$PP2$: Price subsidy coupled with per unit profit tax' in stage 2 of the *modified-'extended game'*, in the equilibrium the government subsidizes sales at the rate $s^* = (m + \bar{\psi} - \Delta) - \beta (> 0$, by Assumption 1) per unit of the vaccine and the monopolist pays tax $t_{subsidy} = \frac{s^*}{\Pi(\theta=1, s=s^*)} = \frac{s^*}{\beta - C(1) + s^*} \in (0,1)$, by Assumptions 1 and 2, per unit of its profit. Lastly, if the government opted for the policy '$PP3$: Mandated full coverage and short-fall tax' in stage 2 of the *modified-'extended game'*, the monopolist does not pay any tax, since it covers the vaccine market fully under $PP3$, in the equilibrium.

8 Conclusion

Given that individuals have preferences regarding the effects of their actions on others' payoffs — referred to here as social concerns— and operate within a voluntary vaccination setting, we examine equilibrium vaccination behaviour in a monopoly vaccine market characterised by network externalities. We treat vaccine quality, defined as its effectiveness in providing immunity against infection, as a continuous variable. In our framework, a perfectly effective vaccine arises only as a limiting case. We analyse the implications of vaccine quality, the intensity of network externalities, 'mean-preserving, spread-increasing' and 'mean-increasing, spread-preserving' shifts in the distribution of social concern, and perfect price discrimination on equilibrium market coverage for any given level of vaccine quality. Additionally, we consider endogenous determination of vaccine quality by the monopolist through investment in vaccine R&D, under conditions of market coverage regulation.

We have demonstrated that it is always optimal for the monopolist to cover only part of the vaccine market, regardless of the quality of the vaccine, the strength of network externalities, or the extent of heterogeneity in social concern. By contrast, in our framework, social optimality always requires full market coverage. Nonetheless, there are three plausible, balanced-budget public policy interventions, each of which can successfully induce the monopolist to achieve full market coverage: (1) government procurement coupled with a per-unit profit tax, (2) a price subsidy coupled with a per-unit profit tax, and (3) mandated full coverage coupled with a per-unit profit tax. Interestingly, the monopolist earns the same amount of post-tax profit under each of these three public policy interventions.

We have also shown that a 'mean-increasing spread-preserving' shift in the distribution of individuals' social concerns results in a higher market coverage in the equilibrium, provided that the extent of heterogeneity in social concern is sufficiently high. Otherwise, the opposite is true. On the other hand, a 'mean-preserving spread-increasing' shift in the social concern distribution leads to a higher market coverage in the equilibrium, if the vaccine quality and its marginal direct health benefit are very high. These results suggest the following. (a) The market is likely to penalize a society more in which individuals' preferences are closely aligned to each other and have higher social concerns, compared to a society in which also individuals' preferences are closely aligned to each other but have lower social concerns, by contracting vaccine supply. (b) If the vaccine is of sufficiently high quality and its direct health benefit is also high, the market may reward a more heterogeneous (in terms of variation in social concerns) society by reducing the prevalence of the disease through vaccination in the equilibrium.

Further, we have shown that higher net intensity of externality enhances equilibrium market coverage if the extent of heterogeneity in social concern is sufficiently large. This result contrasts sharply with the findings of Kessing and Nuscheler (2006) and Amir et al. (2023a,b) and challenges the conventional wisdom that profit-oriented vaccine suppliers would always find it optimal to keep disease prevalence high if the disease is more contagious. This conventional wisdom is based on the assumption that individuals care only about their own well-being. Our findings highlight the importance of considering empirically grounded, realistic preferences of individuals, both for formulating business strategies and for gauging public health outcomes in market equilibrium. This result also suggests that the market serves a sufficiently heterogeneous society (in terms of social concern) better if the disease is more contagious.

We have also shown that equilibrium market coverage is lower if the vaccine is of higher quality, unless both the extent of heterogeneity in social concern and the marginal direct health benefit of the vaccine are sufficiently high, suggesting that quality regulation alone may result in an undesirable public health outcome. We have also demonstrated that the efficiency of perfect price discrimination crucially depends on vaccine quality and its impact on direct health benefits.

Finally, we have shown that under public policy interventions targeted towards improving equilibrium market coverage, the monopolist under-invests in vaccine R&D and serves a lower-quality vaccine compared to the socially optimal standard. To correct the problem of under-provision in vaccine quality and under-coverage of the vaccine market at equilibrium, it is necessary to design a comprehensive vaccine policy, which involves (i) a performance-linked R&D subsidy scheme and (ii) appropriate public policy interventions (as discussed above) to achieve the desired level of market coverage.

Our analysis leads to several testable implications. First, a mean-increasing shift in the distribution of individuals' social concerns, while keeping the spread at a high level, results in greater market coverage. Second, if vaccine quality exceeds a critical level, a monopolist vaccine supplier covers a larger share of the market when there is greater heterogeneity in social concern. Third, the contagiousness of a disease positively affects vaccine supply when individuals are more heterogeneous in terms of their social concerns. Fourth, higher vaccine quality has a negative effect on vaccine supply if individuals have similar levels of social concern. Fifth, perfect price discrimination in the market for vaccines against contagious diseases is socially efficient. Although gathering relevant data from real-world cases may be challenging, it would be interesting to test these hypotheses in laboratory settings. We leave this for future experimental studies.

There are three maintained assumptions in our analysis. First, we assume that individuals' social concern is uniformly distributed. While our results are likely to hold qualitatively as long as the social concern distribution remains symmetric, it would be worthwhile to extend the analysis to more general distribution functions. Second, we assume that the social planner can credibly commit to its announced policy measures. Relaxing this assumption would likely alter the efficiency of the proposed policies. Developing policy measures to improve vaccine market equilibrium outcomes in the absence of full policy credibility is an area for future research. Third, we assume that individuals are heterogeneous in only one dimension, i.e., social concern. This simplification keeps the analysis focused and tractable. It goes without saying that, in reality, individuals differ from one another in multiple dimensions, such as social concern, income, health status, and education. Results in a framework of multi-dimensional heterogeneity would depend crucially on the direction and strength of correlations among these variables. Our qualitative findings would likely hold if there were a sufficiently strong positive correlation between social concern and other variables — though this does not appear to be an empirically valid assumption. This issue lies beyond the scope of the present paper and remains an open question for future research.

References

Amir, R. (2000). Modelling imperfectly appropriable R&D via spillovers. *International Journal of Industrial Organization*, 18(7):1013–1032.

Amir, R., Garcia, F., and Topolyan, I. (2023a). First-best health policy in vaccine markets with health and network externalities. *Journal of Public Economic Theory*, 25(6):1229–1250.

Amir, R., Liu, Z., and Tian, J. (2023b). Negative network effects and public policy in vaccine markets. *Journal of Economic Behavior & Organization*, 216:136–149.

Arnesen, S., Bærøe, K., Cappelen, C., and Carlsen, B. (2018). Could information about herd immunity help us achieve herd immunity? evidence from a population representative survey experiment. *Scandinavian Journal of Public Health*, 46:854–858.

Arnould, R. and DeBrock, L. (1996). The application of economic theory to the vaccine market. In Pauli, M., Robonson, C., Sepe, S., and Willian, M., editors, *Supplying vaccine: An economic analysis of critical issues*. IOS Press, USA.

Brito, D. L., Sheshinski, E., and Intriligator, M. D. (1991). Externalities and compulsary vaccinations. *Journal of Public Economics*, 45(1):69–90.

Buccella, D., Fanti, L., and Gori, L. (2023). Network externalities, product compatibility and process innovation. *Economics of Innovation and New Technology*, 32(8):1156–1189.

Bénabou, R. and Tirole, J. (2003). Intrinsic and Extrinsic Motivation. *Review of Economic Studies*, 70(3):489–520.

Böhm, R. and Betsch, C. (2022). Prosocial vaccination. *Current Opinion in Psychology*, 43:307–311.

Cappelen, A. W., Halvorsen, T., Sorensen, E. O., and Tungodden, B. (2017). Face-saving or fair-minded: What motivates moral behavior? *Journal of the European Economic Association*, 15(3):540–557.

Centers for Disease Control (US). (2011). Morbidity and mortality weekly report: MMWR. US Department of Health, Education, Welfare, Public Health Service.

Danzon, P. M. and Pereira, S. N. (2011). Vaccine supply: Effects of regulation and competition. *International Journal of the Economics of Business*, 28(2):239–271.

Das, U., Pal, R., Rathore, U., and Saha, B. (2023). Rein in pandemic by pricing vaccine: Does social trust matter? `http://www.igidr.ac.in/pdf/publication/WP-2023-008.pdf`IGIDR-WP-2023-008.

d'Aspremont, C. and Jacquemin, A. (1988). Cooperative and noncooperative R&D in duopoly with spillovers. *American Economic Review*, 78(5):1133–1137.

Geoffard, P.-Y. and Philipson, T. (1997). Disease eradication: Private versus public vaccination. *American Economic Review*, 87(1):222–230.

Hafezi, M., Zhao, X., and Zolfagharinia, H. (2023). Together we stand? co-opetition for the development of green products. *European Journal of Operational Research*, 306(3):1417–1438.

Haldar, P., Agrawal, P., Bhatnagar, P., Tandon, R., McGray, S., Zehrung, D., Jarrahian, C., and Foster, J. (2019). Fractional-dose inactivated poliovirus vaccine, india. *Bulletin of the World Health Organization*, 97(5):328.

Heal, G. and Kunreuther, H. (2005). The vaccination game. *Risk Management and Decision Processes Center Working Paper*, (05-10).

Hong, S. (2023). Covid-19 vaccine communication and advocacy strategy: a social marketing campaign for increasing covid-19 vaccine uptake in south korea. *Humanities and Social Sciences Communications*, 10(109).

Katz, M. L. and Shapiro, C. (1985). Network externalities, competition, and compatibility. *American Economic Review*, 75(3):424–440.

Kessing, S. G. and Nuscheler, R. (2003). Monopoly pricing with negative network effects: The case of vaccines. *WZB, Markets and Political Economy Working Paper No. SP II 2003-06*.

Kessing, S. G. and Nuscheler, R. (2006). Monopoly pricing with negative network effects: The case of vaccines. *European Economic Review*, 50(4):1061–1069.

Korn, L., Böhm, R., Meier, N. W., and Betsch, C. (2020). Vaccination as a social contract. *Proceedings of the National Academy of Sciences*, 117(26):14890–14899.

Lake, J., Gerrans, P., Sneddon, J., Attwell, K., Botterill, L. C., and Lee, J. A. (2021). We're all in this together, but for different reasons: Social values and social actions that affect covid-19 preventative behaviors. *Personality and Individual Differences*, 178(110868).

Llanes, G. (2024). Innovation incentives in technical standards. *International Journal of Industrial Organization*, 93:103046.

Meickmann, F. C. (2023). Cooperation in knowledge sharing and R&D investment. *Journal of Economic Behavior & Organization*, 211:146–164.

Murphy, J., Vallières, F., Bentall, R. P., Shevlin, M., McBride, O., Hartman, T. K., McKay, R., Bennett, K., Mason, L., Gibson-Miller, J., Levita, L., Martinez, A. P., Stocks, T. V. A., Karatzias, T., and Hyland, P. (2021). Psychological characteristics associated with covid-19 vaccine hesitancy and resistance in ireland and the united kingdom. *Nature Communications*, 12(29).

Phelan, T. and Toda, A. A. (2022). Optimal epidemic control in equilibrium with imperfect testing and enforcement. *Journal of Economic Theory*, 206:105570.

Reddinger, J. L., Charness, G., and Levine, D. (2024). Vaccination as personal public-good provision. *Journal of Economic Behavior & Organization*, 224(August):481–499.

Scherer, F. (2007). An industrial organization perspective on the influenza vaccine shortage. *Managerial and Decision Economics*, 28(4-5):393–405.

Sorensen, A. (2023). The role of vaccine effectiveness on individual vaccination decisions and welfare. *Journal of Public Economic Theory*, 25(6):1212–1228.

Vilar-Lluch, S., McClaughlin, E., Knight, D., Adolphs, S., and Nichele, E. (2023). The language of vaccination campaigns during covid-19. *Medical Humanities*, 49:487–496.

Xu, X. (1999). Technological improvements in vaccine efficacy and individual incentive to vaccinate. *Economics Letters*, 65(3):359–364.

Yang, J., Zhang, W., and Zhao, X. (2024). How can suppliers strategically involve downstream manufacturers in research and development collaboration? a knowledge spillover perspective. *European Journal of Operational Research*, 314(1):122–135.

Appendix

Proof of Lemma 1.

From equation (12), we get

$\frac{\partial \theta^*}{\partial \psi_h} = -\frac{m+\psi_l}{3(\psi_h-\psi_l)^2} + \frac{(m+\psi_l)(2(m+\psi_h)\varepsilon-(\psi_h-\psi_l))-3\beta\epsilon(\psi_h-\psi_l)}{6(\psi_h-\psi_l)^2\sqrt{(\psi_h-\psi_l+\varepsilon(m+\psi_h))^2-3\epsilon(m+\psi_h)(\psi_h-\psi_l)-3\beta\varepsilon^2(\psi_h-\psi_l)}}$. It can be checked that $\frac{\partial \theta^*}{\partial \psi_h} < 0$ for all $\beta \in (0, \bar{\beta})$.

■

Proof of Proposition 3.

An increase in "net intensity of externality" m leads to (a) an increase in WTP of each consumer by $\frac{\partial p(\cdot)}{\partial m} = (1-\varepsilon\theta)$, and (b) an increase in the negative effect of vaccine coverage on revenues from supra-marginal consumers by $|\theta \frac{\partial}{\partial m}[\frac{\partial p(\cdot)}{\partial \theta}]| = \theta\varepsilon$, ceteris paribus.[22] This is because, a higher m makes individuals more sensitive to externalities arising from the susceptible mass. It follows that $Sign(\frac{\partial \theta^*}{\partial m}) = Sign(\frac{\partial^2 \Pi(\cdot)}{\partial m \partial \theta}|_{\theta=\theta^*}) = Sign(\frac{\partial p(\cdot)}{\partial m}|_{\theta=\theta^*} + \theta^* \frac{\partial(\frac{\partial p(\cdot)}{\partial \theta})}{\partial m}|_{\theta=\theta^*}) = Sign(1-2\varepsilon\theta^*)$, ceteris paribus.[23] It is easy to check that $(1-2\varepsilon\theta^*) > (\leq)0 \Leftrightarrow \delta > (\leq)4\beta\epsilon^2$. It implies that a higher net intensity of externality effect induces the

[22]From Equation (7) after substituting $\theta^e = \theta$.

[23]Note that, from the first order condition of the monopolist's profit maximization problem, $\frac{\partial \Pi(\cdot)}{\partial \theta} = 0$ (assuming that Assumption 1 is satisfied), by using implicit function theorem we can write $\frac{\partial \theta}{\partial m} = -\frac{\frac{\partial}{\partial m}[\frac{\partial \Pi(\cdot)}{\partial \theta}]}{\frac{\partial^2 \Pi(\cdot)}{\partial \theta^2}}$. Also, note that the second order condition $\frac{\partial^2 \Pi(\cdot)}{\partial \theta^2} < 0$ is satisfied.

monopolist to increase (decrease) the vaccine coverage, if $\delta > 4\beta\epsilon^2$ ($\delta < 4\beta\epsilon^2$). Therefore, Proposition 3 follows.

$\blacksquare$

Proof of Proposition 4.

From equation (12), we get $\frac{\partial\theta^*}{\partial\varepsilon} = \frac{1}{3\varepsilon^2}[\frac{2(\psi_h-\psi_l)-\varepsilon(m+\psi_h)}{\sqrt{[2(\psi_h-\psi_l)-\varepsilon(m+\psi_h)]^2-3\varepsilon^2[4\beta(\psi_h-\psi_l)-(m+\psi_h)^2]}} - 1]$, for all $\beta \in (0,\bar{\beta})$. It follows that $\frac{\partial\theta^*}{\partial\varepsilon} \begin{cases} > 0, \text{ if } \delta > \frac{(m+\psi_h)^2}{4\beta} \\ < (=)0, \text{ if } \delta < (=)\frac{(m+\psi_h)^2}{4\beta} \end{cases}, \forall\beta \in (0,\bar{\beta})$. Note that $\delta > \frac{(m+\psi_h)^2}{4\beta} \Leftrightarrow \beta > \frac{(m+\psi_h)^2}{4\delta}$. Now, for both $\frac{(m+\psi_h)^2}{4\delta} < \beta$ and $\beta \in (0,\bar{\beta})$ to be true, we must have $\delta > \frac{m+\psi_h}{2}$ ($\equiv \delta > m + \psi_l$), i.e., the extent of heterogeneity in social concern must be greater than a threshold level.[24] Thus, when individuals are sufficiently heterogeneous in terms of their social concern ($\delta > \frac{m+\psi_h}{2}$) and the direct marginal health benefit of vaccine quality is greater than a critical level ($\beta > \frac{(m+\psi_h)^2}{4\delta}$), the equilibrium vaccine coverage is increasing in vaccine quality. Otherwise, the reverse is true.

$\blacksquare$

Proof of Proposition 6.

From the first order condition of the monopolist's profit maximization problem in Stage 1, $\underset{\theta\in[0,1]}{Max}\,\Pi(\cdot)$, we get $Sign(\frac{\partial\theta^*}{\partial\Delta}) = Sign(f(\theta^*))$, where $f(\theta) = \frac{\partial}{\partial\Delta}[\frac{\partial\Pi}{\partial\theta}] = 1-2(2+\epsilon)\theta+6\epsilon\theta^2$. It is evident that (i) $f(\theta)$ has a unique minimum at $\theta = \theta_0 = \frac{2+\varepsilon}{6\varepsilon}$, where $\theta_0 \in [0,1)$ if $\frac{2}{5} < \varepsilon \leq 1$; otherwise, $\theta_0 > 1$ if $0 < \varepsilon \leq \frac{2}{5}$; (ii) if $0 < \varepsilon < \frac{3}{4}$, $f(\theta) = 0$ at $\theta = \theta_1 = \frac{2+\varepsilon-\sqrt{4-2\varepsilon+\varepsilon^2}}{6\varepsilon} \in (0,1)$; (iii) if $\frac{3}{4} < \epsilon \leq 1$, $f(\theta) = 0$ at $\theta = \theta_1$ and at $\theta = \theta_2 = \frac{2+\varepsilon+\sqrt{4-2\varepsilon+\varepsilon^2}}{6\varepsilon}$, where $0 < \theta_1 < \theta_0 < \theta_2 < 1$. Further, it can be checked that, under Assumption 1, (a) $0 < \theta_1 < \theta^*$ for all $\varepsilon \in (0,1]$, and (b) when $\frac{3}{4} < \varepsilon \leq 1$, $\theta^* > (<)\theta_2$ if $\underline{\beta} < \beta < \bar{\beta}$ ($0 < \beta < \underline{\beta}$); where $\underline{\beta} = \frac{(m+\bar{\psi})(\varepsilon-1+\sqrt{4-(2-\varepsilon)\varepsilon})}{3\varepsilon}$. Therefore, $\frac{\partial\theta^*}{\partial\Delta} > 0$ if $\frac{3}{4} < \varepsilon \leq 1$ and $\underline{\beta} < \beta < \bar{\beta}$; otherwise, $\frac{\partial\theta^*}{\partial\Delta} < 0$.

$\blacksquare$

[24]Note that, when $\delta > \frac{m+\psi_h}{2}$, we have (a) $\frac{\partial\bar{\beta}}{\partial\epsilon} < 0$, and (b) $\bar{\beta} < (=)\beta$ if $\varepsilon > (=)\frac{\psi_h-2\psi_l-m}{\beta+\psi_h-3\psi_l-2m}$. Needless to mention that, if $\bar{\beta} < (=)\beta$, i.e., if Assumption 1 is violated, it is optimal for the monopolist to set $\theta = 1$. So, when $\delta > \frac{m+\psi_h}{2}$, for $\frac{\partial\theta^*}{\partial\varepsilon} > 0$ to hold we need $\varepsilon < \frac{\psi_h-2\psi_l-m}{\beta+\psi_h-3\psi_l-2m}$ along with $\frac{(m+\psi_h)^2}{4\delta} < \beta$. Note that, whenever $\delta > \frac{m+\psi_h}{2}$, we have $\psi_l + m < \frac{(m+\psi_h)^2}{4\delta}$. It implies that, whenever $\delta > \frac{m+\psi_h}{2}$ and $\frac{(m+\psi_h)^2}{4\delta} < \beta$, we have $\frac{\psi_h-2\psi_l-m}{\beta+\psi_h-3\psi_l-2m} < 1$. In other words, when $\delta > \frac{m+\psi_h}{2}$, the condition $\frac{(m+\psi_h)^2}{4\delta} < \beta < \bar{\beta}$ implicitly assumes that $\varepsilon < \frac{\psi_h-2\psi_l-m}{\beta+\psi_h-3\psi_l-2m}(< 1)$.

Proof of Proposition 7.

From equation (13), it follows that the second order condition $\frac{\partial^2 W(\theta)}{\partial \theta^2} < 0$ holds true always. Further, it is easy to observe that $\frac{\partial W(\theta)}{\partial \theta}|_{\theta=0} > 0$ and $\frac{\partial W(\theta)}{\partial \theta}|_{\theta=1} > 0$ for all $\beta > 0, m > 0,\ d \geq 0,\ \varepsilon \in (0,1],\ \psi_h > \psi_l > 0$.[25] Thus, $\underset{\theta \in [0,1]}{Argmax}\, W(\theta) = 1$, i.e., the socially optimal vaccine coverage $\theta^{FB} = 1$.

■

Proof of Proposition 8.

Suppose that under perfect price discrimination the monopolist commits to an output $\theta_p = \frac{\psi_h - \psi_p}{\psi_h - \psi_l}$ and demands the entire WTP from each individual having social concern $\psi \in [\psi_p, \psi_h]$. Then, the perfect price discriminating monopolist's profit, $\Pi(\psi_p)$, is as follows.

$$\begin{aligned}\Pi(\psi_p) &= \int_{\psi_p}^{\psi_h} \left(\beta\varepsilon + (\psi + m)(1 - \frac{\psi_h - \psi_p}{\psi_h - \psi_l}\varepsilon)\right) d\psi \\ &= \beta\varepsilon(\psi_h - \psi_p) + \left(\frac{\psi_h^2 - \psi_p^2}{2} + m(\psi_h - \psi_p)\right)(1 - \frac{\psi_h - \psi_p}{\psi_h - \psi_l}\epsilon) - C(\varepsilon)\end{aligned}$$

The problem of the monopolist under perfect price discrimination can be written as $\underset{\psi_p \in [\psi_l, \psi_h]}{Max} \Pi(\psi_p)$. Now,

$$\frac{\partial \Pi(\psi_p)}{\partial \psi_p}|_{\psi_p = \psi_l} \begin{cases} < 0, \text{ if (a) } 0 < \varepsilon \leq \varepsilon_{ppd} \text{ or (b) } \varepsilon_{ppd} < \varepsilon \leq 1\, and\, \beta > \beta_{ppd} \\ > 0, \text{ if } \varepsilon_{ppd} < \varepsilon \leq 1\, and\, 0 < \beta < \beta_{ppd} \end{cases}, \text{ for all } m \geq 0$$

and $\psi_h > \psi_l \geq 0$; where $\varepsilon_{ppd} = \frac{2m + 2\psi_l}{4m + \psi_h + 3\psi_l}$ and $\beta_{ppd} = \frac{\varepsilon(4m + \psi_h + 3\psi_l) - 2(m + \psi_l)}{2\varepsilon}$. Further, $\beta_{ppd} < (>) \bar{\beta}$ if $\varepsilon < (>) \frac{2}{3}$. Therefore, under Assumption 1, we have the following, for all $m \geq 0$ and $\psi_h > \psi_l \geq 0$.

$$\theta_{ppd} \begin{cases} = 1, \text{ if (a) } 0 < \varepsilon \leq \varepsilon_{ppd} \text{ or (b) } \varepsilon_{ppd} < \varepsilon < \frac{2}{3}\, and\, \beta_{ppd} < \beta < \bar{\beta} \\ < 1, \text{ otherwise} \end{cases}.$$

■

[25] $\frac{\partial W}{\partial \theta} = m + \psi_h + \beta\varepsilon - (\delta + (m + \psi_h)\varepsilon)\theta + \delta\varepsilon\theta^2 + d\varepsilon$. Clearly, $\frac{\partial W(\theta)}{\partial \theta}|_{\theta=0} = m + \psi_h + \beta\varepsilon + d\epsilon > 0$ and $\frac{\partial W(\theta)}{\partial \theta}|_{\theta=1} = (m + \psi_l)(1 - \varepsilon) + (\beta + d)\varepsilon > 0$. Also, $\frac{\partial^2 W}{\partial \theta^2} = -(\delta + (m + \psi_h)\varepsilon) + 2\delta\varepsilon\theta = -(m + \psi_h)\varepsilon(1 - \theta) - (\psi_h - \psi_l)(1 - \varepsilon\theta) - (m + \psi_l)\epsilon\theta < 0$.

Proof of Proposition 10.

Note that $\Pi(\theta = 1, \varepsilon) > 0$, by Assumption 2, and $\frac{\partial^2 \Pi(\theta=1,\varepsilon)}{\partial \varepsilon^2} = -C''(\varepsilon) < 0 \, \forall \varepsilon \in (0, 1]$, by supposition. Further, $\frac{\partial \Pi(\theta=1,\varepsilon)}{\partial \varepsilon}|_{\varepsilon=1} = \beta - (\bar{\psi} + m - \Delta) - C'(1) < 0$, since (a) $\bar{\beta}|_{\varepsilon=1} = (\bar{\psi} + m - \Delta)$ and, by Assumption 1, $0 < \beta < \bar{\beta}$ for any given ε and (b) $C'(\varepsilon) > 0 \, \forall \varepsilon \in (0, 1]$, by supposition. Therefore, it follows that $\varepsilon^* = \underset{\varepsilon \in (0,1]}{Argmax} \, \Pi(\theta = 1, \varepsilon) < 1$.

■

Proof of Proposition 11.

Note that $\frac{\partial \bar{\beta}}{\partial \varepsilon} = \frac{1}{\varepsilon^2}(\bar{\psi} + 2m - 2\Delta)$. Now, suppose $2\Delta > \bar{\psi} + 2m$. Then, $\frac{\partial \bar{\beta}}{\partial \varepsilon} < 0$, which implies that $\bar{\beta}|_{\varepsilon<1} > \bar{\beta}|_{\varepsilon=1}$. In this case, if $(\bar{\psi} + m - \Delta) + C'(\varepsilon) < \beta < \bar{\beta}|_{\varepsilon<1}$ holds true for some $\varepsilon \in (0, 1)$, the monopolist's optimal choice of vaccine quality $\varepsilon^* = \hat{\varepsilon}$, where $\hat{\varepsilon}$ is implicitly given by $C'(\hat{\varepsilon}) = \beta - (\bar{\psi} + m - \Delta)$ and $0 < \hat{\varepsilon} < 1$.[26] Alternatively, if $2\Delta < \bar{\psi} + 2m$, we have $\frac{\partial \bar{\beta}}{\partial \varepsilon} > 0$ and, thus, $\bar{\beta}_{\varepsilon<1} < \bar{\beta}_{\varepsilon=1}$. In the later case, by Assumption 1, we will always have $\beta < (\bar{\psi} + m - \Delta)$, which implies that $\varepsilon^* = \varepsilon_0$ where ε_0 is arbitrarily small and close to zero. Overall, it follows that, if Δ is higher or $\bar{\psi}$ is smaller, the condition $2\Delta > \bar{\psi} + 2m$ is more likely to be satisfied and so $\varepsilon^* = \hat{\varepsilon}(>> 0)$ is more likely to be true. Also, note that $C'(\hat{\varepsilon}) = \beta - (\bar{\psi} + m - \Delta)$ and $C''(\varepsilon) > 0$ imply that $\hat{\varepsilon}$ is higher if Δ is higher or $\bar{\psi}$ is lower. Otherwise, if $2\Delta < \bar{\psi} + 2m$, we will have $\varepsilon^* = \varepsilon_0(\approx 0)$.

■

Proof of Proposition 12.

From equation (15), it is easy to check that $W(\varepsilon|\theta = 1)$ is strictly concave in ϵ, since $C''(\varepsilon) < 0$. Now, $\frac{\partial W(\varepsilon|\theta=1)}{\partial \epsilon}|_{\epsilon=1} > 0 \Leftrightarrow d > \underline{d}$, where $\underline{d} = C'(\varepsilon) - \beta + \frac{3m+3\bar{\psi}-\Delta}{6}$. It follows that the socially optimal vaccine quality $\varepsilon^{FB} = 1$, if $d > \underline{d}$.

■

[26] Note that, for Assumption 1 to be satisfied for $0 < \varepsilon < 1$, we must have $\beta < \bar{\beta}|_{\varepsilon<1}$.