Redesigning Primary Care Delivery: Customized Office Revisit Intervals and E-Visits

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The demand for physician services in primary care is shaped by the number of patients associated with each physician and the frequency of scheduled office visits. While a physician can typically set the size of her patient panel without regard for individual patient preferences, office revisit intervals are determined jointly by the physician and her patients. We analyze these decisions by modeling patient demand for office visits as a function of office revisit intervals. In our model, a physician can manage the demand for her services using two “customization” approaches. On one hand, she can adjust the office revisit intervals based on patient health status. On the other hand, she can divert some of the patient demand away from the office visits and into the “e-visits”, which utilize less of the physician’s service capacity while still maintaining an appropriate quality of care. Using our model, we characterize care settings, defined in terms of patient panel features, parameters of primary care delivery, and physician compensation schemes, that result in increased expected earnings for the physician, larger panel size, and improved patient health. We also describe settings in which customization of care may lead to worse outcomes on at least one of these dimensions.

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1. Introduction

In the complex landscape of the US healthcare reform, one of the central issues is that of redesigning the system of delivering medical care in the presence of tens of millions of patients that, due to expanded coverage, have recently joined the healthcare system. The additional demand has spurred an active search for new approaches to care delivery that would result in better utilization of existing patient care capacity. This issue is particularly relevant for primary care, the major point of access to care for most patients.

The primary care environment is distinctively different from other, more procedural, care settings, in which an exogenously determined stream of arriving patients needs to be handled by one or multiple resources. By contrast, in primary care, the arrivals of patients to the practice is not
just the input to operational decision making, it also is the consequence of operational decisions
the practice makes. Consider the case of a diabetic patient who is presently scheduled to visit the
practice once every four weeks (we will later on define this as the revisit interval, or RVI for short).
What happens if the practice decides to see this patient every eight weeks instead? Now, there
obviously exists a direct effect on physician productivity. Holding everything else constant, the
physician could now handle twice as large of a patient population. But, unfortunately, not every-
thing will remain equal. In particular, our diabetic patient is now more likely to fall sick between
office visits, requiring some urgent (unscheduled) visits to the practice. Such unscheduled visits are
not just inconvenient (and potentially dangerous) to the patient, they also introduce randomness
into the appointment planning process for the practice.

This creates a dual responsibility for a physician: overseeing healthy patients in scheduled (rou-
tine) office visits and helping unhealthy patients during unscheduled (urgent) visits. Balancing the
needs of these two groups of patients has received recent attention as new technologies now enable
physicians to provide some care by leveraging technology. For example, secure messaging between
physicians and patients, also referred to as e-visits, allows a physician to provide some care with-
out the patient coming to the practice and occupying an appointment slot. Such new technology
not only alters physician productivity, but also patient utility (the patient might not like to come
to the practice every four weeks) and health outcomes (unhealthy patients can be identified ear-
lier). Moreover, depending on reimbursement policies, such technologies can also impact physician
compensation. Our model explores a setting in which the physician manages patient demand by
leveraging two forms of care customization. These customization approaches can be applied to
changing the frequency with which the physician schedules routine office visits for different patient
groups. They can also be used to separate channels of care such as e-visits for different types of
patient demand.

To analyze how the introduction of e-visits impacts the healthcare system, we need to develop a
new type of model driving patient demand. This new model does not take arrivals to the practice
as given, but instead explicitly models the underlying health of the patients, thereby effectively
endogenizing patient demand. It also needs to capture the different objectives of the agents involved
in choosing the time of the next visit, physicians and patients.

We present an approach to analyzing primary care demand that treats both physicians and
patients as active entities reacting to the changes in the care delivery system. In our model, patients
define a range of acceptable values for their scheduled office revisit intervals (RVIs), and the physi-
cian chooses the patient panel size and the RVI value to maximize her expected daily revenue
subject to her daily appointment capacity. A patient determines the range of acceptable RVI values
based on the trade-off between the cost associated with making an office visit and the disutility
of falling sick. As a result, patient demand for primary care emerges as an endogenous process governed by both patient preferences and physician financial incentives. On the physician side, the problem is a capacity-based revenue management model (Talluri and Van Ryzin 2005). The physician selects the size of her patient panel and patient revisit intervals to maximize her compensation, which may be a mix of “fee-for-service” (receiving a fixed fee for each office visit), and “capitation” (receiving a fixed fee for each patient on her panel) payments.

The RVI selection process involves adapting the frequency of scheduled office visits to patient health status. For example, the physician may assign a lower RVI to “sicker” patients to check on them more frequently, while reserving less frequent office visits for “healthier” patients. In practice, the RVI values are often significantly influenced by subjective factors, in addition to objective patient characteristics (Welch et al. 1999, Schwartz et al. 1999, DeSalvo et al. 2000). In particular, Schectman et al. (2005) state that “provider practice style may reflect scheduling habits acquired from previous training independent of the patients’ medical needs. For example, providers have often been trained to schedule their patients every 3 or 4 months routinely, regardless of disease severity.” This observation underscores a potential opportunity for improving the utilization of physician care capacity by incorporating patient health status into the process of selecting the RVI values.

The channel of care customization focuses on leveraging technological innovations such as e-visits to provide certain types of care without the need for in-office visits. Provided this technology, the physician may choose to divert to e-visits only those visits for which an e-visit and office visit offer similar quality of care. Since e-visits are likely to be less expensive for the patient than office visits, and can save the physician’s time that can be used for providing more in-office care when it is required, both parties should be willing to adopt this innovation as long as the physician receives sufficient compensation for this type of care. We demonstrate the conditions under which e-visits are feasible with respect to patient preferences and physician compensation.

Our analysis focuses on a heterogeneous patient population and examines the impact of these care customization approaches on three key performance measures: physician revenue, patient health, and patient panel size. These indicators reflect the impact of changes in care delivery on three major groups of stakeholders: physicians, patients, and society as a whole. In our model, physician revenue is calculated as the average daily compensation comprised of a mix of fee-for-service and capitation-based payments. We use this performance measure as an indicator of how attractive the care customization is to physicians. On the patient side, we consider a panel comprised of two distinct patient groups and define patient health as the expected portion of in-office visits devoted to routine check-ups as opposed to urgent matters related to “flare-ups” in chronic conditions or acute sickness episodes. The changes in the panel’s overall health level reflect the impact of care
customization on patients. Finally, we treat the changes in the size of patient panel as an important societal measure of performance of the primary care system in providing primary care coverage.

A key novel feature of our analysis is modeling the responses of both patients and physicians to changes in the ways care is managed. The endogenous nature of these responses has a direct impact on care outcomes. For example, the introduction of e-visits may change the degree of flexibility that patients display with respect to the range of RVI values they are willing to accept. Since in our model the RVI values are jointly selected by patients and their physicians, the balance between the scheduled and urgent visits may be altered as well, resulting in changes in patient health, as well as physician compensation, and the number of patients that a physician can accommodate on her panel. Ignoring the endogeneity in patient and physician responses may lead to starkly different conclusions about the impact of primary care innovations.

We present our results using as a benchmark the case where neither mechanism of care customization is employed. We begin by showing the impact of RVI customization on the three key performance measures: physician revenue, patient health, and patient panel size. Next, we study the impact of e-visits on these performance indicators. We also illustrate the combined impact of RVI and care channel customization using a numerical example in Appendix B. The results of our analysis can be summarized as follows:

1. We provide the analytical characterization of the optimal RVI values in the settings with and without RVI customization (Propositions 1 and 2).
2. We show that although RVI customization increases physician revenue, it may lead to smaller panel sizes and lower patient health. In particular, if the majority of patients are not healthy, patient health may decrease, while if the majority of patients are healthy, panel size may decrease. We also derive analytical bounds on the improvement in physician revenue resulting from RVI customization (Proposition 3).
3. We analytically characterize the patients’ joint decision on e-visit adoption and the value of RVI (Proposition 4). We show that the “sicker” patients are more likely to adopt e-visits, and that the “healthier” patients gravitate towards e-visits only when those replace a sufficiently large fraction of regular office visits. Also, we characterize the optimal RVI values in the presence of e-visits (Propositions 5 and 6) and analyze the impact of e-visits on physician revenue, patient health and panel size.
4. We show that if e-visits, as well as routine and urgent visits, are compensated proportionally to their duration, then their introduction increases both physician revenue and panel size with no negative impact on patient health (Proposition 7). If, however, the compensation that the physician receives for providing e-visits is not adequate, physician revenue, panel size, and patient health may all suffer (Propositions 8 and 9).
Our paper is organized as follows. Section 2 reviews the relevant literature. Section 3 introduces the model we use to quantify the benefits of adapting the RVI values to patient health status. In Section 4 we model and analyze the impact of using e-visits. We conclude by discussing our findings in Section 5.

2. Literature Review

In the operations management literature, several papers focus on matching patient demand and treatment capacity in primary care settings. Green et al. (2007) provide guidelines on patient panel sizing in primary care. Green and Savin (2008) and Liu and Ziya (2014) apply queuing analysis to study the effects of patient no-shows on physician panel sizes, and Zacharias and Armony (2016) study the joint problem of panel sizing and appointment scheduling. Ozen and Balasubramanian (2013) quantify the impact of case-mix on physician utilization and panel sizes, and Balasubramanian et al. (2012) show the advantages of provider flexibility and quantify the trade-off between access to and continuity of care. A key modeling element in these papers is the exogenous nature of patient demand for care. In contrast, we treat patient demand as an endogenous process governed by the physician’s choice of RVI values consistent with patient preferences.

The related literature includes a number of studies that show the impact of compensation schemes on the policies healthcare providers adopt (e.g., Adida et al. 2016, Andritsos and Tang 2018, Adida and Bravo 2018, Guo et al. 2019). Our model of physician compensation resembles the one in McGuire (2000), as it has both a fee-for-service and capitation component. Similar to Shumsky and Pinker (2003), we study the response of primary care physicians to alternative compensation schemes, but, instead of looking at the role of a physician as a gatekeeper to the healthcare system, we study the physician’s choice of office revisit intervals and patient panel size.

We also contribute to the literature that studies e-visits and telemedicine. Zhong et al. (2016) model the patient workflow in a primary care system in the presence of e-visits and evaluate the impact of a new mode of delivering care on the length of patient office visits. In our paper, we focus on the impact of e-visits on key performance indicators, such as patient health, physician revenue and patient panel size. In related work, Çakici and Mills (2016) study teletriage, a system that provides medical advice to patients, and show that the effectiveness of teletriage depends on how patient respond to its introduction based on their perceived level of health.

Rajan et al. (2018) study the operational impact of telemedicine on a specialist serving a heterogeneous patient population suffering from chronic conditions. Our modeling approach differs from Rajan et al. (2018) in multiple ways as their model is geared toward a specialist rather than a primary care physician. First, the physician in their model optimizes patient service rate and service price, while we take these two quantities as given and focus instead on a physician’s decision on patient revisit intervals. Second, the physician compensation contract in our model is a
mix of fee-for-service and capitation, a feature that is common in primary care, as compared to the fee-for-service contract considered in Rajan et al. (2018). Third, we study the impact of RVI customization as compared to uniform RVI policy that is prevalent primary care (Schectman et al. 2005). Fourth, e-visit payments by patients and e-visit compensation for the physician we consider fee-for-service and capitation elements, both of which affect the physician and patient decisions regarding RVIs, while in their model the patient is only responsible for a copay that is modeled as a fraction of the price not covered by insurance.

This paper is related to the work of Bavafa et al. (2019) in that both papers examine key primary care system outcomes (patient health, panel size, and physician compensation) and endogenize RVI values based on patient and physician preferences. Beyond that, the papers differ along every key dimension. For example, the present paper studies e-visits, a cost-based intervention, along with RVI customization by patient health status, whereas the focus of Bavafa et al. (2019) is on the impact of non-physician providers, a quality-based intervention. The theoretical models and subsequent results thus differ due to the separate goals of these papers. For example, the present paper examines variation in visit type compensation, physician compensation regime (allowing for combinations of fee-for-service and capitation payments), and patient heterogeneity, none of which is studied in Bavafa et al. (2019).

Our model also builds on the extant literature on preventive maintenance (McCall 1965, Wu and Zuo 2010). The problem faced by the patient is a special case of the “age replacement” policy (Glasser 1967), and the physician’s problem is related to the “machine interference” or “repairman problem” (Stecke and Aronson 1985, Cho and Parlar 1991, Haque and Armstrong 2007). In healthcare, Deo et al. (2013) study a related problem of determining revisit intervals for asthma patients in community-based chronic care setting using a Markovian disease progression model. The novel feature of our model, not addressed in the existing literature, is the interaction between the incentives of the patient (“machine”) and the physician (“repairman”). In particular, in our model we allow not only the “repairman” but also the “machines” to actively respond to changes in care delivery, such as introduction of e-visits.

One of the key features of our model is the physician’s decision regarding the frequency of patient scheduled visits, i.e., RVI values. In particular, under RVI customization in our model, the physician’s decision on RVIs is a function of patient health. Therefore, our work is related to prior work that study the timing of disease screening and treatment. A group of studies in this literature focus on screening tests to detect the first incidence of a disease (Kirch and Klein 1974, Maillart et al. 2008, Rauner et al. 2010, Brailsford et al. 2012, Helm et al. 2015, Güneş et al. 2015, Deo et al. 2015), while another group is focused on treatment decisions for a previously detected condition (Alagoz et al. 2004, Shechter et al. 2008, Ayer et al. 2012, Lavieri et al. 2012). Our
work differs from this literature since our goal is to develop insights on the interaction between patient preferences and physician incentives when deciding on patient revisit intervals rather than to develop a detailed high-fidelity model of a particular primary-care practice.

3. Revisit Interval Customization: Model and Analysis

In this section, we consider a primary care setting where a single physician provides in-office service to her patients. We look at a heterogeneous patient panel that includes two mutually exclusive and collectively exhaustive groups of patients: “healthy” and “sick”. When a patient falls into the sick state, he is immediately treated by the physician in an office visit during which the patient is “restored” to the healthy state. We assume that, following an office visit, a patient of group $i$ will fall into the sick state in the absence of care and will require an office visit after a random time period $T_i$. We model $T_i$ as taking one of the two discrete values:

$$T_i = \begin{cases} T_l, & \text{with probability } q_i, \\ T_h, & \text{with probability } 1 - q_i, \end{cases}$$

with $T_l < T_h$ and $0 \leq q_i \leq 1$, so that $E[T_i] = q_l T_l + (1 - q_i) T_h$ and $\text{Var}[T_i] = 2(1 - q_i) q_i (T_h - T_l)^2$. This simplified representation of the stochastic process of “falling sick” allows for tractable analysis of the care delivery. Also, the process described by (1) possesses the increasing failure rate (IFR) property. The IFR implies, plausibly, that, as time since the last office visit increases, the patient is more likely to get sick. Note that our model does not rely on the patient being restored to “full health” by an office visit after falling sick. We assume that the patient is being restored to a baseline state (which we call “healthy”). The goal of our modeling of patient health dynamics is to represent the IFR, i.e., the increased likelihood for patients to get healthier if they visit their physician more frequently. After an office visit, the patient still falls sick with probability $q$ after $T_l$ time, so, for example, having a chronic condition would still translate into a pattern of office visits.

We assume that all patients on the panel, irrespective of the group they belong to, transition between “healthy” and “sick” states independently from each other. Note that the value of $q_i$ can be characterized as the level of overall “health” of a particular patient group, as $T_i$ is stochastically decreasing in $q_i$, so that the lower is $q_i$, the healthier is the patient group. In our modeling, we focus on the impact of the difference in health levels between patient groups on the choice of the office revisit intervals and the size of the overall patient panel. In particular, we consider a case with two patient groups and treat them as being identical in all characteristics except for their health levels, $q_1$ and $q_2 \neq q_1$.

In our model, the physician and her patients jointly select the RVI, which is the time until the next scheduled office visit. The use of scheduled office visits is analogous to the “age replacement”
policy in the machine maintenance literature (Glasser 1967). In primary care, patients play an active role in setting the RVI values (Welch et al. 1999), so we use a two-stage model for the process of selecting the RVI that considers both patient and physician incentives. At the first stage, patients select a range of RVI values they find acceptable. At the second stage, the physician chooses the RVI value among the alternatives provided by the patients. The role of the patients can be thought of as that of a Stackelberg leader that provides a constraint on the RVI values for the physician’s optimization problem.

This modeling approach is similar to the classic “divide-and-choose” procedure (Brams and Taylor 1996) and is different from the Nash bargaining alternative for selecting the RVI. Under the Nash bargaining approach, the RVI value is set as a “compromise” between physician and patient preferences and is determined by optimizing a joint objective function constructed from the objectives of the two parties using a parameter that describes their relative bargaining power (Ellis and McGuire 1990). We consider the “divide-and-choose” approach to be more realistic in healthcare settings for two reasons. First, in practice, patients are likely to be willing to accept a range of revisit interval values instead of insisting on a single value. Second, the Nash bargaining approach relies on the knowledge of the “bargaining power” parameter that is difficult to reliably estimate in practice.

3.1. Patient Preferences for Office Revisit Intervals

Suppose that, upon completion of every office visit of a patient from group $i = 1, 2$, the next visit is scheduled in $r_i$ time units. The patient’s actual next office visit will occur after the random time interval $\min(T_i, r_i)$. The expected value of this time between office visits calculated over the two-scenario distribution of $T_i$ is given by

$$T_i(r_i) = \begin{cases} 
  r_i, & r_i \leq T_l, \\
  q_iT_l + (1-q_i)r_i, & T_l < r_i \leq T_h, \\
  q_iT_l + (1-q_i)T_h, & r_i > T_h,
\end{cases}$$

(2)

that is an increasing concave function of the RVI value $r_i$. Note that, in presence of the scheduled revisit interval $r_i$, every office visit falls into one of two categories we label as “routine” and “urgent”. Under the routine visit, the patient comes to the physician’s office while still in the “healthy” state, while under the urgent visit, the patient is in the “sick” state. For a given value of $r_i$, the probability that a particular office visit of a patient from group $i$ falls into the “routine” category is given by

$$\rho^r_i(r_i) = P(T_i \geq r_i) = \begin{cases} 
  1, & r_i \leq T_l, \\
  1 - q_i, & T_l < r_i \leq T_h, \\
  0, & r_i > T_h.
\end{cases}$$

(3)
Note that when \( r_i = T_h \), and the patient falls sick after \( T_l \) time units and visits the physician with an urgent visit, the patient’s previous appointment corresponding to \( T_h \) is canceled. For such a patient, another appointment is scheduled for \( T_h \) time units upon the completion of the urgent visit.

We assume that during a “routine” visit to the physician’s office a patient from any group incurs the cost \( c_o \), while during an “urgent” visit the same patient incurs the cost of \( c_o (1 + \eta) \), with \( \eta \geq 0 \). The factor \( \eta \) captures the additional cost associated with the patient being sick when visiting the office. Thus, expressed in the units of \( c_o \), the expected cost associated with an office visit is

\[
C_i(r_i) = \rho(r_i) + (1 + \eta) (1 - \rho(r_i)) = \begin{cases} 
1, & r_i \leq T_l, \\
1 + q_i \eta, & T_l < r_i \leq T_h, \\
1 + \eta, & r_i > T_h.
\end{cases}
\] (4)

Patient preferences for the RVI values is governed by the objective of minimizing the long-run average cost. We use the standard renewal process framework to calculate the patient’s long-run average cost. Consider the following counting process for the number of patient visits in the interval \([0, t]\):

\[
A(t) = \max \left\{ n : \sum_{j=1}^{n} \min \{ T_{i,j}, r_i \} \leq t \right\},
\] (5)

where \( T_{i,j} \) is the \( j \)th value of \( T_i \) in the \([0, t]\) interval.

The reward (cost in the units of \( c_o \)) earned by the patient until time \( t \) is given by

\[
R(t) = \sum_{j=1}^{A(t)} \mathbb{1}_{\{T_{i,j} \geq r_i\}} + \mathbb{1}_{\{T_{i,j} < r_i\}} (1 + \eta).
\] (6)

Then, the patient’s long-run average cost is the following:

\[
D_i^o(r_i) = \lim_{t \to \infty} \frac{R(t)}{t} = \frac{C_i(r_i)}{T_i(r_i)} = \begin{cases} 
\frac{1}{r_i}, & r_i \leq T_l, \\
\frac{1 + q_i \eta}{q_i T_l + (1 - q_i) r_i}, & T_l < r_i \leq T_h, \\
\frac{1}{r_i + (1 + \eta) T_h}, & r_i > T_h,
\end{cases}
\] (7)

where we used the standard result for renewal reward processes in (7).

Under the two-scenario distribution (1) the RVI value that minimizes (7) is either \( T_l \) or \( T_h \). Since (7) is a decreasing function of \( r_i \) for \( r_i \leq T_l \) and for \( r_i \in (T_l, T_h] \), the global minimum of \( D_i^o(r_i) \) is either \( T_l \) or \( T_h \). Comparing \( D_i^o(T_l) \) and \( D_i^o(T_h) \), we get the following result.

**Lemma 1.** For given values of \( \eta \) and \( q_i \), the global minimizer of (7) is

\[
\bar{r}_i^o = \begin{cases} 
T_l, & q_i > \frac{1}{1 + \frac{1}{q_i T_l} - 1}, \\
T_h, & q_i \leq \frac{1}{1 + \frac{1}{q_i T_l} - 1}.
\end{cases}
\] (8)
Lemma 1 states that the patient preference for RVI values switches from the lowest possible value of $T_l$ to the highest possible value when the health level of a patient group exceeds a certain threshold, i.e., when $q_i$ drops below $\frac{1}{1 + \frac{\eta}{T_l - 1}}$. Note that the threshold value for $q_i$ is a decreasing function of the “sickness factor” $\eta$, indicating that the higher is patient’s sickness cost, the easier it is for him to select more frequently scheduled office visits.

If patients knew the values of $T_l$, $T_h$, and $q_i$ with perfect precision, the outcome of patient RVI optimization problem would result in a single RVI value. In reality, however, patients are often more flexible. To model this observation, we assume that while the values of $T_l$, $T_h$, and $q_i$ are known to patients (as well as to their physicians), patients do not know the value of their sickness factor $\eta$ with certainty, but, rather, know that this value is located in the interval $[\eta_{\text{min}}, \eta_{\text{max}}]$. To describe this interval we use the following notation: we denote the center of the interval with $c = \frac{\eta_{\text{min}} + \eta_{\text{max}}}{2}$, and the half-length of the interval with $c\Delta = \frac{\eta_{\text{max}} - \eta_{\text{min}}}{2}$ with $\Delta \in [0, 1]$. Using this notation, the patient knows that $\eta$ is in the interval $[c(1 - \Delta), c(1 + \Delta)]$. Thus, in our model, the patient group $i$ is characterized by a set of three parameters $(q_i, c, \Delta)$. In this set, the value of $q_i$ describes the degree of overall health of patient group $i$: groups with high (low) values of $q_i$ can be characterized as “sick” (“healthy”). The value of $c$, on the other hand, reflects the expected degree of tolerance of being “sick” that patients display: low values of $c$ describe “stoic” patients, while high values of $c$ correspond to “worried” patients. Finally, $\Delta$ stands for the degree of flexibility that a patient displays with respect to the choice of the RVI value: low values of $\Delta$ correspond to “inflexible” patients, while high values of $\Delta$ correspond to “flexible” patients.

Given the uncertainty in the value of the sickness factor $\eta$, patients may accept either exactly one of the RVI values described in Lemma 1, or both values, depending on the value of the flexibility parameter $\Delta$. In particular, if inequality $q_i < \frac{1}{1 + \frac{\eta}{T_l - 1}}$ holds for any $\eta \in [c(1 - \Delta), c(1 + \Delta)]$, then the patients will select $T_h$ as their preferred RVI value. In a similar fashion, if $q_i > \frac{1}{1 + \frac{\eta}{T_l - 1}}$ holds for any $\eta \in [c(1 - \Delta), c(1 + \Delta)]$, then the patients will select $T_l$ as their preferred RVI value. However, if $\frac{1}{1 + \frac{\eta}{T_l - 1}} \leq q_i \leq \frac{1}{1 + \frac{\eta}{T_h - 1}}$, then the patients will be willing to accept any of the two RVI values, $T_l$ or $T_h$. By letting $\{r_i^-, r_i^+\}$ denote the two RVI values that patients in group $i$ are willing to accept, we can formally express these observations as follows.

**Lemma 2.**

\[
\{r_i^-, r_i^+\} = \begin{cases} 
\{T_h, T_h\}, & q_i < q^-(c, \Delta), \\
\{T_l, T_l\}, & q_i > q^+(c, \Delta), \\
\{T_l, T_h\}, & q^-(c, \Delta) \leq q_i \leq q^+(c, \Delta), 
\end{cases}
\]

where

\[
q^-(c, \Delta) = \frac{1}{1 + \frac{\eta}{T_l - 1}},
\]

\[
q^+(c, \Delta) = \frac{1}{1 + \frac{\eta}{T_h - 1}}.
\]
Lemma 2 describes the impact of the level of health $q_i$ on the RVI values acceptable for a particular patient group. In particular, if patient health level is low (high), the patient group is “inflexible” and will insist on the lowest (highest) RVI value. On the other hand, for the health levels in the intermediate range, patient are “flexible” with respect to the choice of the RVI value, allowing the physician to make that choice according to her preferences.

### 3.2. Appointment Capacity Allocation and Physician Compensation Schemes

We consider a physician who serves a heterogeneous panel of $N$ patients, with $N_i = \kappa_i N$ patients belonging to the patient group $i = 1, 2$, with $\kappa_1 + \kappa_2 = 1$. Note that, for the simplicity of our analysis, we assume that $N$ can take fractional values. We also assume that demand for the physician’s services is sufficiently high and the physician is able to select the overall size of her patient panel $N$. The fractions $(\kappa_1, \kappa_2)$ represent exogenous quantities that reflect the composition of the patient population in the physician’s local area. The physician may be able to select the RVI values for each patient group, $r_i$, within the range of values acceptable to patients, but she can only control the size of each patient group, $N_i$, by varying the panel size $N$. This assumption reflects the reality of care delivery in the US where a physician, in general, cannot “close” her panel to any particular patient group. While it is possible for a physician to exercise an indirect control of the size of some patient groups by refusing to accept a particular kind of insurance coverage (for example, reducing the number of elderly patients by rejecting the Medicare coverage), we consider this possibility atypical and do not model it in our analysis.

We assume that the physician has to provide sufficient daily appointment capacity to deal with the total expected daily demand from all patient groups. Using the standard renewal process framework (similar to (5)-(7)), the physician’s capacity constraint is given by

$$N \left( \kappa_1 \left( \rho_1^r (r_1) \frac{\tau^r}{T_1 (r_1)} + (1 - \rho_1^r (r_1)) \frac{\tau^u}{T_1 (r_1)} \right) + \kappa_2 \left( \rho_2^r (r_2) \frac{\tau^r}{T_2 (r_2)} + (1 - \rho_2^r (r_2)) \frac{\tau^u}{T_2 (r_2)} \right) \right) \leq A, \tag{12}$$

where $\tau^r$ ($\tau^u$) is the time required by a routine (urgent) patient visit, and $A$ is the physician’s total daily service capacity. We assume that an urgent visit requires longer time commitment from a physician, so that $\tau^u > \tau^r$.

In choosing the size of her patient panel $N$ and the revisit intervals $r_i$ for each patient group, a physician is guided by her compensation scheme. In our analysis, we focus on two common ones: fee-for-service (FFS) and capitation (CAP). We assume that under the fee-for-service incentive scheme a physician is paid a fixed amount $R^r$ for each routine visit and $R^u$ for each urgent visit, no matter which group a patient belongs to. An urgent visit, requiring a longer time commitment
physician’s compensation scheme is a pure fee-for-service. For example, if
where \( \delta^u \) refers to the proportion of physician daily compensation that is based on the FFS scheme.

Under the capitation scheme a physician is paid a fixed amount (per time period, e.g., a year) for each patient on her panel. Thus, a “capitation” physician, effectively, focuses on maximizing the size of her patient panel \( N \):

\[
\Pi_{CAP}(N, r_1, r_2) = N (\kappa_1 R_1^d + \kappa_2 R_2^d) = NR^d,
\]

where \( R^d \) is the fixed daily compensation for each patient, whether from group 1 or group 2.

The physician’s total compensation may be a combination of fee-for-service and capitation components that reflects a mix of insurance policies used by patients on her panel:

\[
\Pi_d(N, r_1, r_2) = \delta \Pi_{FFS}(N, r_1, r_2) + (1 - \delta) \Pi_{CAP}(N, r_1, r_2)
\]

\[
= N \left( (1 - \delta)R^d + \delta \kappa_1 \left( \frac{\rho_1^u(r_1) R^c + (1 - \rho_1^u(r_1)) R^u}{T_1(r_1)} \right) + \delta \kappa_2 \left( \frac{\rho_2^u(r_2) R^c + (1 - \rho_2^u(r_2)) R^u}{T_2(r_2)} \right) \right),
\]

where \( \delta \) refers to the proportion of physician daily compensation that is based on the FFS scheme.

In summary, the problem of selecting patient panel size \( N \) and the office revisit intervals \( r_1 \) and \( r_2 \) that a physician faces can be formulated as

\[
\max_{N, r_1, r_2} \Pi_d(N, r_1, r_2)
\]

\[
s.t. \quad N \left( \kappa_1 \left( \frac{\rho_1^u(r_1) \tau^c + (1 - \rho_1^u(r_1)) \tau^u}{T_1(r_1)} \right) + \kappa_2 \left( \frac{\rho_2^u(r_2) \tau^c + (1 - \rho_2^u(r_2)) \tau^u}{T_2(r_2)} \right) \right) \leq A,
\]

\[
r_1 \in \{r_1^-, r_1^+\}, r_2 \in \{r_2^-, r_2^+\}.
\]

(16)-(18) reflect the “divide-and-choose” approach to selecting the RVI values, where a physician chooses the optimal values among the ones acceptable to patients. We use the notation \( \{\hat{N}, \hat{r}_1, \hat{r}_2\} \) to denote the values of patient panel size and revisit intervals that optimize (16)-(18). To simplify the analysis of (16)-(18), we will assume that the daily service capacity \( A \) and the patient panel size \( N \) can take fractional values. Below we describe the values of \( \{\hat{N}, \hat{r}_1, \hat{r}_2\} \) for the setting with two “flexible” patient groups.

Note that while models that consider a revenue-maximizing physician are common in the literature (e.g., Gupta and Wang 2008, Liu 2016), other terms such as patient health or social welfare may appear in the objective function of the physician.
3.3. Quantifying the Impact of Revisit Interval Customization

In this section we analyze the benefits of adapting frequency of scheduled office visits to patient health status. In particular, we will characterize the optimal RVI decisions in the setting where both patient groups are flexible. Specifically, we consider 2 patient groups such that \( q_i \in [q^-(c, \Delta), q^+(c, \Delta)] \), \( i = 1, 2 \) which is equivalent to \( r_i^- = r_i^+ = T_i \) and \( r_i^+ = r_i^- = T_h \). In the setting with 2 flexible patient groups, the physician can set the total panel size as well as the RVI values for both patient groups. Note that if one of the patient groups is inflexible, the problem reduces to one with a homogeneous panel and reduced appointment capacity, and if both patient groups are inflexible, the physician has no choice regarding patient RVI values.

In order to provide the analytical characterization of the optimal solution to (16)-(18), we introduce the following quantities:

\[
\bar{q}^- = \frac{1}{1 + \left( \frac{c^u - 1}{T_l} \right)}, \tag{19}
\]

\[
\bar{q}^R = \frac{1}{1 + \left( \frac{c^u - 1}{T_h} \right)}, \tag{20}
\]

\[
Q^T = \frac{T_h}{T_l} - 1, \tag{21}
\]

\[
\bar{R} = 1 + \frac{(1 - \delta) R^d T_i}{\delta R^R}, \tag{22}
\]

\[
\Sigma = \left( 1 - \frac{\bar{q}^-}{\bar{q}^R} \right) \left( \frac{\delta R^R}{1 - \delta) R^d T_i} \right). \tag{23}
\]

The quantities in (19)-(23) appear in future analytical derivations. The value of \( \bar{q}^- \) is a measure of heterogeneity in terms of the time that the physician has to invest on routine and urgent visits. In a similar fashion, \( \bar{q}^R \) measures heterogeneity in the revenue generated by routine and urgent visits. \( Q^T \) measures the spread of the RVI values for routine and urgent visits, e.g., if \( T_h \) and \( T_i \) values are close, \( Q^T \to +\infty \), while if they are far apart, \( Q^T \to 1 \). Both \( \bar{R} \) and \( \Sigma \) are composite measures that describe the contributions of the capitation and fee-for-service elements of physician compensation. \( \bar{R} \) measures solely the revenue aspects and is monotone in \( \delta \), e.g., as \( \delta \to 0 \) we have \( \bar{R} \to +\infty \), and as \( \delta \to 1 \) we have \( \bar{R} \to 1 \). The expression for \( \Sigma \), however, includes \( \bar{q}^- \), \( \bar{q}^R \), and \( \bar{R} \); therefore, it is a composite measure that combines \( \bar{R} \) with the factors that describe heterogeneity in revenue and capacity consumption between urgent and routine visits.

Below we derive the expressions for the optimal panel size and the RVI values in the “heterogeneous” setting. In order to characterize the value of using different RVIs for different patient groups, we first look at the “base” case where the physician assigns the same RVI to both groups.
of patients and, hence, forgoes the potential advantages of customizing the RVI values to patient health. We use the term “uniform RVI” to describe this policy.

**Proposition 1 (Uniform RVI policy).** Consider a heterogeneous patient panel with \( q_i \in [q^- (c, \Delta), q^+ (c, \Delta)] \), \( i = 1, 2 \), \( q_1 < q_2 \), and define

\[
\hat{\kappa}_1 = \frac{1}{1 + \left( \frac{q^- - q_1}{q^+ - q_1} \right) \left( \frac{q^+ - q_2}{q^- - q_2} \right)}.
\]  

(24)

Suppose that the physician applies the same RVI value, \( \hat{r} \), to both patient groups. Then, the optimal \( \hat{r} \) in (16)-(18) is given by

\[
\hat{r} = \begin{cases} 
T_l, & \text{if } \frac{q^+}{(1+\Sigma)^+} < q_1 < q_2, \text{ or } q_1 \leq \frac{q^+}{(1+\Sigma)^+} < q_2 \text{ and } \kappa_1 \leq \hat{\kappa}_1, \\
T_h, & \text{if } q_1 < q_2 \leq \frac{q^+}{(1+\Sigma)^+}, \text{ or } q_1 \leq \frac{q^+}{(1+\Sigma)^+} < q_2 \text{ and } \kappa_1 > \hat{\kappa}_1.
\end{cases}
\]  

(25)

Proposition 1 characterizes the optimal value of the “uniform” RVI in three separate settings. In first setting \( q_1 < q_2 \leq \frac{q^+}{(1+\Sigma)^+} \), both patient groups are relatively healthy, and the optimal “uniform” RVI value is \( T_h \). The second setting is the opposite of the first one: when \( \frac{q^+}{(1+\Sigma)^+} < q_1 < q_2 \), both patient groups are relatively “sick”, and \( T_l \) becomes the optimal RVI to apply to both groups.

In the third setting we have \( q_1 < \frac{q^+}{(1+\Sigma)^+} < q_2 \), and there is tension between the two patient groups since patients of groups 1 are relatively healthy, while patients of group 2 are relatively sick. If all patients on the physician’s panel were of group 1, the physician would choose \( T_h \), while if all patients were of group 2, the physician would choose \( T_l \). If both patient groups are on the physician’s panel, and the physician chooses a single RVI for both groups, the optimal RVI depends on the value of \( \kappa_1 \). In particular, the physician chooses \( T_h \) if and only if the fraction of healthy patients on the panel is large enough, i.e., if and only if \( \kappa_1 > \hat{\kappa}_1 \). In other words, \( \hat{\kappa}_1 \) is the critical fraction of healthy patients on the panel beyond which the physician ignores the less healthy patients and assigns an RVI of \( T_h \) to both patient groups. Figure 1 shows how this critical panel fraction value \( \hat{\kappa}_1 \) depends on the indicator of group 1’s health, \( q_1 \). As the value of \( q_1 \) increases, and the group 1 becomes less healthy, the physician will become increasingly inclined to apply \( T_l \) to both patient groups.

We now turn our attention to the setting where the physician can assign different RVI values to the two groups of patients. We use the term “customized RVI” to describe this setting.

**Proposition 2 (Customized RVI).** Consider a heterogeneous patient panel with \( q_i \in [q^- (c, \Delta), q^+ (c, \Delta)] \), \( i = 1, 2 \) and \( q_1 < q_2 \). Then, the optimal RVI values in (16)-(18) are given by

\[
\hat{r}_1 = \begin{cases} 
T_h, & q_1 \leq \frac{q^+}{(1+\Sigma)^+}, \\
T_l, & \text{otherwise},
\end{cases}
\]  

(26)
Figure 1: Critical fraction of the group 1 patients on the panel, \( \hat{r}_1 \), as a function of group 1’s health indicator \( q_1 \).

\[
q_1 = \frac{\bar{q}^r (1 + \Sigma)}{(1 + \Sigma)^+}
\]

Figure 2 illustrates the optimal RVI values for two patient groups in settings with \( \bar{q}^r < \bar{q}^R \) (Figure 2a) and \( \bar{q}^r > \bar{q}^R \) (Figure 2b). Note that \( \bar{q}^r < \bar{q}^R \) describes, according to (19) and (20), a setting with \( \frac{R_u}{\tau_u} < \frac{R^r}{\tau^r} \), i.e., a setting where routine visits are compensated disproportionately more than urgent visits, while the setting with \( \bar{q}^r > \bar{q}^R \) is the one where \( \frac{R_u}{\tau_u} > \frac{R^r}{\tau^r} \), and urgent visits are compensated, on a per-unit-of-time basis, better than routine visits. In Figure 2 we set \( c = 1000 \) and \( \Delta = 1 \), which results in \( q^- (c, \Delta) \approx 0.001 \) and \( q^+ (c, \Delta) = 1 \), allowing us to focus on the choices of RVI values made by a physician facing “nearly perfectly” flexible patients. In both settings, it is optimal to apply the same RVI to both patient groups if their health parameters are close in value.

\[
\hat{r}_2 = \begin{cases} 
T_h, & q_1 \leq \frac{\bar{q}^r}{(1 + \Sigma)^+}, q_2 \leq \bar{q}^r \left( \frac{Q^R - q_1 (1 + \Sigma)}{(1 + \Sigma) Q^R - \kappa_1 (1 + \Sigma)} \right) 

T_l, & \text{otherwise},
\end{cases}
\]

where \( x^+ = \max(x, 0) \).

The results of Proposition 2 outline the nature of the trade-offs between the revenue contributions and the capacity requirements of patient groups “competing” for the limited service capacity. Note that the choice of the RVI value for the “healthier” patient group (group 1) is affected only by the health level of patients from that group, and not by the health level of group 2 patients. In contrast, the decision of how much of the physician’s service capacity must be allocated to “sicker” patients is, in general, strongly affected by the health level of “healthier” patients. RVI decisions, however, are not affected by the amount of the daily service capacity \( A \).
In particular, when both $q_1$ and $q_2$ are small, so that both patient groups are similarly “healthy”, the optimal RVI is $T_h$ for both patient groups. In a similar fashion, when both patient groups are similarly “sick”, so that both $q_1$ and $q_2$ are high, the RVI for both patient groups are set to $T_l$. On the other hand, if the patient population exhibits a significant degree of heterogeneity, i.e., if patient group 1 is significantly healthier than patient group 2, the physician will benefit from applying different RVI values to two patient groups, seeing group 2 patients as often as possible, and group 1 patients as infrequently as possible. It is interesting to observe that, when the group 1 patients are healthy ($q_1 < \bar{q} \tau (1+\Sigma)$), the threshold value of the degree of healthiness of group 2 which induces the switch in the RVI value for that group from $T_h$ to $T_l$, is a monotone decreasing function of $q_1$ for $\Sigma > 0$ (Figure 2a) and a monotone increasing function of $q_1$ for $\Sigma < 0$ (Figure 2b). Thus, in settings where urgent visits are “undercompensated”, the healthier the group 1 patients are, the more the physician is inclined to apply the same high revisit interval value to both patient groups. This effect is reversed in the settings where the urgent visits are “overcompensated”: the healthier the group 1 patients are, the more the physician is inclined to apply different RVIs to the two patient groups.

Note that in both settings shown in Figure 2 we have $\Sigma > \bar{q} \tau - 1$, so that there exists a range of values of $q_1 > \frac{\bar{q} \tau}{1+\Sigma}$ for which the optimal RVI value for group 1 patients is $T_l$. Figure 3 looks at the settings with $\Sigma < \bar{q} \tau - 1$, i.e., at the settings with extreme “overcompensation” for urgent visits. Once the degree of urgent visit “overcompensation” crosses the threshold defined by $\Sigma = \bar{q} \tau - 1$, the optimal RVI for group 1 is set at $T_h$ irrespective of the value of $q_1$ (Figure 3a). If the urgent visit “overcompensation” grows even further, reaching the level of $\Sigma = (\bar{q} \tau - 1) \frac{Q^T}{Q^T - \kappa_1}$, it becomes optimal for the physician to see patients as infrequently as possible by setting the RVI values for both patient groups at $T_h$, irrespective of patients’ health levels (Figure 3b).
The expressions for the optimal RVI decisions simplify in the settings with “proportional” compensation rates, where $\frac{R^r}{\tau^r} = \frac{R^u}{\tau^u}$.

**Corollary 1.** Consider a heterogeneous patient panel with $q_i \in [q^- (c, \Delta), q^+ (c, \Delta)], i = 1, 2$ and $q_1 < q_2$ under the “proportional” compensation ($\frac{R^r}{\tau^r} = \frac{R^u}{\tau^u}$). Then, the optimal RVI values in (16)-(18) are given by

$$\hat{r}_i = \begin{cases} T_l, & q_i \geq \bar{q}^r, \\ T_h, & q_i < \bar{q}^r, \end{cases}, i = 1, 2.$$  

(28)

As Corollary 1 states, the “proportional” compensation for urgent and routine visits “decouples” the RVI decisions for the two patient groups, allowing each to be evaluated in isolation. In particular, whether the physician decides to see patients of a particular group as often or as infrequently as possible is governed exclusively by the health level of that group, with the value of $\bar{q}^r$ serving as a “switching threshold”.

Below we look at how the RVI customization influences the three outcomes of interest: physician revenue, panel size, and panel health. The expected daily revenue as well as the overall health of the patient panel in the physician’s care are key performance indicators that reflect the impact of the RVI customization on the physician and patients. The changes in the size of patient panel is an important indicator of whether adapting the RVI values to patient health status is beneficial in terms of overall primary care coverage that a given number of primary care physicians provides. Thus, these outcomes of interest reflect the potential attractiveness of the RVI customization to three key groups of stakeholders: physicians, patients, and the social planner.

As a measure of panel health, we define $H(r_1, r_2)$ as the portion of office visits that are routine:

$$H(r_1, r_2) = \kappa_1 r_1 (r_1) + \kappa_2 r_2 (r_2).$$  

(29)
Figure 4: The impact of RVI customization on three key performance indicators as a function of the fraction of healthy group $\kappa_1$

$$(q_1 = 0.2, q_2 = 0.8, R^d = 0.1, \Delta = 0.95, T_h = 360, T_l = 90, r^r = 1, \tau^r = 1.5, \delta = 0.25, R^u = 220, R^v = 200).$$

Note that high values of $H(r_1, r_2)$ correspond to a well-maintained patient panel whose primary care needs are served mainly through regular visits. If both patient groups on the panel have an RVI of $T_l$, then panel health is equal to its highest possible value, 1. Alternatively, if both patient groups have an RVI of $T_h$, the value of panel health drops to its lowest possible value, $\kappa_1(1 - q_1) + \kappa_2(1 - q_2)$.

Figure 4 shows how RVI customization can affect all three outcomes of interest. Note that in this figure we define $\hat{N}^U$ as the optimal panel size under the uniform RVI policy. We expect physician revenue to be higher in the presence of RVI customization than under the “uniform RVI” policy since the physician’s revenue maximization problem in former case is the relaxed version of the problem in the latter case. We also observe that the highest percentage increase in physician revenue occurs at $\kappa_1 = \hat{\kappa}_1$. In addition, the impact of RVI customization on physician revenue is smaller for high and low values of $\kappa_1$ since in those cases the patient panel is close to being homogeneous.
On the other hand, panel size may increase or decrease as a result of RVI customization depending on the fraction of healthy patients $\kappa_1$. Panel size increases under RVI customization if and only if $\kappa_1 \leq \hat{\kappa}_1$. When the value of $\kappa_1$ increases beyond $\hat{\kappa}_1$, the optimal RVI value under the “uniform RVI” policy switches from $T_l$ to $T_h$, resulting in a decrease in panel size. Note that since patient group 2 is “sicker” than patient group 1 ($q_2$ is higher than $q_1$) changing RVI from $T_l$ to $T_h$ leads to a “surge” in the number of urgent appointments which take longer to serve.

Similar to the panel size, panel health can improve or deteriorate upon the introduction of RVI customization, depending on the value of $\kappa_1$. For small values of $\kappa_1$, the physician assigns $T_l$ to both patient groups under the “uniform RVI” policy, so that all visits are routine. When the RVI customization is used, however, healthy patients (group 1) are assigned the RVI of $T_h$, while sick patients (group 2) are assigned the RVI of $T_l$. Thus, for small values of $\kappa_1$, the overall panel health is lower under the RVI customization because the RVI values increase for patients in group 1. This effect is reversed for high values of $\kappa_1$ where the RVI values decrease for group 2 patients.

For the next proposition, we define the following notation:

$$\xi(q_i) = \frac{1 + q_i \left( \frac{1}{q_i} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right)}{1 + q_i \left( \frac{1}{q_i} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right)}.$$ (30)

We also define the relative loss of revenue for the physician resulting from using the uniform RVI policy by

$$L(\kappa_1) = 1 - \frac{\Pi(\hat{\tau}, \hat{\tau})}{\Pi(\hat{\tau}_1, \hat{\tau}_2)}.$$ (31)

Note that both $\Pi(\hat{\tau}, \hat{\tau})$ and $\Pi(\hat{\tau}_1, \hat{\tau}_2)$ are function of $\kappa_1$.

**Proposition 3 (Upper bound on physician revenue gap).** Consider a heterogeneous patient panel with $q_i \in [q^- (c, \Delta), q^+ (c, \Delta)]$, $i = 1, 2$ and $q_1 \leq \bar{q} < q_2$ in a proportional compensation setting. Then, for $T_l \geq \frac{1}{2} T_h$, the relative loss of revenue for the physician resulting from applying the same RVI to both patient groups, $L(\kappa_1)$, has the following properties:

a) For $\kappa_1 \leq \hat{\kappa}_1$, the relative loss of revenue is

$$L(\kappa_1) = 1 - \frac{\bar{R}}{1 + (\bar{R} - 1) \left( \frac{1}{1 + \kappa_1 (\xi(q_1) - 1)} \right)},$$ (32)

an increasing function of $\kappa_1$.

b) For $\kappa_1 > \hat{\kappa}_1$, the relative loss of revenue is

$$L(\kappa_1) = 1 - \frac{1 + (\bar{R} - 1) \left( \frac{1}{\xi(q_2) + \kappa_1 (\xi(q_1) - \xi(q_2))} \right)}{1 + (\bar{R} - 1) \left( \frac{1}{1 + \kappa_1 (\xi(q_1) - 1)} \right)},$$ (33)

a decreasing function of $\kappa_1$. 
Therefore, the relative loss is maximized at $\kappa_1 = \hat{\kappa}_1$ and is given by

$$
\epsilon^U = L(\hat{\kappa}_1) = \frac{\hat{\kappa}_1 \left( \bar{R} - 1 \right) \left( 1 - \xi(q_1) \right)}{\bar{R} + \hat{\kappa}_1 \left( \xi(q_1) - 1 \right)}.
$$

(34)

Parts a) and b) of Proposition 3 provide analytical expressions for the physician revenue loss resulting from applying a single RVI value to a heterogeneous patient panel: one for when the majority of the patients on the panel are “healthy” ($\kappa_1 > \hat{\kappa}_1$) and the other one for when the majority of patients are “sick” ($\kappa_1 \leq \hat{\kappa}_1$). They also show that the loss of revenue is increasing in $\kappa_1$ for $\kappa_1 \leq \hat{\kappa}_1$ and decreasing in $\kappa_1$ for $\kappa_1 > \hat{\kappa}_1$. Given these results, part c) of Proposition 3 provides an upper bound on the fraction of physician revenue that is lost when the “uniform RVI” policy is applied in a setting with sufficiently heterogeneous patient population. Figure 5a shows the changes in this upper bound as a function of group 1’s health indicator, $q_1$. As the value of $q_1$ increases, the heterogeneity between the two patient groups decreases and so does the value of customizing RVIs for different patient groups. Note also that the “uniform RVI” policy produces no loss of revenue when $q_1 = \bar{q}$, because at that point the physician becomes indifferent to setting the RVI at $T_l$ or at $T_h$ for patients in group 1 (Corollary 1). Therefore, $T_l$ is the optimal RVI for all patients under both RVI policies.

Figure 5b plots the upper bound as a function of $\delta$, the proportion of the fee-for-service component in physician compensation. This figure suggests that RVI customization has the most pronounced impact on physician revenue when capitation payments dominate the compensation structure. In contrast, if the physician is compensated exclusively on a fee-for-service basis, there is no gap in revenue between the uniform and customized RVI policies, since, under the proportional fee-for-service structure, the compensation rate is the same for both urgent and routine office visits.

Note that $\epsilon^U$ is a tight bound only when $\kappa_1 = \hat{\kappa}_1$. For instance, $\epsilon^U$ is a conservative bound when $\kappa_1$ equals 0 or 1, because there is no revenue gap for these $\kappa_1$ values. Therefore, $\epsilon^U$ is a useful bound for cases in which the exact value of $\kappa_1$ while being difficult to establish with certainty, is unlikely to be close to 0 or 1.

4. Customizing Care Channel Using E-Visits: Model and Analysis

In this section we analyze the impact of the customization of the channel used to provide patient care. In particular, we will look at how the introduction of e-visits alters the choice of revisit intervals for different patient groups, the total size of patient panel, as well as physician compensation.

On the physician side, e-visits are characterized by the service time $\tau^e < \tau^r$ they require, and the per-visit, fee-for-service compensation $R^e < R^r$, as well as the daily capitation compensation $R^d_e < R^d$. For simplicity, we assume that the service times and the physician compensation amounts associated with e-visits are the same for both patient groups.
Figure 5: Upper bound on physician revenue gap, $\epsilon^U$, as a function of group 1’s health indicator, $q_1$, and the proportion of physician daily compensation based on the fee-for-service scheme, $\delta$

\[ (q_1 = 0.1, q_2 = 0.9, R^d = 0.2, \Delta = 0.95, T_h = 300, T_l = 180, \tau^r = 1, \tau^u = 2, \delta = 0.25, R^u = 200, R^r = 400) \]

In the presence of e-visits, a fraction of patient demand for primary care is safely handled without patients having to come to the physician's office, via an e-mail or another technology-driven solution. We assume that the quality of online visits for this group of patient care requests is the same as the quality of face-to-face visits. There is evidence that such tasks exist in primary care (Pelak et al. 2015), e.g., medication review. In our model, we also assume that only a fraction of routine office visits, $\alpha^r$, fits into such “e-visit” category and that all urgent visits must still be handled at the office. While we believe that the latter is a realistic assumption, our model can be readily extended to the case where a finite fraction of urgent visits can also be attended to remotely.

We consider a general setting where “diverting” some of the routine visits to an “e-visit” channel of care, on the one hand, saves a physician some service time that can be allocated to more demanding and urgent cases, while, on the other hand, leading to a potential revenue loss due to lower compensation that “e-visits” may bring. At present, there is little evidence that Medicare or any private insurance companies are willing to offer any compensation for “e-visits”. At the same time, a number of physician practices are experimenting with charging patients fixed annual fees (an analogue of $R^d_c$) as well as per-e-mail fees (an analogue of $R^u_c$) in exchange for offering e-visits (Reijonsaari et al. 2005, Fairview Health Services 2013). We treat $\alpha^r_c$ as an “average” (over a patient panel) fraction of routine visits replaced by “e-visits”. In the absence of insurance support, the entire physician compensation for providing e-visits comes from patient out-of-pocket payments, and, as we discuss later, patients can choose not to adopt e-visits. Note that, even in the absence of out-of-pocket costs, a patient may not be able to use e-visit as a substitute for all routine visits, since some routine visits may require in-office care. Thus, we assume that $\alpha^r_c < 1$. Further, if a
patient avoids coming to the office for the routine visit, and uses an e-visit instead, he does not incur the cost of visit \( c_o \).

E-visits alter the trade-off that a physician faces in allocating her service capacity among two patient groups. In particular, the physician’s objective function changes from (15) to

\[
\Pi_\delta(N, r_1, r_2) = \delta \Pi_{FFS}^c(N, r_1, r_2) + (1 - \delta) \Pi_{CAP}^c(N, r_1, r_2)
\]

\[
= N \left( (1 - \delta) R_e^d + \delta N \left( \frac{\rho_1^c(r_1) \bar{R}_e^c + (1 - \rho_1^c(r_1)) \bar{R}_o^c}{T_1(r_1)} \right) + \delta \left( \frac{\rho_2^c(r_2) \bar{R}_e^c + (1 - \rho_2^c(r_2)) \bar{R}_o^c}{T_2(r_2)} \right) \right) ,
\]

where

\[
\bar{R}_e^c = \alpha_e^c R_e^c + (1 - \alpha_e^c) R^c,
\]

\[
\bar{R}_e^d = R_e^d + R^d,
\]

so that the physician’s problem becomes

\[
\max_{N, r_1, r_2} \Pi_\delta(N, r_1, r_2)
\]

s.t. \( N \left( \alpha_e^c \bar{R}_e^c + (1 - \alpha_e^c) \bar{R}_o^c \right) + \left( \frac{\rho_2^c(r_2) \bar{R}_e^c + (1 - \rho_2^c(r_2)) \bar{R}_o^c}{T_2(r_2)} \right) \leq A,
\]

\[
r_1, r_2 \in \{ T_i, T_h \},
\]

\[
(\text{38})
\]

\[
(\text{39})
\]

\[
(\text{40})
\]

where

\[
\bar{\tau}_e = \alpha_e^c \bar{\tau}_e + (1 - \alpha_e^c) \tau^c.
\]

Note that for \( \alpha_e^c \in (0, 1] \), \( \bar{R}_e^c < R^c \) and \( \bar{\tau}_e < \tau^c \). We will denote the RVI values optimizing (38)-(40) as \( \bar{r}_1^e \) and \( \bar{r}_2^e \).

While e-visits allow patients to avoid the cost \( c_o \) of coming to the office for some routine visits, patient still incur the cost \( c_o(1 + \eta) \) for an unscheduled visit. Thus, if the scheduled office revisit interval for patients from group \( i = 1, 2 \) is set at \( r_i \), the expected cost, in units of \( c_o \), associated with an office visit in the presence of e-visits with \( \alpha_e^c > 0 \) is

\[
\bar{C}_i^c(r_i) = \frac{R_e^c}{c_o} \alpha_e^c \rho_i^c(r_i) + (1 - \alpha_e^c) \rho_i^c(r_i) + (1 + \eta)(1 - \rho_i^c(r_i))
\]

\[
= \begin{cases} 
1 - \left(1 - \frac{R_e^c}{c_o}\right) \alpha_e^c, & r_i \leq T_1, \\
(1 - q_i) \left(1 - \frac{R_e^c}{c_o}\right) \alpha_e^c + q_i(1 + \eta), & T_1 < r_i \leq T_h, \\
1 + \eta, & r_i > T_h.
\end{cases}
\]

Similar to (7), we can define the expected daily cost for a patient from group \( i = 1, 2 \) as

\[
\bar{D}_i^c(r_i) = R_e^d + \frac{\bar{C}_i^c(r_i)}{T_i(r_i)} = \begin{cases} 
R_e^d + \frac{1 - \left(1 - \frac{R_e^c}{c_o}\right) \alpha_e^c}{T_i(r_i)}, & r_i \leq T_1, \\
R_e^d + \frac{(1 - q_i) \left(1 - \frac{R_e^c}{c_o}\right) \alpha_e^c + q_i(1 + \eta)}{q_i T_i(1 - q_i) r_i}, & T_1 < r_i \leq T_h, \\
R_e^d + \frac{1 + \eta}{q_i T_i(1 - q_i) T_h r_i}, & r_i > T_h.
\end{cases}
\]
The RVI value that minimizes \( D_i^c(r_i) \) is denoted by \( \bar{r}_i^c \). Note that the patient has the option to not sign up for e-visits. In such a case, the patient’s expected daily cost is given by (7). We model this by

\[
\bar{\theta}_i = \begin{cases} 
1, & D_i^c(\bar{r}_i^c) \leq D_i^c(r_i^c), \\
0, & \text{o.w.,}
\end{cases}
\]  

where the patient’s long-run average cost is given by

\[
D_i(\bar{\theta}_i, r_i) = \begin{cases} 
D_i^c(r_i), & \bar{\theta}_i = 1, \\
D_i(o), & \bar{\theta}_i = 0.
\end{cases}
\]

The patient’s choices of RVI value and e-visit adoption are given by the following result, where \( \bar{\theta}_i \) and \( \bar{r}_i^c \) represent the patient’s decisions regarding e-visit adoption and RVI value, respectively.

**Proposition 4.** Under e-visits, for given values of \( \alpha^c_e, \eta, \) and \( q_i \), the global minimizers of the patient’s long-run average cost, \( D_i(\bar{\theta}_i, r_i) \), are

\[
(\bar{\theta}_i, \bar{r}_i) = \begin{cases} 
(0, T_i), & q_i \geq \frac{1}{1 + \frac{\eta_q}{T_i-1}}, \left(1 - \frac{R^c_e}{q_i}\right) \alpha^c_e < R^d_e T_i, \\
(0, T_h), & q_i \leq \frac{1}{1 + \frac{\eta_q}{T_i-1}}, \left(1 - \frac{R^c_e}{q_i}\right) \alpha^c_e < \frac{R^d_e(q_i T_i + (1-q_i) T_h)}{(1-q_i)}, \\
\cup \left\{ \begin{array}{l}
\left(1, T_i\right), \quad \left(1 - \frac{R^c_e}{q_i}\right) \alpha^c_e \geq R^d_e T_i, \\
\cup \left(1, T_h\right), \quad q_i \leq \frac{1}{1 + \frac{\eta_q}{T_i-1}}, \left(1 - \frac{R^c_e}{q_i}\right) \alpha^c_e \geq \frac{R^d_e(q_i T_i + (1-q_i) T_h)}{(1-q_i)},
\end{array} \right. \\
\end{cases}
\]

where

\[
\eta^c_e = \frac{\eta + \left(1 - \frac{R^c_e}{q_i}\right) \alpha^c_e}{1 - \left(1 - \frac{R^c_e}{q_i}\right) \alpha^c_e}.
\]  

Figure 6a illustrates the conditions described in (46). In particular, for low values of e-visit impact factor, \( \left(1 - \frac{R^c_e}{q_i}\right) \alpha^c_e \), patients choose not to adopt e-visits as the capitation fee, \( R^d_e \), is too high to be covered by the savings from substituting some of routine office visits with e-visits; the areas labeled with \((\bar{\theta}_i, \bar{r}_i) = (0, T_h)\) and \((\bar{\theta}_i, \bar{r}_i) = (0, T_i)\) represent such conditions. Also, when patients opt to adopt e-visits, as e-visit impact factor increases patients gravitate toward more frequent scheduled routine visits (in-office and e-visit). Figure 6a also shows that relatively sicker patients are more
likely to adopt e-visits, and healthier patients only gravitate toward e-visits when a relatively large fraction of office visits are replaced by e-visits (i.e., when the impact factor of e-visits is high).

As before, patients know that their sickness factor, $\eta$, is in the interval $[c(1-\Delta), c(1+\Delta)]$. Therefore, they may be flexible in terms of the RVI values that they find acceptable. When e-visits are introduced, patients decide on e-visit adoption and the acceptable range of RVIs simultaneously. We model this in the following way: patients reject e-visits if they increase the patients’ long-run average cost for all value of $\eta \in [c(1-\Delta), c(1+\Delta)]$. Figure 6b shows how patients’ choice of e-visit adoption and RVI values change as they become flexible ($\Delta = 0.9$). In the area marked as $(1, T_h) \sim (1, T_l)$ patient choose to adopt e-visits and accept both RVI values of $T_l$ and $T_h$, and in the area marked as $(0, T_l) \sim (0, T_h)$ patients do not adopt e-visits but are flexible with both RVI values of $T_l$ and $T_h$. In the rest of the areas, patients are inflexible with respect to RVI but may choose to adopt e-visits or not.

The areas where patients are flexible in Figure 6b become narrower as the e-visit impact factor increases. This is because e-visits lead to RVI inflexibility with $T_l$ for the relatively sicker patients as the cost of a routine e-visits is smaller than the cost of a routine office visits. We also observe that in Figure 6b the area where patients adopt e-visits and remain flexible with respect to RVI values is in the middle of the plot: if e-visits are not effective enough in terms of replacing office visits, patients do not adopt e-visits, and if e-visits are too effective in replacing office visits, patient adopt e-visits but become inflexible with the RVI of $T_l$.

Similar to (10)-(11), if patients adopt e-visits there exist “critical” threshold values for patient health level that separate “flexible” patients from “inflexible” ones:
\[ q_e^-(c, \Delta, R^*_e, \alpha^*_e) = \frac{1}{1 + \frac{c(1+\Delta)+\left(1-R_e^*\alpha^*_e\right)}{\left(1-(1-R_e^*\alpha^*_e)\right)\left(\frac{T_h}{T_l}-1\right)}}, \]  
\[ q_e^+(c, \Delta, R^*_e, \alpha^*_e) = \frac{1}{1 + \frac{c(1+\Delta)+\left(1-R_e^*\alpha^*_e\right)}{\left(1-(1-R_e^*\alpha^*_e)\right)\left(\frac{T_h}{T_l}-1\right)}}, \]  
\[ (48) \]
\[ (49) \]

For the analysis below it is convenient to introduce the following threshold values for \( \alpha^*_e \):

\[ \bar{\alpha}^*_e(q_i) = \left(\frac{1}{q_i} - 1\right)\left(\frac{T_h}{T_l} - 1\right) - c(1-\Delta) \left(\frac{1-R_e^*}{c_0}\right), \]  
\[ (50) \]
\[ \alpha^*_e(q_i) = \left(\frac{1}{q_i} - 1\right)\left(\frac{T_h}{T_l} - 1\right) - c(1+\Delta) \left(\frac{1-R_e^*}{c_0}\right). \]  
\[ (51) \]

As we discuss below, the introduction of e-visits can transform a flexible patient group into an inflexible one, and vice versa.

**Proposition 5 (patient flexibility with e-visits).** Consider a setting where patients choose to adopt e-visits. a) A flexible patient group remains flexible upon the introduction of e-visits if and only if \( q^- (c, \Delta) \leq q_i \leq q^+ (c, \Delta) \) and \( \alpha^*_e \leq \bar{\alpha}^*_e(q_i) \).

b) A flexible patient group becomes inflexible upon the introduction of e-visits if and only if \( q^- (c, \Delta) \leq q_i \leq q^+ (c, \Delta) \) and \( \alpha^*_e > \bar{\alpha}^*_e(q_i) \).

c) An inflexible patient group becomes flexible upon the introduction of e-visits if and only if \( q_i < q^- (c, \Delta) \) and \( \alpha^*_e(q_i) \leq \alpha^*_e \leq \bar{\alpha}^*_e(q_i) \).

Parts b) and c) of Proposition 5 describe the critical levels of the e-visit “impact factor” \( \left(1 - \frac{R_e^*}{c_0}\right)\alpha^*_e \) that change the “identity” of a patient group with respect to the flexibility of RVI values. Since the fraction of e-visits \( \alpha^*_e \) is monotone in \( R_e^* \) and \( R^d_e \), these results can also be recast in terms of the critical levels of patient out-of-pocket compensation parameters that lead a patient group pass the RVI flexibility boundary.

Figure 7 illustrates the results of Proposition 5 for a patient group with the expected sickness factor \( c = 2 \), flexibility parameter \( \Delta = 0.5 \) and the shortest and the longest “sickness” times of \( T_l = 90 \) and \( T_h = 360 \), respectively. In this figure, the e-visit impact factor \( \left(1 - \frac{R_e^*}{c_0}\right)\alpha^*_e \) is allowed to vary between 0 (“unattractive” e-visits) to 1 (costless e-visits that perfectly replace all routine visits). The results of part a) and part b) of Proposition 5 are illustrated by the behavior of patients with the “intermediate” level of health, \( q_i = 0.6 \). These patients remain flexible while the attractiveness of e-visits and their impact is low. They become inflexible and opt for most frequent scheduled visits as the “e-visit” channel becomes more attractive. On the other hand, patients with “low” health level (\( q_i = 0.4 \)) exhibit behavior described in part c) of Proposition 5: while being
Figure 7: RVI flexibility for different patient health levels $q_i$ as a function of e-visits impact factor \( \left( 1 - \frac{R^r_e}{c_0} \right) \alpha^r_e \) 
\( (c = 2, \Delta = 0.5, T_h = 360, T_l = 90) \).

Inflexible and insisting on the most infrequent scheduled visits in the absence of e-visit channel, these patients become flexible once the level of attractiveness of e-visits rises. As the e-visits impact grows further, such patients may become inflexible again, but this time opting for the most frequent scheduled visits.

4.1. E-Visits for Heterogeneous Patient Panel with Two Flexible Patient Groups

In the following analysis we focus on characterizing the impact of e-visits in a heterogeneous setting with two patient groups that are both flexible in the absence of e-visits. In particular, we will look at three separate settings: the setting where the influence of e-visits is moderate enough to preserve patient flexibility in both groups, the setting where e-visits remove the flexibility of one of the patient groups, and, finally, the setting where both patient groups become inflexible after e-visits. Note that the results that follow can be extended to include settings in which at least one of the patient groups is inflexible before e-visits are introduced. Some of these cases are trivial, e.g., a patient group that is inflexible with $T_l$ before e-visits is guaranteed to stay inflexible with $T_l$ under e-visits, and thus the physician has no choice for the RVI of this patient group. Also, as we showed in Proposition 5, it is possible that a patient group that is inflexible in the absence of e-visits becomes flexible after e-visits are introduced. Our results on the optimal RVI values under e-visits are also applicable in such a setting, but we exclude them for brevity.
Similar to (19)-(22), we will use the following quantities to characterize the optimal solution to (38)-(40):

\[
\bar{q}_e^c = \frac{1}{1 + \left(\frac{\bar{\tau}_e}{\bar{\tau}_r} - 1\right)}, \quad (52)
\]

\[
\bar{q}_e^R = \frac{1}{1 + \left(\frac{\bar{\tau}_e}{\bar{\tau}_r} - 1\right)}, \quad (53)
\]

\[
\bar{R}_e = 1 + \frac{(1 - \delta) \bar{R}_e^C T_i}{\delta \bar{R}_r}, \quad (54)
\]

\[
\Sigma_e = \left(1 - \frac{\bar{q}_e^c}{\bar{q}_e^R}\right) \left(\frac{\delta \bar{R}_e}{(1 - \delta) \bar{R}_e^C T_i}\right). \quad (55)
\]

These quantities are the e-visit parallels of the ones we described earlier in (19)-(23).

Note that as we showed in Proposition 4 the patients’ choice of e-visit adoption is a function of patient health level \( q \). Therefore, it is possible that one group of patients chooses to adopt e-visits while the other one does not adopt e-visits. In the next proposition, we focus on the case where both patient groups choose to adopt e-visits.

**Proposition 6 (Heterogeneous patient panel with e-visits).** Consider a setting where patients choose to adopt e-visits, and the patient panel is heterogeneous with \( q_i \in [q^- (c, \Delta), q^+ (c, \Delta)], i = 1, 2 \) and \( q_1 < q_2 \).

a) Suppose that \( \alpha_e^c \leq \hat{\alpha}_e^c (q_2) \). Then, the optimal RVI values in (38)-(40) are given by

\[
\hat{r}_1^c = \begin{cases} T_h, & q_1 \leq \bar{q}_e^c \left(1 + \Sigma_e\right)^+, \\ T_l, & \text{otherwise}, \end{cases}
\]

\[
\hat{r}_2^c = \begin{cases} T_h, & q_1 \leq \bar{q}_e^c \left(1 + \Sigma_e\right)^+, q_2 \leq \bar{q}_e^R \left(\frac{Q^T - q_1 (1 + \Sigma_e) (1 + \Sigma_e - q_1 (1 + \Sigma_e))}{(1 + \Sigma_e) Q^T - \alpha_e^c (1 + \Sigma_e - q_1 (1 + \Sigma_e))}\right), \\ T_l, & \text{otherwise}, \end{cases}
\]

where \( x^+ = \max(x, 0) \).

b) Suppose that \( \alpha_e^c (q_2) < \alpha_e^c (q_1) \). Then the optimal RVI values in (38)-(40) are given by

\[
\hat{r}_1^c = \begin{cases} T_h, & q_1 \leq \bar{q}_e^c \left(1 + \Sigma_e\right)^+, \\ T_l, & \text{otherwise}, \end{cases}
\]

and \( \hat{r}_2^c = T_l \).

c) Suppose that \( \alpha_e^c > \hat{\alpha}_e^c (q_1) \). Then the optimal RVI values in (38)-(40) are given by \( \hat{r}_1^c = \hat{r}_2^c = T_l \).

Proposition 6 describes the physician’s choice of optimal RVI values under e-visits. In particular, there are three parts in this proposition: part a) describes a setting in which e-visits replace a relatively small fraction of routine office visits (\( \alpha_e^c \leq \hat{\alpha}_e^c (q_2) \)). In such a setting, patients remain
flexible with respect to RVI values under e-visits, and the structure of the optimal RVI values stays
similar to the one described in Proposition 2. As the fraction of routine office visits replaced by
e-visits increases, some patient groups may become inflexible under e-visits, with an RVI of \( T_1 \) as
discussed in Proposition 5. Parts b) and c) of Proposition 6 describe the physician’s optimal choice
of RVI when at least one of the patient groups is inflexible, demanding frequent office visits with
RVI equal to \( T_1 \).

The results of Proposition 6 can be simplified in the case where “proportional” compensation
rates in the absence of e-visits are augmented by the proportional compensation for e-visits (i.e.,
\( R_{r} = R_{u} = R_{e} \) and \( R_{d} = 0 \)).

**Corollary 2.** Consider a heterogeneous patient panel with \( q_i \in [q^{-}(c, \Delta), q^{+}(c, \Delta)] \), \( i = 1, 2 \)
and \( q_1 < q_2 \) in the presence of e-visits under “proportional” compensation (\( R_{r} = R_{u} = R_{e} \) and \( R_{d} = 0 \)). The optimal RVI values in (38)-(40) are given by

\[
\hat{r}^e_1 = \begin{cases} \hat{T}_h, & q_1 < \bar{q}_e, \quad \alpha_r \leq \bar{\alpha}_r(q_1), \\ \hat{T}_l, & \text{otherwise}, \end{cases}
\]

and

\[
\hat{r}^e_2 = \begin{cases} \hat{T}_h, & q_2 < \bar{q}_e, \quad \alpha_r \leq \bar{\alpha}_r(q_2), \\ \hat{T}_l, & \text{otherwise}. \end{cases}
\]

Similar to Corollary 1, Corollary 2 shows that under “proportional” compensation for all types of
visit, the choice of optimal RVI for the two patient groups is decoupled: the optimal RVI values
for each patient group depend only on that group’s characteristics. Note that under proportional
e-visit compensation patients are guaranteed to adopt e-visits because \( R_{e} < R_{r} \) and \( R_{d} = 0 \).

**4.2. The Impact of E-Visits on System Outcomes**

In this section we characterize the changes in the three outcomes of interest—physician revenue,
panel size, and panel health—resulting from the introduction of e-visit channel for primary care.
In particular, we focus on a homogeneous, flexible patient panel with

\[
q \in [q^{-}(c, \Delta), q^{+}(c, \Delta)],
\]

and a physician with “proportional” compensation for routine and urgent in-office visits and a
mixture of fee-for-service and capitation compensations modes:

\[
\frac{R_{r}}{\tau_{r}} = \frac{R_{u}}{\tau_{u}}, \quad 0 < \delta < 1.
\]

Note that in this section we focus on a homogeneous patient panel to be able to maintain ana-
lytical tractability and to provide sharper insights. We consider two possible scenarios of e-visit
incentives: “proportional fee-for-service e-visit compensation” and “capitation e-visit compensa-
tion”. Under proportional fee-for-service e-visit compensation, the physician is only paid per e-visit and the e-visit compensation is proportional to the duration of e-visit, i.e., $R_{r\tau} = R_u = R_{r\tau}$. Under capitation e-visits compensation, the physician is not paid for each e-visit, but receives a daily capitation payment per patient for providing e-visits, i.e., $R_c = 0, R_e^d > 0$.

**Proposition 7 (Proportional fee-for-service e-visit compensation).** Consider the setting described by (61) and (62) under “proportional fee-for-service e-visit compensation” ($R_{r\tau} = R_u = R_{r\tau}, R_c = 0$). Noting that in such a setting patients are guaranteed to adopt e-visits, suppose that patients stay flexible after e-visit adoption, i.e., $\alpha_e^r = \bar{\alpha}_e^r (q)$. Then, the introduction of e-visits produces the following effects:

a) Panel health improves if $\bar{q}_e^r \leq q \leq \bar{q}_e^r$, and remains unchanged otherwise.

b) Panel size increases.

c) Physician revenue increases.

Proposition 7 describes the impact of e-visits on system outcomes when the physician is paid a proportional rate for e-visits, so her revenue per visit duration is the same for all types of visits (routine in-office, routine e-visit, and urgent in-office). The proposition also focuses on a setting in which patients are flexible both before and after e-visits are introduced. Note that since $R_c^d = 0$ in Proposition 7, patients always opt to adopt e-visits because the long-run average cost is guaranteed to be lower with e-visits. The first insight from Proposition 7 is that, panel health is unaffected by e-visits if the panel is comprised of either rather sick or very healthy patients. Patient health, however, will improve for moderately healthy panels. The range of values for which panel health improves is between $\bar{q}_e^r$ and $\bar{q}_e^r$. In this range of $q$, the physician assigns an RVI of $T_l$ after e-visits, while before e-visits, the physician’s choice of RVI was $T_h$. Note that changes in panel health outlined in Proposition 7 are caused exclusively by physician incentives, since, in this particular setting, e-visits do not alter the degree of patient flexibility.

Both panel size and physician revenue increase when a proportional fee-for-service approach is used for compensating e-visit care provided to flexible patients. In this setting, e-visits are on equal footing with other visit types in terms of revenue and are time-saving for the physician. As a result, the physician uses e-visits to expand her panel size and earn more revenue.

For further analysis, it is convenient to introduce the following notation:

$$
\tilde{R}_c^d = \left( \frac{\delta}{1-\delta} \right) \left( 1 - \frac{\alpha_e^r}{T_l} \right) \left( \frac{1 - \frac{\bar{q}_e^r}{q}}{q - T_l} \right) - \frac{R_c^d}{\tilde{R}_e^r},
$$

$$
\tilde{q}^\alpha = \tilde{q}_c^\alpha \left( \frac{1 - (1 - Q_f(T)) \alpha_e^r \left( 1 - \frac{\bar{q}_e^r}{q} \right)}{1 - (1 - \bar{q}_c^\alpha) \alpha_e^r \left( 1 - \frac{\bar{q}_e^r}{q} \right)} \right),
$$
\[ \Xi_{0,1} = \left\{ (q, R^d_e) \mid q^e < q \leq \frac{q^e}{(1 + \Sigma_e)^{\tau_e}}, \frac{R^d_e}{R^e} < \tilde{R}_e \right\}, \quad (65) \]

\[ \Xi_{1,0} = \left\{ (q, R^d_e) \mid \frac{q^e}{(1 + \Sigma_e)^{\tau_e}} < q \leq q^\tau, \frac{R^d_e}{R^e} \geq \tilde{R}_e \right\}, \quad (66) \]

\[ G(I, I_e) = \frac{\tilde{R}_e + \left( \frac{q - q^R}{q^R(Q^T - q)} \right) I_e}{1 + \left( \frac{q - q^R}{q^R(Q^T - q)} \right) I_e} - \frac{\tilde{R} + \left( \frac{q - q^R}{q^R(Q^T - q)} \right) I}{1 + \left( \frac{q - q^R}{q^R(Q^T - q)} \right) I}. \quad (67) \]

**Proposition 8 (Capitation e-visit compensation).** Consider a setting where patients choose to adopt e-visits. Under “capitation e-visit compensation” \((R^e_c = 0, R^d_e > 0)\) and the conditions described by (61) and (62), suppose that patients stay flexible after e-visits are introduced, i.e., \(\alpha_e^r \leq \alpha_e^r(q)\). Then, the introduction of e-visits produces the following effects:

a) Panel health decreases if \((q, R^d_e) \in \Xi_{0,1}\), improves if \((q, R^d_e) \in \Xi_{1,0}\), and remains unchanged otherwise.

b) Panel size decreases if and only if

\[ (1 + \Sigma_e)^{\tau_e} \leq \frac{1 - (1 - q^e) \alpha_e^r(1 - \frac{q^\tau}{q^T})}{1 - (1 - Q^T) \alpha_e^r(1 - \frac{q^\tau}{q^T})}, \quad q^e \leq q \leq \frac{q^e}{(1 + \Sigma_e)^{\tau_e}}, \frac{R^d_e}{R^e} < \tilde{R}_e. \quad (68) \]

c) Physician revenue decreases if and only if

\[
\begin{align*}
&\left\{ q < \min \left\{ \frac{q^e}{(1 + \Sigma_e)^{\tau_e}}, q^\tau \right\}, \quad G(1, 1) < 0 \right\} \cup \left\{ q > \max \left\{ \frac{q^e}{(1 + \Sigma_e)^{\tau_e}}, q^\tau \right\}, \quad G(0, 0) < 0 \right\} \\
&\cup \left\{ (q, R^d_e) \in \Xi_{0,1}, \quad G(0, 1) < 0 \right\} \cup \left\{ (q, R^d_e) \in \Xi_{1,0}, \quad G(1, 0) < 0 \right\}. \quad (69)
\end{align*}
\]

Similar to the previous Proposition, Proposition 8 considers a setting in which patients are flexible both before and after the introduction of e-visits. In the present setting, however, the physician is compensated for providing e-visits on a capitation basis.

Compared to the setting without e-visits, panel health stays the same if patients are either very healthy or rather sick. If patient health level is in the intermediate range, however, panel health may improve or deteriorate, depending on the amount of capitation payment for e-visits. In particular, panel health improves for high values of capitation payment and deteriorates for low values of the capitation payment.

Panel size may decrease if patient health level is in the intermediate range and e-visit capitation payment is small. In this case, the physician uses high RVI values to divert care from routine appointments to urgent ones to earn more revenue because e-visits provide no per-visit compensation to the physician.

Proposition 8 describes the impact of e-visits in settings where patients that are flexible in the absence of e-visits remain flexible after e-visits are introduced. Below we analyze settings where
patient flexibility changes upon the introduction of e-visits. In our analysis, we use the following notation:

\[
\tilde{q}^\alpha = \frac{1}{1 - q^\tau} \frac{1 - \bar{q}^\tau \left( 1 - \tilde{\alpha}_e^r (1 - \bar{\alpha}_e^r) \right)}{1 - \bar{q}^\tau \left( 1 - \bar{\alpha}_e^r (1 - \bar{\alpha}_e^r) \right)}.
\]  

(70)

**Proposition 9 (Impact of e-visits when patient flexibility changes).** Consider a setting where patients choose to adopt e-visits. Under the conditions described by (61) and (62), suppose that patients are not flexible after e-visits are introduced, i.e., \( \alpha^r_e > \bar{\alpha}_e^r (q) \). Then, the introduction of e-visits produces the following effects:

a) Panel health improves if \( q \leq \tilde{q}^\tau \), and remains unchanged otherwise.

b) Panel size decreases if and only if \( q \leq \tilde{q}^\alpha \).

c) Physician revenue increases under proportional fee-for-service compensation for e-visits if and only if \( q > \tilde{q}^\alpha \). Physician revenue decreases under capitation compensation for e-visits if and only if

\[
\{q \leq \tilde{q}^\tau, \ G(1,0) < 0\} \cup \{q > \tilde{q}^\tau, \ G(0,0) < 0\}.
\]  

(71)

In the settings described by Proposition 9, patients accept both RVI values, \( T_l \) and \( T_h \), in the absence of e-visits, while insisting on \( T_l \) upon the introduction of e-visits. Changes in patient flexibility have no effect on RVI values when \( q > \tilde{q}^\tau \) because, in the absence of e-visits, for those value of \( q \) the RVI value that maximizes physician revenue is also \( T_l \). When \( q \leq \tilde{q}^\tau \), however, the physician chooses the RVI of \( T_h \) before e-visits are introduced, but patients become inflexible with RVI equal to \( T_l \) when they adopt e-visits. Overall, Proposition 9 shows that changes in RVI values as a results of patients becoming inflexible under e-visits will improve patient health but may make e-visits unsustainable as they do not encourage physician participation by negatively impacting physician revenue and panel size.

Figures 8-10 illustrate our theoretical results in Propositions 7 and 8. In these figures we use proportional compensation for office visits (both routine and urgent) and show how the capitation and fee-for-service elements of e-visit compensation affect system outcomes. In particular, we highlight three effects: (1) e-visits increasing patient health, (2) e-visits decreasing panel health, and (3) e-visits decreasing panel size.

We start by Figure 8 where we observe improvement in patient health for a certain set of fee-for-service, \( R_e^r \), and capitation, \( R_e^d \), e-visit payments. Figure 8a shows the area where the patients and physician are willing to use e-visits, an area we call the “feasible area”. Patients are unwilling to adopt e-visits when the e-visit fees are too high. Therefore, the area where patients reject e-visits is in the top-right corner of Figure 8a. Recall that we discussed patient adoption of e-visits in Proposition 4 and Figure 6. The physician can also be worse off in terms of revenue if e-visit compensation is not generous enough. In such cases, the physician rejects e-visits. There remains
an area in the top-left corner of the figure where the patients and physician are willing to adopt e-visits.

Figures 8b and 8c show the impact of e-visits on panel size and patient health, respectively. The relevant area for these two figures is the area where patients and physician are willing to adopt e-visits as discussed in Figure 8a. In Figure 8b, we observe that for “feasible” values of $R^e_r$ and $R^d_e$, panel size increases. In Proposition 7 we showed that if e-visits are compensated proportionally with no e-visit capitation compensation, panel size increases. The proportional e-visit compensation is...
Figure 8 is where $R^r = 40$ (calculated as $200 \times \tau^r$) and $R^d_c = 0$. In Figure 8b we observe that panel size increases for a wider set $R^r_c$ and $R^d_c$ values, e.g., $R^d_c = 0$ and $25 \leq R^r_c < 40$.

Figure 8c shows that panel health improves only for part of the feasible area. Note that in this figure $q = 0.49$ which is chosen to be between $\bar{q}^r = 0.5$ and $\bar{q}^r_c = 0.3$, two terms that are measures of heterogeneity in terms of the time that the physician has to invest in routine and urgent visits under the traditional and e-visit modes, respectively. Recall that Proposition 7 shows that under proportional e-visit compensation panel health improves when $\bar{q}^r_c \leq q \leq \bar{q}^r$ because the physician assigns an RVI of $T_l$ to patients under e-visits as compared to $T_h$ under the traditional mode. We observe this in Figure 8c for $R^r = 40$ and $R^d_c = 0$. A new observation in Figure 8c is that patient health stays the same when $R^r$ values fall below a certain threshold which is a function of $R^d_c$.

In Figure 9, $q = 0.51$ which is slightly above $\bar{q}^r = 0.5$. The pattern in Figures 9a and 9b are similar to the ones we observed in Figures 8a and 8b, respectively. Changes in patient health as shown in Figure 9c, however, are different. In this case, patient health is constant for most combinations of $R^r_c$ and $R^d_c$, and in some cases patient health deteriorates. The observations close to the $y$-axis are consistent with Proposition 7: we do not observe changes in patient health for $q > \bar{q}^r$. The values of $R^r_c$ and $R^d_c$ that lead to lower patient health in Figure 9c are not included Proposition 8 because they represent a combination of fee-for-service and capitation e-visit compensation. The intuition that was developed in Proposition 8, however, is applicable here: for sufficiently low values of $R^d_c$ and $R^r_c$, the physician picks an RVI of $T_h$ for patients who had an RVI of $T_l$ under the traditional case. This change of RVI increases physician revenue by diverting patient visits from routine visits that are less compensated under e-visits to urgent visits.

Figure 10 shows a case where e-visits can lead to smaller panel sizes. Note that there are few changes between the parameters in Figure 10 and the ones in Figures 8 and 9. The e-visits replace a lower fraction of routine visits, $\alpha^r_e = 0.2$, and take relatively less time to conduct, $\tau^r = 0.1$, the patient panel is healthier, $0.3 = q < \bar{q}^r_e = 0.41$, and proportion of physician compensation that is on a fee-for-service basis increased from 25% to 75%. Given these parameters, the proportional fee-for-service compensation for e-visits would be $R^r = 20$ (calculated as $200 \times \tau^r$). As before, we observe that for proportional e-visits compensation and $q < \bar{q}^r_e$ patient health is unchanged and panel size increases (Figures 10b and 10c). As the fee-for-service element of e-visit compensation, $R^r_e$, increases, however, we observe improvements in patient health and decreases in panel size. The reason for this change is the following: as per e-visit compensation becomes disproportionately generous, the physician shifts patient demand from urgent visits to routine visits (which include e-visits) by assigning the RVI of $T_l$ to patients that have the RVI of $T_h$ under the traditional mode.

To ensure the analytical tractability, Propositions 7, 8, and 9 are focused on the setting in which the patient population is homogeneous, and in-office urgent and routine visits are proportionally
compensated. In Appendix B, we consider a more general setting, and numerically illustrate the combined impact of RVI and care channel customization. In particular, we provide examples in which RVI customization and e-visits move system outcomes in the same or opposite directions.

5. Conclusion

The US health care system is facing challenging times as an increasing fraction of population receives care, and the government and private insurers experiment with new approaches for compensating care providers. To control costs and provide care for a larger number of patients, the
primary care system may have to augment the traditional care delivery mode with other approaches such as e-visits. Both patients and physicians are likely to adjust their behavior in the presence of these new approaches, impacting critical system metrics such as patient panel size and office revisit intervals. Understanding these changes is crucial for designing effective policies that aid a safe transition in primary care without compromising patient health or physician panel size.

Our study addresses the complexity of physician and patient interactions under different modes of primary care delivery. In our model, patients respond to changes in the way care is delivered by
adjusting the range of office revisit interval values they are willing to accept. On the physician side, we consider fee-for-service and capitation compensation schemes, and model the physician’s choice of patient panel size and office revisit intervals consistent with patient preferences. We characterize the optimal RVI and panel size values under both RVI and channel of care customization, and show how each impacts panel health, panel size, and physician earnings. We also examine the case where both forms of care customization are used and illustrate the resulting outcomes via numerical analysis for a range of plausible model parameters. The numerical analysis helps characterize the impact of customized decisions on the quality of provided care and on physician time savings, which enable the physician to expand her panel size or see patients more frequently.

We show that patient and physician responses to the changes in primary care delivery influence the magnitude and even the direction of changes in system outcomes. We find that although RVI customization is guaranteed to not decrease physician revenue, it can lead to (1) lower panel health if the fraction of healthy patients on the panel is sufficiently small, and (2) lower panel size if the fraction of healthy patients on the physician’s panel is sufficiently large.

A key focus in our study is on the pricing (physician compensation) of e-visits, which is a topical question as healthcare systems attempt to price them accurately. Our work yields several insights for system outcomes depending on how e-visits are compensated relative to office visits. The main conclusion from our exercise is that healthcare systems should attempt to match the revenue rates on e-visits and office visits as much as possible (e.g., ensuring both channels provide a similar “per minute” revenue to the physician) so as to avoid distorted incentives. We show that if the compensation of e-visits, as well as routine and urgent visits, is proportional to their duration, physician revenue and panel size increase, and panel health either improves or remains unchanged. In contrast, if physician e-visit compensation has large enough deviations from proportional compensation, all of the three mentioned outcomes may suffer. In particular, we provide evidence for two such scenarios in the paper. On one hand, if the fee-for-service element of e-visit compensation is not sufficiently high, the physician increases patient RVIs to divert patient demand away from routine visits (because e-visits reduce the physician revenue from routine visits). This will lead to lower patient health. On the other hand, if physician compensation for e-visits is sufficiently above the proportional level, the physician will decrease patient RVIs to benefit from the generously compensated e-visits. This will improve patient health but may lead to lower panel size.

We model the patients’ joint decision on e-visit adoption and the value of RVI. We show that e-visit adoption is more appealing to less healthy patients, which has important implications for how this channel of care affects system outcomes. We also show that healthier patients will only adopt e-visits if this channel can substitute a large enough portion of office visits, which is relevant in considering e-visit design. We also highlight insights for patients with an intermediate health
level. For these patients, if e-visits are not effective enough in terms of replacing office visits, they do not adopt e-visits; alternatively, if e-visits are too effective in replacing office visits, patients adopt e-visits but become inflexible with respect to the RVI values, demanding frequent office visits. Note that changes in patient flexibility under e-visits will not hurt patient health, but they can negatively impact panel size and physician revenue.

This paper provides the first attempt at modeling both the patient and the physician responses to care delivery innovations such as e-visits in primary care. Our analysis focuses on practice-oriented recommendations that are based on a limited number of easy-to-estimate parameters. As a result, it relies on several simplifying assumptions.

First, we model patient heterogeneity using two patient groups. In reality, patients may display a significant degree of heterogeneity with respect to many observable and unobservable characteristics, and, as a result, any patient panel will include sub-populations with substantially different levels of health, sensitivities to the cost of healthcare, disutilities associated with being sick, and levels of awareness of their health level. Consequently, it may be necessary to recast the issue of setting the “right” panel size as a problem of finding the optimal “portfolio” of different patient groups. While such an approach may allow for extraction of additional efficiency, it also raises a set of potential ethical and legal issues associated with limiting the ability for specific groups of patients to join the physician’s panel. We also assume an “exogenous” separation of patients into groups, an assumption that treats patient “identity” as fixed and not affected by the choice of RVI or other physician actions. In reality, the patient mix can be affected by physician RVIs. We believe, however, that the simplified approach we employ goes a long way in capturing the key trade-offs in this setting.

In our model a patient that falls sick receives same-day access to treatment, and there is no backlog of patient appointments. This assumption allows for closed-form characterization of system outcomes. While the “open access” model has been gaining a wider acceptance in recent years, appointment backlogs are very common in practice, and one potential extension to our work would include an analysis of alternative care delivery modes in the presence of backlogs.

Finally, we characterize physician compensation using a mix of two standard forms in current practice, fee-for-service and capitation payments. While significant changes to the physician compensation structure may not be likely in the short run, there has been interest in performance-based incentives that reward physicians for improvements in the quality of patient care. Future research could examine the impact of such incentives on system outcomes in primary care.
References


Online Appendix for “Redesigning Primary Care Delivery: Customized Office Revisit Intervals and E-Visits”

Appendix A: Proofs of Analytical Results

Proof of Lemma 1
A patient’s preference for the RVI value is governed by the objective of minimizing the long-run average cost defined by (7). Under the two-scenario distribution in (1) the RVI value that minimizes (7) is either $T_l$ or $T_h$. Since (7) is a decreasing function of $r_i$ for $r_i \leq T_l$ and for $r_i \in (T_l, T_h]$, the global minimum of $D_i^o (r_i)$ is either $T_l$ or $T_h$. Comparing $D_i^o (T_l)$ and $D_i^o (T_h)$, we get the desired result. The minimizer is $T_l$ if $q_i$ is such that

$$\frac{1}{T_l} < \frac{1 + q_i \eta}{q_i T_l + (1 - q_i) T_h}.$$  (A1)

Solving (A1) for $q_i$, we have

$$q_i > \frac{1}{1 + \frac{\eta}{T_l}}.$$  (A2)

□

Proof of Lemma 2
Note that $q^- (c, \Delta) = \frac{1}{1 + \frac{c(1 + \Delta)}{T_l}} < \frac{1}{1 + \frac{c(1 - \Delta)}{T_h}} = q^+ (c, \Delta)$ for $\Delta > 0$. Then, the value of $q_i$ can fall in three possible intervals:

1) $q_i < q^- (c, \Delta)$: using Lemma 1, $T_h$ is the minimizer of patient cost in (7) for both $\eta = c(1 - \Delta)$ and $\eta = c(1 + \Delta)$.

2) $q_i > q^+ (c, \Delta)$: using Lemma 1, $T_l$ is the minimizer of patient cost in (7) for both $\eta = c(1 - \Delta)$ and $\eta = c(1 + \Delta)$.

3) $q^- (c, \Delta) \leq q_i \leq q^+ (c, \Delta)$: using Lemma 1, $T_l$ is the minimizer of patient cost in (7) for $\eta = c(1 + \Delta)$, and $T_h$ is the minimizer of patient cost in (7) for $\eta = c(1 - \Delta)$. Therefore, the patients in group $i$ are willing to accept both $T_l$ and $T_h$.

□

Proof of Proposition 1
When a physician applies the same RVI value $r$ to both patient groups she can choose either $r = r_1 = r_2 = T_h$ or $r = r_1 = r_2 = T_l$. Therefore, we need to compare the values of the objective function (15) for $r = r_1 = r_2 = T_l$ and $r = r_1 = r_2 = T_h$. For $r = r_1 = r_2 = T_l$, the objective function value is

$$\frac{(1 - \delta) R^d + \delta R^e}{T_l},$$  (A3)
while for \( r = r_1 = r_2 = T_h \), the objective function value is

\[
(1 - \delta)R^d + \delta \left( \frac{\kappa_1 \left( (1-q_1)R^r + q_1R^u \right)}{(1-q_1)T_h + q_1T_i} + \kappa_2 \left( (1-q_2)R^r + q_2R^u \right) \right) \left( \frac{1-q_1}{1-q_1} \right)
\]

\[
\geq \frac{\kappa_1 \left( (1-q_1)R^r + q_1R^u \right)}{(1-q_1)T_h + q_1T_i} + \kappa_2 \left( (1-q_2)R^r + q_2R^u \right)
\]

\[
= \left( \frac{1}{\pi^r_T} \right) \frac{\kappa_1 \left( (1-q_1)R^r + q_1R^u \right)}{(1-q_1)T_h + q_1T_i} + \kappa_2 \left( (1-q_2)R^r + q_2R^u \right)
\]

\[
(1 - \delta)R^d + \delta \left( \frac{1-q_1}{1-q_1} \right) = \left( \frac{1}{\pi^r_T} \right),
\]

which is equivalent to

\[
(1 - \delta)R^d + \delta \left( \frac{1-q_1}{1-q_1} \right) \geq \left( \frac{1}{\pi^r_T} \right),
\]

For \( r = r_1 = r_2 = T_h \) to be optimal, we need to have, from (A3) and (A4),

\[
\left( 1 - \delta \right)R^d + \delta \left( \frac{1-q_1}{1-q_1} \right) \geq \left( \frac{1}{\pi^r_T} \right),
\]

or equivalently

\[
\left( 1 - \delta \right)R^d + \delta \left( \frac{1-q_1}{1-q_1} \right) \geq \left( \frac{1}{\pi^r_T} \right),
\]

which follows from (A6).

The optimality of \( r = r_1 = r_2 = T_i \) for the setting \( \frac{q^*}{(1+\Sigma)^r} < q_1 < q_2 \) is established in the same fashion.

For \( q_1 \leq \frac{q^*}{(1+\Sigma)^r} < q_2 \), we define the following notation:

\[
x_i = \delta \left( \frac{1-q_1}{1-q_1} \right),
\]

\[
y_i = \frac{1-q_1}{1-q_1} T_i + q_1 T_i,
\]

\[
\frac{1-q_1}{1-q_1} R^d + \delta \frac{\pi^r_T}{T_i},
\]

\[
a = (1 - \delta)R^d.
\]

Then, we simplify (A7) to

\[
\frac{a + \kappa_1 x_1 + \kappa_2 x_2}{\kappa_1 y_1 + \kappa_2 y_2} > b,
\]

which simplifies to

\[
a + \kappa_1 x_1 + \kappa_2 x_2 > b \left( \kappa_1 y_1 + \kappa_2 y_2 \right).
\]
We re-express (A15) as
\[ \kappa_1 (x_1 - by_1) + \kappa_2 (x_2 - by_2) > -a, \] (A16)
which, given that \( \kappa_2 = 1 - \kappa_1 \), is equivalent to
\[ \kappa_1 ((x_1 - by_1) - (x_2 - by_2)) > -a - (x_2 - by_2). \] (A17)
Note that because of the conditions on \( q_1 \) and \( q_2 \) in this setting, from (A6) we have \( a + x_1 - by_1 \geq 0 \) and \( a + x_2 - by_2 < 0 \). Therefore, \( (x_1 - by_1) - (x_2 - by_2) > 0 \). We further simplify (A17) to
\[ \kappa_1 > \frac{1}{1 - \frac{a + (x_1 - by_1)}{a + (x_2 - by_2)}}. \] (A18)
The term in (A18) is \( \hat{\kappa}_1 \), and we simplify it using (A25) and (A27) in the following way:
\[
\begin{align*}
a + (x_i - by_i) &= (1 - \delta)R^d + \frac{\delta R^r}{T_i} \left( 1 + \frac{q_i - \bar{q}^R}{\bar{q}^R (Q^T - q_i)} \right) - \left( \frac{\tau}{T_i} \left( 1 + \frac{q_i - \bar{q}^T}{\bar{q}^T (Q^T - q_i)} \right) \right) \left( \frac{(1 - \delta) R^d + \delta R^r}{T_i} \right) = \\
&\quad \left( \frac{\delta R^r}{T_i} \right) + \left( 1 + \frac{q_i - \bar{q}^R}{\bar{q}^R (Q^T - q_i)} \right) - \left( 1 + \frac{q_i - \bar{q}^T}{\bar{q}^T (Q^T - q_i)} \right) \left( \frac{(1 - \delta) R^d T_i + \delta R^r}{\delta R^r} \right) = \\
&\quad \left( \frac{q_i - \bar{q}^R}{\bar{q}^R (Q^T - q_i)} \right) - \left( \frac{q_i - \bar{q}^T}{\bar{q}^T (Q^T - q_i)} \right) \hat{R} = \frac{q_i - \bar{q}^R}{\bar{q}^R (Q^T - q_i)} - \frac{q_i - \bar{q}^T}{\bar{q}^T (Q^T - q_i)} \frac{\hat{R}}{Q^T - q_i} = \\
&\quad \left( \frac{\hat{R} - 1}{Q^T - q_i} \right) + \left( \frac{q_i - \bar{q}^R}{\bar{q}^R (Q^T - q_i)} \right) - \left( \frac{q_i - \bar{q}^T}{\bar{q}^T (Q^T - q_i)} \right) \frac{\hat{R} - 1}{Q^T - q_i} = \\
&\quad \left( \frac{\hat{R} - 1}{Q^T - q_i} \right) + \left( \frac{q_i - \bar{q}^R}{\bar{q}^R (Q^T - q_i)} \right) - \left( \frac{q_i - \bar{q}^T}{\bar{q}^T (Q^T - q_i)} \right) \frac{\hat{R} - 1}{Q^T - q_i} + \frac{\hat{R} - 1}{Q^T - q_i} \left( \frac{q_i (1 + \Sigma) - \bar{q}^T}{\bar{q}^T (Q^T - q_i)} \right). \quad (A19)
\end{align*}
\]
The result then follows from (A18).

\[ \square \]

**Proof of Proposition 2**

Note that since both (16) and (17) are increasing functions of \( N \), (16)-(18) is equivalent to
\[
\max_{r_1, r_2} \frac{(1 - \delta) R^d + \delta \kappa_1 \left( \frac{\rho_{x_1}^*(r_1) R^r + (1 - \rho_{x_1}^*(r_1)) R^u}{T_1(r_1)} \right) + \delta \kappa_2 \left( \frac{\rho_{x_2}^*(r_2) R^r + (1 - \rho_{x_2}^*(r_2)) R^u}{T_2(r_2)} \right)}{\kappa_1 \left( \frac{\rho_{x_1}^*(r_1) R^r + (1 - \rho_{x_1}^*(r_1)) R^u}{T_1(r_1)} \right) + \kappa_2 \left( \frac{\rho_{x_2}^*(r_2) R^r + (1 - \rho_{x_2}^*(r_2)) R^u}{T_2(r_2)} \right)} s.t. r_1, r_2 \in \{T_l, T_h\}, \quad (A20)\]
\[ (A21) \]
with the optimal panel size determined by
\[ \hat{N} = \frac{A}{\kappa_1 \left( \frac{\rho_i^r(r_i) r^r + (1 - \rho_i^r(r_i)) r^u}{T_i(r_i)} \right) + \kappa_2 \left( \frac{\rho_i^2(r_2) r^r + (1 - \rho_i^2(r_2)) r^u}{T_2(r_2)} \right)} \]  
(A22)

Let \( S_l (S_h) \) be the set of patient group indices for which the optimal revisit interval is set at \( T_l (T_h) \). Since
\[ \rho_i (T_l) = 1, T_i (T_l) = T_l, i = 1, 2, \]  
(A23)

and
\[ \rho_i (T_h) = 1 - q_i, T_i (T_h) = q_i T_l + (1 - q_i) T_h, i = 1, 2, \]  
(A24)

the expression in the numerator of objective function in (A20) can be expressed as
\[ \frac{\rho_i^r (r_i) R^r + (1 - \rho_i^r (r_i)) R^u}{T_i (r_i)} = \frac{R^r}{T_l} \left( 1 + \frac{q_i - \bar{q}^R}{q_i (Q^r - q_i)} Y_i \right), \]  
(A25)

where
\[ Y_i = \begin{cases} 0, & i \in S_l, \\ 1, & i \in S_h. \end{cases} \]  
(A26)

We can re-write the expression in the denominator of (A20) as
\[ \frac{1}{T_i (r_i)} (\rho_i^r (r_i) \tau^r + (1 - \rho_i^r (r_i)) \tau^u) = \tau^r \left( 1 + \frac{q_i - \bar{q}^r}{q_i (Q^r - q_i)} Y_i \right), \]  
(A27)

Introducing
\[ R_i = \kappa_1 \left( \frac{q_i - \bar{q}^R}{q_i (Q^r - q_i)} \right), i = 1, 2, \]  
(A28)

\[ A_i = \kappa_1 \left( \frac{q_i - \bar{q}^r}{q_i (Q^r - q_i)} \right), i = 1, 2, \]  
(A29)

we note that the optimization problem (A20)-(A21) is equivalent to
\[ \max_{Y_1, Y_2} R + R_1 Y_1 + R_2 Y_2 \]  
\[ \text{s.t. } Y_1, Y_2 \in \{0, 1\}. \]  
(A30)

(A31)

Note that the optimal combination of \( Y_1 \) and \( Y_2 \) values is one of the four possible ones: (0, 0), (1, 0), (0, 1) and (1, 1). The four values for the objective function corresponding to those combinations are
\[ \bar{R}, \frac{\bar{R} + R_1}{1 + A_1}, \frac{\bar{R} + R_2}{1 + A_2}, \text{ and } \frac{\bar{R} + R_1 + R_2}{1 + A_1 + A_2}. \]  
In order to determine which of these four values is the highest, we will look at several different cases describing the signs of \( R_1, A_1, R_2, \) and \( A_2 \). Note that the signs of these quantities are determined by the values of \( q_i - \bar{q}^r \) and \( q_i - \bar{q}^r \), \( i = 1, 2 \). For the analysis below, we will need the following result.
Lemma A1. For \( q_i \leq \bar{q}^R, i = 1, 2 \), we have

\[
|\mathcal{R}_1| + |\mathcal{R}_2| \leq \bar{R}, \tag{A32}
\]

and, for \( q_i \leq \bar{q}^\tau, i = 1, 2 \), we have

\[
|\mathcal{A}_1| + |\mathcal{A}_2| \leq 1. \tag{A33}
\]

Proof of Lemma A1:

Note that for \( q_i \leq \bar{q}^R \),

\[
|\mathcal{R}_i| = \kappa_i \frac{\bar{q}^R - q_i}{\bar{q}^R (\bar{q}^\tau - q_i)} \tag{A34}
\]

is a decreasing function of \( q_i \) (due to \( \bar{q}^\tau > 1 > \bar{q}^R \)). Then, we have

\[
|\mathcal{R}_i| = \kappa_i \frac{\bar{q}^R - q_i}{\bar{q}^R (\bar{q}^\tau - q_i)} \leq \frac{\kappa_i}{\bar{q}^\tau}. \tag{A35}
\]

Thus,

\[
\bar{R} - |\mathcal{R}_1| - |\mathcal{R}_2| \geq 1 - \frac{\kappa_1}{\bar{q}^\tau} - \frac{\kappa_2}{\bar{q}^\tau} \geq \left( 1 - \frac{1}{\bar{q}^\tau} \right) > 0. \tag{A36}
\]

In a similar fashion, for \( q_i \leq \bar{q}^\tau \), we have

\[
|\mathcal{A}_i| = \kappa_i \frac{\bar{q}^\tau - q_i}{\bar{q}^\tau (\bar{q}^\tau - q_i)} \leq \frac{\kappa_i}{\bar{q}^\tau}, \tag{A37}
\]

and

\[
\bar{1} - |\mathcal{A}_1| - |\mathcal{A}_2| \geq 1 - \frac{\kappa_1}{\bar{q}^\tau} - \frac{\kappa_2}{\bar{q}^\tau} \geq \left( 1 - \frac{1}{\bar{q}^\tau} \right) > 0. \tag{A38}
\]

Assuming that \( q_1 < q_2 \), we will analyze 12 separate cases. Note that \( \Sigma \) defined in (23) is non-negative if and only if \( \bar{q}^\tau \leq \bar{q}^R \).

Case 1: \( \bar{q}^\tau \leq \bar{q}^R, q_1 < q_2 < \bar{q}^\tau \).

In this case, we have \( \mathcal{R}_i, \mathcal{A}_i < 0, i = 1, 2 \). Then,

\[
\frac{\bar{R} + \mathcal{R}_1}{1 + \mathcal{A}_1} = \frac{\bar{R} - |\mathcal{R}_1|}{1 - |\mathcal{A}_1|}, \tag{A39}
\]

\[
\frac{\bar{R} + \mathcal{R}_2}{1 + \mathcal{A}_2} = \frac{\bar{R} - |\mathcal{R}_2|}{1 - |\mathcal{A}_2|}, \tag{A40}
\]

\[
\frac{\bar{R} + \mathcal{R}_1 + \mathcal{R}_2}{1 + \mathcal{A}_1 + \mathcal{A}_2} = \frac{\bar{R} - |\mathcal{R}_1| - |\mathcal{R}_2|}{1 - |\mathcal{A}_1| - |\mathcal{A}_2|}. \tag{A41}
\]
Thus, the optimal combination of $Y_1$ and $Y_2$ is $(1, 1)$, corresponding to the optimal RVI values $\hat{r}_1 = \hat{r}_2 = T_k$.

Now, suppose that $\frac{|\mathcal{A}_1|}{|\mathcal{A}_2|} \leq \bar{R} < \frac{|\mathcal{R}_2|}{|\mathcal{A}_2|}$. Note that

$$\frac{1 - \frac{q_1}{q^r}}{1 - \frac{q_2}{q^r}} \leq \bar{R}$$

(A50)

is equivalent to

$$q_1 \leq \frac{\bar{q}^r}{1 + \Sigma}$$

(A51)
with $\Sigma$ defined by (23). In a similar fashion,

$$\frac{1 - \frac{q_2}{\bar{q}^2}}{1 - \frac{q_1}{\bar{q}^2}} > \bar{R}$$

is equivalent to

$$q_2 > \frac{\bar{q}^2}{1 + \Sigma}.$$  

Then,

$$\bar{R} \leq \bar{R} - \frac{|R_1|}{1 - |A_1|},$$  

$$\bar{R} > \bar{R} - \frac{|R_2|}{1 - |A_2|},$$

and

$$\bar{R} - |R_1| - |R_2| - \frac{\bar{R} - |R_1| - |R_2|}{1 - |A_1|} = |A_2| \left( \frac{\bar{R} - |R_1| - |R_2|}{1 - |A_1|} \right) \left( \frac{1}{1 - |A_1| - |A_2|} \right)$$

$$= \frac{|A_2| (1 - |A_1|)}{(1 - |A_2|) (1 - |A_1| - |A_2|)}.$$

We define

$$\bar{R}^* = \frac{\bar{R} + R_1}{1 + A_1} = \frac{\bar{R} - \frac{\bar{R}_1}{\bar{q}^2 - q_1} \left( 1 - \frac{q_1}{\bar{q}^2} \right)}{1 - \frac{\bar{R}_1}{\bar{q}^2 - q_1} \left( 1 - \frac{q_1}{\bar{q}^2} \right)},$$

and observe that, in the setting with $R_1, A_1 < 0$ we have

$$\bar{R}^* = \frac{\bar{R} - |R_1|}{1 - |A_1|}.$$  

For $\frac{|R_1|}{|A_1|} \leq \bar{R},$

$$\bar{R}^* - \bar{R} = \frac{\bar{R} - |R_1|}{1 - |A_1|} - \bar{R} = \frac{|A_1| \left( \frac{\bar{R} - |R_1|}{|A_1|} \right)}{1 - |A_1|} > 0,$$

we see that the optimal combination of $Y_1$ and $Y_2$ is $(1, 0)$ for $\bar{R} \leq \bar{R}^* < \frac{|R_2|}{|A_2|}$ and $(1, 1)$ for $\bar{R} < \frac{|R_2|}{|A_2|} \leq \bar{R}^*$, so that the optimal RVI values $\hat{r}_1 = T_h$ and $\hat{r}_2 = T_i$ for $\bar{R} \leq \bar{R}^* < \frac{|R_2|}{|A_2|}$ and $\hat{r}_1 = \hat{r}_2 = T_h$ for $\bar{R} < \frac{|R_2|}{|A_2|} \leq \bar{R}^*$. Note that

$$\frac{|R_2|}{|A_2|} < \frac{\bar{R} - |R_1|}{1 - |A_1|} = \bar{R}^*,$$

(A60)
is equivalent to
\[ q_2 < q^\tau \frac{\bar{R}^* - 1}{\bar{R}^* - \frac{q^\tau}{q^\tau}}. \]  \hfill (A61)

The expression on the right-hand side of (A61) can be re-written as
\[ \frac{\bar{R}^* - 1}{\bar{R}^* - \frac{q^\tau}{q^\tau}} = \frac{\bar{R} - 1 - |A_1|}{1 - |A_1|}. \]  \hfill (A62)

Further,
\[ \bar{R}^* - 1 = \frac{\bar{R} - |R_1|}{1 - |A_1|} - 1 = \frac{\bar{R} - 1 - |R_1| + |A_1|}{1 - |A_1|} > 0, \]  \hfill (A63)

and
\[ \bar{R}^* - \frac{q^\tau}{q^\tau} = \frac{\bar{R} - |R_1|}{1 - |A_1|} - \frac{q^\tau}{q^\tau} = \frac{\bar{R} - 1 - |R_1| + \frac{q^\tau}{q^\tau} |A_1|}{1 - |A_1|} > 0, \]  \hfill (A64)

since \( \bar{R}^* \geq \bar{R} \geq 1 \), so that
\[
\frac{\bar{R}^* - 1}{\bar{R}^* - \frac{q^\tau}{q^\tau}} = \frac{\bar{R} - 1 - |R_1| + |A_1|}{\bar{R} - \frac{q^\tau}{q^\tau} - |R_1| + \frac{q^\tau}{q^\tau} |A_1|} = \frac{\bar{R} - 1 - \frac{q^\tau}{q^\tau} \left( \frac{\kappa_1}{Q^T - q_1} \right) \left( 1 - \frac{q^\tau}{q^\tau} \right)}{\bar{R} - \frac{q^\tau}{q^\tau} - \left( \frac{\kappa_1}{Q^T - q_1} \right) \left( 1 - \frac{q^\tau}{q^\tau} \right)} \frac{Q^T - q_1 - \frac{q^\tau}{q^\tau} \kappa_1 \Sigma}{1 + \Sigma - \left( \frac{\kappa_1}{Q^T - q_1} \right) \Sigma} = \frac{Q^T - q_1 - \frac{q^\tau}{q^\tau} \kappa_1 \Sigma}{(1 + \Sigma) Q^T - \kappa_1 \Sigma - q_1 (1 + \Sigma)}. \]  \hfill (A65)

Note that for \( \Sigma > 0 \) and \( q_1 \leq \frac{q^\tau}{1+\Sigma} \), the denominator of the expression on the right-hand side of (A65) is positive. Thus, (A61) is equivalent to (27) for \( \Sigma > 0 \). Note that the right-hand side of (A65) is a decreasing function of \( q_1 \), and it reaches its maximum value on the interval \( q_1 \in [0, q^\tau] \) at \( q_1 = 0 \). That maximum value,
\[ \frac{Q^T}{(1 + \Sigma) Q^T - \kappa_1 \Sigma} \]  \hfill (A66)

in decreasing in \( Q^T \) and increasing in \( \kappa_1 \), and, thus, reaches its highest value, equal to 1, at \( Q^T = \kappa_1 = 1 \). Thus
\[ q_2 \leq q^\tau \left( \frac{Q^T - q_1 \left( 1 + \frac{\kappa_1 \Sigma}{q^\tau} \right)}{(1 + \Sigma) Q^T - \kappa_1 \Sigma - q_1 (1 + \Sigma)} \right) \]  \hfill (A67)

implies that \( q_2 < q^\tau \).

Finally, suppose that \( 1 \leq \bar{R} \leq \frac{|R_1|}{1 - |A_1|} \). Then,
\[ \bar{R} > \frac{\bar{R} - |R_1|}{1 - |A_1|}, \]  \hfill (A68)
ensures that as we showed in (A51), \( \bar{Y} \), so that the optimal combination of \( \bar{Y} \).

Thus, the optimal combination of \( Y_1 \) and \( Y_2 \) is \((0, 0)\), and the optimal RVI values are \( \hat{r}_1 = \hat{r}_2 = T_i \).

Case 2: \( q^r \leq q^R \), \( q_1 < q^r \leq q_2 \leq q^R \).

In this case, we have \( R_1, R_2, A_1 < 0 \), and \( A_2 \geq 0 \). Then,

\[
\frac{\bar{R} + R_1}{1 + A_1} = \frac{\bar{R} - |R_1|}{1 - |A_1|},
\]

\[
\frac{\bar{R} + R_2}{1 + A_2} = \frac{\bar{R} - |R_2|}{1 + |A_2|},
\]

\[
\frac{\bar{R} + R_1 + R_2}{1 + A_1 + A_2} = \frac{\bar{R} - |R_1| - |R_2|}{1 - |A_1| + |A_2|},
\]

where

\[
|R_i| = \kappa_i \left( \frac{1 - \frac{q_i}{q^r}}{Q^T - q_i} \right), \quad i = 1, 2,
\]

\[
|A_1| = \kappa_1 \left( \frac{1 - \frac{q_1}{q^r}}{Q^T - q_1} \right),
\]

\[
|A_2| = \kappa_2 \left( \frac{q_2}{q^r} - 1 \right). \frac{1}{Q^T - q_1}.
\]

Note that the optimal value for \( Y_2 \) is 0, and the optimal value of \( Y_1 \) depends on the relative values of \( \bar{R} \) and \( \frac{\bar{R} - |R_1|}{1 - |A_1|} \). We have

\[
\frac{\bar{R} - |R_1|}{1 - |A_1|} = \frac{\bar{R} - |A_1| - |R_1|}{1 - |A_1|}.
\]

Thus, the optimal combination of \( Y_1 \) and \( Y_2 \) is \((1, 0)\) for \( \bar{R} \geq \frac{R_1}{|A_1|} \) and \((0, 0)\) for \( \bar{R} < \frac{R_1}{|A_1|} \), so that the optimal RVI values \( \hat{r}_1 = \hat{r}_2 = T_i \) for \( \bar{R} < \frac{R_1}{|A_1|} \) and \( \hat{r}_1 = T_h \) and \( \hat{r}_2 = T_i \) for \( \bar{R} \geq \frac{R_1}{|A_1|} \). Note that, as we showed in (A51), \( \bar{R} \geq \frac{R_1}{|A_1|} \) is equivalent to \( q_1 \leq \frac{q^r}{1 + \Sigma} \). Also, as we have shown earlier, \( q_2 > q^r \) ensures that

\[
q_2 > q^r \left( \frac{Q^T - q_1 - \frac{q_1}{q^r} k_1 \Sigma}{Q^T - q_1} \right) = \frac{Q^T - q_1}{(1 + \Sigma) Q^T - k_1 \Sigma - q_1 (1 + \Sigma)}.
\]

Case 3: \( q^r \leq q^R \), \( q_1 < q^r \leq q^R < q_2 \).
In this case, we have \( R_1, A_1 < 0 \), and \( R_2, A_2 \geq 0 \). Then,

\[
\begin{align*}
\bar{R} + R_1 &= \bar{R} - |R_1| + \frac{1 - q_1}{\hat{Q}^T - q_1}, \\
\bar{R} + R_2 &= \bar{R} + |R_2| + \frac{1 - q_1}{\hat{Q}^T - q_1}, \\
\bar{R} + R_1 + R_2 &= \bar{R} - |R_1| + |R_2| \quad (A79)
\end{align*}
\]

where

\[
|R_1| = \kappa_1 \left( 1 - \frac{q_1}{\hat{Q}^T - q_1} \right) \quad (A82)
\]

\[
|R_2| = \kappa_2 \left( \frac{q_2}{\hat{Q}^T - q_2} - 1 \right) \quad (A83)
\]

\[
|A_1| = \kappa_1 \left( 1 - \frac{q_1}{\hat{Q}^T - q_1} \right) \quad (A84)
\]

\[
|A_2| = \kappa_2 \left( \frac{q_2}{\hat{Q}^T - q_2} - 1 \right) \quad (A85)
\]

Note that in this case we have

\[
\frac{|R_2|}{|A_2|} \leq 1 \leq \frac{|R_1|}{|A_1|} \quad (A86)
\]

Suppose that \( \bar{R} \geq \frac{|R_1|}{|A_1|} \). Then,

\[
\bar{R} \leq \frac{\bar{R} - |R_1|}{1 - |A_1|} \quad (A87)
\]

\[
\bar{R} \geq \frac{\bar{R} + |R_2|}{1 + |A_2|} \quad (A88)
\]

Further, we have

\[
\begin{align*}
\frac{\bar{R} - |R_1| + |R_2|}{1 - |A_1| + |A_2|} - \frac{\bar{R} - |R_1|}{1 - |A_1|} &= -|A_2| (\bar{R} - |R_1|) + |R_2| (1 - |A_1|) \quad (A89)
\end{align*}
\]

Thus, the optimal combination of \( Y_1 \) and \( Y_2 \) is \((1, 0)\), corresponding to the optimal RVI values \( \hat{r}_1 = T_h, \hat{r}_2 = T_l \). Note that, as we showed in \((A51)\), \( \bar{R} \geq \frac{|R_1|}{|A_1|} \) is equivalent to \( q_1 \leq \frac{\hat{Q}^T}{1 + |A_2|} \).

Now, suppose that \( \frac{|R_2|}{|A_2|} \leq 1 \leq \bar{R} \leq \frac{|R_1|}{|A_1|} \). Then,

\[
\bar{R} > \frac{\bar{R} - |R_1|}{1 - |A_1|} \quad (A90)
\]
\[
\tilde{R} > \frac{\bar{R} + |R_2|}{1 + |A_2|},
\]  
(A91)

and

\[
\bar{R} - \frac{|R_1| + |R_2|}{1 - |A_1| + |A_2|} - \bar{R} = \frac{|A_1| \left( \bar{R} - \frac{|R_1|}{A_1} \right) + |A_2| \left( \frac{|R_2|}{A_2} - \bar{R} \right)}{1 - |A_1| + |A_2|} \leq 0,
\]  
(A92)

so that the optimal combination of \(Y_1\) and \(Y_2\) is \((0,0)\), corresponding to the optimal RVI values \(\hat{r}_1 = T_1, \hat{r}_2 = T_1\).

Case 4: \(\bar{q}^r \leq \bar{q}^R, \bar{q}^r \leq q_1 < q_2 \leq \bar{q}^R\).

In this case, we have \(R_1, R_2 \leq 0\), and \(A_1, A_2 \geq 0\). Then,

\[
\frac{\bar{R} + R_1}{1 + A_1} = \frac{\bar{R} - |R_1|}{1 + |A_1|},
\]  
(A93)

\[
\frac{\bar{R} + R_2}{1 + A_2} = \frac{\bar{R} - |R_2|}{1 + |A_2|},
\]  
(A94)

\[
\frac{\bar{R} + R_1 + R_2}{1 + A_1 + A_2} = \frac{\bar{R} - |R_1| - |R_2|}{1 + |A_1| + |A_2|},
\]  
(A95)

and \(\bar{R}\) is the highest value among the four possibilities. Thus, optimal combination of \(Y_1\) and \(Y_2\) is \((0,0)\), corresponding to the optimal RVI values \(\hat{r}_1 = T_1, \hat{r}_2 = T_1\).

Case 5: \(\bar{q}^r \leq \bar{q}^R, \bar{q}^r \leq q_1 \leq q_2 < \bar{q}^R\).

In this case, we have \(R_1 \leq 0, R_2 > 0\), and \(A_1 \geq 0, A_2 > 0\). Then,

\[
\frac{\bar{R} + R_1}{1 + A_1} = \frac{\bar{R} - |R_1|}{1 + |A_1|},
\]  
(A96)

\[
\frac{\bar{R} + R_2}{1 + A_2} = \frac{\bar{R} + |R_2|}{1 + |A_2|},
\]  
(A97)

\[
\frac{\bar{R} + R_1 + R_2}{1 + A_1 + A_2} = \frac{\bar{R} - |R_1| + |R_2|}{1 + |A_1| + |A_2|},
\]  
(A98)

and the optimal value of \(Y_1\) is 0. The optimal value of \(Y_2\) depends on the relative values of \(\bar{R}\) and \(\frac{\bar{R} + |R_2|}{1 + |A_2|}\). Note that

\[
\bar{R} + \frac{|R_2|}{1 + |A_2|} - \bar{R} = \frac{|A_2| \left( \frac{|R_2|}{A_2} - \bar{R} \right)}{1 + |A_2|} < 0,
\]  
(A99)

since \(\bar{R} \geq 1\), and, for \(\bar{q}^r \leq \bar{q}^R < q_2\), we have \(\frac{|R_2|}{|A_2|} \leq 1\). Thus, the optimal combination of \(Y_1\) and \(Y_2\) is \((0,0)\), corresponding to the optimal RVI values \(\hat{r}_1 = T_1, \hat{r}_2 = T_1\).

Case 6: \(\bar{q}^r \leq \bar{q}^R, \bar{q}^R < q_1 < q_2\).
In this case, we have $\mathcal{R}_1, \mathcal{R}_2 > 0$, and $\mathcal{A}_1, \mathcal{A}_2 > 0$. Then,

$$|\mathcal{R}_1| = \kappa_1 \left( \frac{q_1 - 1}{q_T - q_1} \right), \tag{A100}$$

$$|\mathcal{R}_2| = \kappa_2 \left( \frac{q_2 - 1}{q_T - q_2} \right), \tag{A101}$$

$$|\mathcal{A}_1| = \kappa_1 \left( \frac{q_1 - 1}{q_T - q_1} \right), \tag{A102}$$

$$|\mathcal{A}_2| = \kappa_2 \left( \frac{q_2 - 1}{q_T - q_1} \right). \tag{A103}$$

and

$$\frac{|\mathcal{R}_1|}{|\mathcal{A}_1|} < \frac{|\mathcal{R}_2|}{|\mathcal{A}_2|} \leq 1 \leq \bar{R}. \tag{A104}$$

Note that in this case, we also have

$$\bar{R} + \mathcal{R}_1 = \frac{\bar{R} + |\mathcal{R}_1|}{1 + |\mathcal{A}_1|}, \tag{A105}$$

$$\bar{R} + \mathcal{R}_2 = \frac{\bar{R} + |\mathcal{R}_2|}{1 + |\mathcal{A}_2|}, \tag{A106}$$

$$\bar{R} + \mathcal{R}_1 + \mathcal{R}_2 = \frac{\bar{R} + |\mathcal{R}_1| + |\mathcal{R}_2|}{1 + |\mathcal{A}_1| + |\mathcal{A}_2|}. \tag{A107}$$

Further, we have

$$\frac{\bar{R} + \mathcal{R}_1}{1 + \mathcal{A}_1} - \bar{R} = \frac{\mathcal{A}_1 \left( \frac{\mathcal{R}_1}{\mathcal{A}_1} - \bar{R} \right)}{1 + \mathcal{A}_1} \leq 0, \tag{A108}$$

$$\frac{\bar{R} + \mathcal{R}_2}{1 + \mathcal{A}_2} - \bar{R} = \frac{\mathcal{A}_2 \left( \frac{\mathcal{R}_2}{\mathcal{A}_2} - \bar{R} \right)}{1 + \mathcal{A}_2} \leq 0, \tag{A109}$$

$$\frac{\bar{R} + \mathcal{R}_1 + \mathcal{R}_2}{1 + \mathcal{A}_1 + \mathcal{A}_2} - \bar{R} = \frac{\mathcal{A}_1 \left( \frac{\mathcal{R}_1}{\mathcal{A}_1} - \bar{R} \right) + \mathcal{A}_2 \left( \frac{\mathcal{R}_2}{\mathcal{A}_2} - \bar{R} \right)}{1 + \mathcal{A}_1 + \mathcal{A}_2} \leq 0, \tag{A110}$$

so that the optimal combination of $Y_1$ and $Y_2$ is $(0,0)$, corresponding to the optimal RVI values $\hat{r}_1 = T_1, \hat{r}_2 = T_1$.

Case 7: $\bar{q}^T > \bar{q}^R$, $q_1 < q_2 < \bar{q}^R$.

In this case, we have $\mathcal{R}_i, \mathcal{A}_i < 0$, $i = 1, 2$. Then,

$$\frac{\bar{R} + \mathcal{R}_1}{1 + \mathcal{A}_1} = \frac{\bar{R} - |\mathcal{R}_1|}{1 - |\mathcal{A}_1|}, \tag{A111}$$

$$\frac{\bar{R} + \mathcal{R}_2}{1 + \mathcal{A}_2} = \frac{\bar{R} - |\mathcal{R}_2|}{1 - |\mathcal{A}_2|}, \tag{A112}$$

$$\frac{\bar{R} + \mathcal{R}_1 + \mathcal{R}_2}{1 + \mathcal{A}_1 + \mathcal{A}_2} = \frac{\bar{R} - |\mathcal{R}_1| - |\mathcal{R}_2|}{1 - |\mathcal{A}_1| - |\mathcal{A}_2|}. \tag{A113}$$
where
\[ |\mathcal{R}_1| = \kappa_i \left( \frac{1 - q_i}{Q^T - q_i} \right), i = 1, 2, \]
\[ |\mathcal{A}_1| = \kappa_i \left( \frac{1 - q_i}{Q^T - q_i} \right), i = 1, 2. \]  
(A114)
(A115)

Note that because \( q_1 < q_2 \) and \( \bar{q}^r > \bar{q}^R \), we have
\[ |\mathcal{R}_i| < |\mathcal{A}_i|, i = 1, 2, \]  
(A116)
\[ |\mathcal{R}_2| < |\mathcal{A}_1| < 1, \]  
(A117)

so that \( \bar{R} \geq 1 \left| \frac{\mathcal{R}_1}{\mathcal{A}_1} \right| > \left| \frac{\mathcal{R}_2}{\mathcal{A}_2} \right| \). Then,
\[ \bar{R} - \frac{\bar{R} - |\mathcal{R}_1|}{1 - |\mathcal{A}_1|} \leq 0, \]  
(A118)
\[ \bar{R} - \frac{\bar{R} - |\mathcal{R}_2|}{1 - |\mathcal{A}_2|} \leq 0, \]  
(A119)

\[ \frac{\bar{R} - |\mathcal{R}_1|}{1 - |\mathcal{A}_1|} - \frac{\bar{R} - |\mathcal{R}_1| - |\mathcal{R}_2|}{1 - |\mathcal{A}_1| - |\mathcal{A}_2|} = \frac{|\mathcal{A}_2|}{1 - |\mathcal{A}_1| - |\mathcal{A}_2|} \left( \frac{\mathcal{R}_2}{|\mathcal{A}_2|} - \frac{\mathcal{R}_1}{|\mathcal{A}_1|} \right) \leq 0, \]  
(A120)

so that the optimal combination of \( Y_1 \) and \( Y_2 \) is \((1, 1)\), corresponding to the optimal RVI values \( \hat{r}_1 = T_h, \hat{r}_2 = T_h \).

Note that the conditions in this case also satisfy the conditions in (27). \( \bar{q}^r > \bar{q}^R \) guarantees that \( \Sigma < 0 \), so that \( q_i < \bar{q}^R < \bar{q}^r, i = 1, 2 \) will also guarantee \( q_1 < \frac{\bar{q}^r}{(1 + \Sigma)^+} \). Also, consider
\[ q_2 < \bar{q}^r \left( \frac{Q^T - q_1 \left( 1 + \frac{\Sigma}{\bar{q}^r} \right)}{(1 + \Sigma) Q^T - \kappa_1 \Sigma - q_1 (1 + \Sigma)} \right) \]  
(A122)
in the case where
\[ (1 + \Sigma) Q^T - \kappa_1 \Sigma - q_1 (1 + \Sigma) > 0. \]  
(A123)
First, suppose $-1 < \Sigma < 0$. Then, right-hand side of (A122) is a decreasing function of $q_1$, and the minimum of that expression on $q_1 \in [0, \bar{q}_R]$ is reached at $q_1 = \bar{q}_R$. This minimum is equal to

$$
\frac{Q^T - \bar{q}_R \left(1 + \frac{q_1}{\bar{q}} \Sigma\right)}{(1 + \Sigma) Q^T - \kappa_1 \Sigma - \bar{q}_R (1 + \Sigma)}.
$$
(A124)

Then, since for $\Sigma < 0$, (A124) is a decreasing function of $\kappa_1$, we have its smallest value for $\kappa_1 = 1$:

$$
\frac{Q^T - \bar{q}_R \left(1 + \frac{1}{\bar{q}} \Sigma\right)}{(1 + \Sigma) Q^T - \Sigma - \bar{q}_R (1 + \Sigma)}.
$$
(A125)

Given that $1 + \Sigma > 0$, and $Q^T > 1$, we have $(1 + \Sigma) Q^T - \Sigma > 1 > \bar{q}^\tau$, so that (A125) is an increasing function of $\bar{q}_R$. Taking the smallest possible value of $\bar{q}_R = 0$, we get a lower bound on (A125):

$$
\frac{Q^T}{(1 + \Sigma) Q^T - \Sigma}.
$$
(A126)

Since for $\Sigma < 0$ (A126) is an increasing function of $Q^T$, the smallest possible value of (A126) is obtained for $Q^T = 1$ and is equal to 1. Thus, the right-hand side of (A122) is greater than or equal to $\bar{q}^\tau$, and (A122) is satisfied for any $q_2 < \bar{q}_R$.

Now, suppose that $\Sigma \leq -1$. Then, we can re-express (A122) as

$$
q_2 < \bar{q}^\tau \left(\frac{Q^T - q_1 \left(1 - \frac{\kappa_1 |\Sigma|}{\bar{q}}\right)}{(1 - |\Sigma|) Q^T + \kappa_1 |\Sigma| - q_1 \left(1 - |\Sigma|\right)}\right).
$$
(A127)

As the right-hand side of (A127) is an increasing function of $Q^T$, its lowest value is achieved for $Q^T = 1$, and is given by

$$
\frac{1 - q_1 \left(1 - \frac{\kappa_1 |\Sigma|}{\bar{q}}\right)}{(1 - |\Sigma|) + \kappa_1 |\Sigma| - q_1 \left(1 - |\Sigma|\right)}.
$$
(A128)

The right-hand side of (A128) is a decreasing function of $\kappa_1$, and by setting $\kappa_1 = 1$, we get the lowest possible value

$$
\frac{1 - q_1 \left(1 - \frac{1}{\bar{q}} |\Sigma|\right)}{1 - q_1 \left(1 - |\Sigma|\right)}.
$$
(A129)

which is an increasing function of $q_1$, reaching its minimum, $\bar{q}^\tau$ at $q_1 = 0$. Thus, the right-hand side of (A122) is greater than or equal to $\bar{q}^\tau$.

Case 8: $\bar{q}^\tau > \bar{q}_R$, $q_1 < \bar{q}_R \leq q_2 < \bar{q}^\tau$.

In this case, we have $R_1, A_2, A_1 < 0$, and $R_2 \geq 0$. Then,

$$
\frac{R_2 + R_1}{1 + A_2} = \frac{R_1 - |R_1|}{1 - |A_1|},
$$
(A130)
\[
\begin{align*}
\frac{\bar{R} + \mathcal{R}_2}{1 + A_2} &= \frac{\bar{R} + |\mathcal{R}_2|}{1 - |A_2|}, \\
\frac{\bar{R} + \mathcal{R}_1 + \mathcal{R}_2}{1 + A_1 + A_2} &= \frac{\bar{R} - |\mathcal{R}_1| + |\mathcal{R}_2|}{1 - |A_1| - |A_2|},
\end{align*}
\]

where
\[
|\mathcal{R}_1| = \kappa_1 \left( 1 - \frac{\bar{q}_1}{Q^T - q_1} \right), \\
|\mathcal{R}_2| = \kappa_2 \left( \frac{\bar{q}_2 - 1}{Q^T - q_2} \right), \\
|A_i| = \kappa_i \left( 1 - \frac{q_i}{Q^T - q_1} \right), i = 1, 2.
\]

Note that the optimal value for \( Y_2 \) is 1, and the optimal value of \( Y_1 \) depends on the relative values of \( \frac{\bar{R} + |\mathcal{R}_2|}{1 - |A_2|} \) and \( \frac{\bar{R} - |\mathcal{R}_1| + |\mathcal{R}_2|}{1 - |A_1| - |A_2|} \). We have
\[
\frac{\bar{R} + |\mathcal{R}_2|}{1 - |A_2|} - \frac{\bar{R} - |\mathcal{R}_1| + |\mathcal{R}_2|}{1 - |A_1| - |A_2|} = \frac{|A_1| \left( \frac{|\mathcal{R}_1|}{|A_1|} - \frac{\bar{R} + |\mathcal{R}_2|}{1 - |A_2|} \right)}{1 - |A_1| - |A_2|} \leq 0.
\]

Thus, the optimal combination of \( Y_1 \) and \( Y_2 \) is \((1, 1)\), and the optimal RVI values \( \hat{r}_1 = \hat{r}_2 = T_h \). Note that the conditions in this case also satisfy the conditions in (27). \( \bar{q}^F > \bar{q}^R \) guarantees that \( \Sigma > 0 \), so \( q_i < \bar{q}^T \) will also guarantee \( q_i < \frac{\bar{q}^T}{(1 + \Sigma)^F} \), and, similarly to the analysis in Case 7, that
\[
q_2 < \bar{q}^T \frac{Q^T - q_1 \left( 1 + \frac{q_1}{\bar{q}} \Sigma \right)}{((1 + \Sigma) Q^T - \kappa_1 \Sigma - q_1 (1 + \Sigma))^T}.
\]

Case 9: \( \bar{q}^T > \bar{q}^R \), \( q_1 < \bar{q}^R < \bar{q}^T \leq q_2 \).

In this case, we have \( \mathcal{R}_1, A_1 < 0 \), and \( \mathcal{R}_2, A_2 \geq 0 \). Then,
\[
\begin{align*}
\frac{\bar{R} + \mathcal{R}_1}{1 + A_1} &= \frac{\bar{R} - |\mathcal{R}_1|}{1 - |A_1|}, \\
\frac{\bar{R} + \mathcal{R}_2}{1 + A_2} &= \frac{\bar{R} + |\mathcal{R}_2|}{1 + |A_2|}, \\
\frac{\bar{R} + \mathcal{R}_1 + \mathcal{R}_2}{1 + A_1 + A_2} &= \frac{\bar{R} - |\mathcal{R}_1| + |\mathcal{R}_2|}{1 - |A_1| + |A_2|},
\end{align*}
\]

where
\[
|\mathcal{R}_1| = \kappa_1 \left( 1 - \frac{q_1}{Q^T - q_1} \right),
\]
|\mathcal{R}_2| = \kappa_2 \left( \frac{\frac{q_2}{\hat{R}} - 1}{Q^T - q_2} \right), \quad (A142) \\
|\mathcal{A}_1| = \kappa_1 \left( \frac{1 - \frac{q_1}{\hat{R}}}{Q^T - q_1} \right), \quad (A143) \\
|\mathcal{A}_2| = \kappa_2 \left( \frac{\frac{q_2}{\hat{R}} - 1}{Q^T - q_2} \right). \quad (A144)

Note that, we have \( \tilde{R} \geq 1 > |\mathcal{R}_1|/|\mathcal{A}_1| \), but \( |\mathcal{R}_2|/|\mathcal{A}_2| > 1 \). Suppose that \( \tilde{R} \geq |\mathcal{R}_2|/|\mathcal{A}_2| \). Then,

\[
\tilde{R} - \frac{\tilde{R} - |\mathcal{R}_1|}{1 - |\mathcal{A}_1|} \leq 0, \\
\tilde{R} - \frac{\tilde{R} + |\mathcal{R}_2|}{1 + |\mathcal{A}_2|} \geq 0, \quad (A145) \quad (A146)
\]

\[
\frac{\tilde{R} - |\mathcal{R}_1|}{1 - |\mathcal{A}_1|} - \frac{\tilde{R} - |\mathcal{R}_1| + |\mathcal{R}_2|}{1 - |\mathcal{A}_1| + |\mathcal{A}_2|} = \frac{|\mathcal{A}_2| \left( \frac{\tilde{R} - |\mathcal{R}_1|}{1 - |\mathcal{A}_1|} - \frac{|\mathcal{R}_2|}{|\mathcal{A}_2|} \right)}{1 - |\mathcal{A}_1| + |\mathcal{A}_2|} \geq 0, \quad (A147)
\]

so that the optimal combination of \( Y_1 \) and \( Y_2 \) is \( (1, 0) \), corresponding to the optimal RVI values \( \hat{r}_1 = \hat{T}_h \), \( \hat{r}_2 = \hat{T}_1 \).

Suppose now that \( \tilde{R} < \frac{|\mathcal{R}_2|}{|\mathcal{A}_2|} \). Then,

\[
\tilde{R} - \frac{\tilde{R} - |\mathcal{R}_1|}{1 - |\mathcal{A}_1|} \leq 0, \quad (A148) \\
\tilde{R} - \frac{\tilde{R} + |\mathcal{R}_2|}{1 + |\mathcal{A}_2|} \leq 0, \quad (A149)
\]

\[
\frac{\tilde{R} + |\mathcal{R}_2|}{1 + |\mathcal{A}_2|} - \frac{\tilde{R} - |\mathcal{R}_1| + |\mathcal{R}_2|}{1 - |\mathcal{A}_1| + |\mathcal{A}_2|} = \frac{|\mathcal{A}_1| \left( \frac{|\mathcal{R}_1|}{|\mathcal{A}_1|} - \frac{\tilde{R} + |\mathcal{R}_2|}{1 + |\mathcal{A}_2|} \right)}{1 - |\mathcal{A}_1| + |\mathcal{A}_2|} \leq 0. \quad (A150)
\]

Calculating

\[
\frac{\tilde{R} - |\mathcal{R}_1|}{1 - |\mathcal{A}_1|} - \frac{\tilde{R} - |\mathcal{R}_1| + |\mathcal{R}_2|}{1 - |\mathcal{A}_1| + |\mathcal{A}_2|} = \frac{|\mathcal{A}_2| \left( \frac{\tilde{R} - |\mathcal{R}_1|}{1 - |\mathcal{A}_1|} - \frac{|\mathcal{R}_2|}{|\mathcal{A}_2|} \right)}{1 - |\mathcal{A}_1| + |\mathcal{A}_2|}, \quad (A151)
\]

and using (A57), we observe that the optimal combination of \( Y_1 \) and \( Y_2 \) is \( (1, 0) \) for \( \tilde{R} < \frac{|\mathcal{R}_2|}{|\mathcal{A}_2|} \leq \)
\( \tilde{R}^* = \frac{\tilde{R} - |R_1|}{1 - |A_1|} \) and \((1, 1)\) for \(1 \leq \tilde{R} \leq \tilde{R}^* < \frac{|R_2|}{|A_2|}\). Thus, the optimal RVI values are \(\hat{r}_1 = T_h\), \(\hat{r}_2 = T_l\) for \(\tilde{R} < \frac{|R_2|}{|A_2|} \leq \tilde{R}^*\) and \(\hat{r}_1 = \hat{r}_2 = T_h\) for \(1 \leq \tilde{R} \leq \tilde{R}^* < \frac{|R_2|}{|A_2|}\).

Note that \(\tilde{R} < \frac{|R_2|}{|A_2|}\) is equivalent to
\[
\frac{\frac{q_2^*}{q^*_R} - 1}{\frac{q_2^*}{q^*_R} - 1} > \tilde{R},
\]

or
\[
\tilde{R} - 1 > \frac{q_2^*}{q^*_R} \left( \tilde{R} - \frac{q^*_R}{q^*_R} \right),
\]

and \(\tilde{R}^* < \frac{|R_2|}{|A_2|}\) is equivalent to
\[
\tilde{R}^* - 1 > \frac{q_2^*}{q^*_R} \left( \tilde{R}^* - \frac{q^*_R}{q^*_R} \right).
\]

In a similar manner, \(\tilde{R} > \frac{|R_1|}{|A_1|}\) for \(q_1 < \bar{q} < q^*_R\) is equivalent to
\[
\tilde{R} - 1 > \frac{q_1}{q^*_R} \left( \tilde{R} - \frac{q^*_R}{q^*_R} \right).
\]

Given that \(\tilde{R} \leq \tilde{R}^*\), we have to consider three separate scenarios. Under the first scenario, we have \(1 < \frac{q^*_R}{q^*_R} < \tilde{R} \leq \tilde{R}^*\), and
\[
\tilde{R}^* - 1 = \frac{\tilde{R} - |R_1|}{1 - |A_1|} - 1 = \frac{\tilde{R} - 1 - |R_1| + |A_1|}{1 - |A_1|},
\]

and
\[
\tilde{R}^* - \frac{q^*_R}{q^*_R} = \frac{\tilde{R} - |R_1|}{1 - |A_1|} - \frac{q^*_R}{q^*_R} = \frac{\tilde{R} - \frac{q^*_R}{q^*_R} - |R_1| + \frac{q^*_R}{q^*_R} |A_1|}{1 - |A_1|},
\]

so that
\[
\frac{\tilde{R}^* - 1}{\tilde{R}^* - \frac{q^*_R}{q^*_R}} = \frac{\tilde{R} - 1 - |R_1| + |A_1|}{\tilde{R} - \frac{q^*_R}{q^*_R} - |R_1| + \frac{q^*_R}{q^*_R} |A_1|}
\]
\[
= \frac{\tilde{R} - 1 - \frac{q_1}{q^*_R} \left( \frac{\kappa_1}{Q^*_R - q_1} \right) \left( 1 - \frac{q^*_R}{q^*_R} \right)}{\tilde{R} - \frac{q^*_R}{q^*_R} \left( \frac{\kappa_1}{Q^*_R - q_1} \right) \left( 1 - \frac{q^*_R}{q^*_R} \right)} = \frac{Q^*_R - q_1 \left( 1 + \frac{\kappa_1}{q^*_R} \right)}{(1 + \Sigma) Q^*_R - \kappa_1 \Sigma - q_1 (1 + \Sigma)},
\]

with
\[
\Sigma = \left(1 - \frac{q^*_R}{q^*_R} \right) \left( \frac{\delta R^*_R}{(1 - \delta) R^*_R T_l} \right) < 0,
\]
for $\bar{q} > \bar{q}^R$. Thus, under this scenario ($\bar{R} > \frac{\bar{q}^T}{q^T}$), we have

$$q_2 < \bar{q}^T \left( \frac{Q^T - q_1 \left(1 + \frac{\kappa_1}{q^T} \Sigma \right)}{(1 + \Sigma) Q^T - \kappa_1 \Sigma - q_1 (1 + \Sigma)} \right), \tag{A160}$$

for (A154), and

$$q_1 < \bar{q}^T \frac{\bar{R} - 1}{\bar{R} - \frac{\bar{q}^T}{q^T}} = \frac{\bar{q}^T}{1 + \Sigma}, \tag{A161}$$

for (A153), with $-1 < \Sigma < 0$. (A161) is satisfied for any $q_1 < \bar{q}^R < \bar{q}^T$. Note that the right-hand side of (A160) is a decreasing function of $q_1$, and the minimum of that expression on $q_1 \in [0, \bar{q}^R]$ is reached at $q_1 = \bar{q}^R$. This minimum is equal to

$$\left(1 + \frac{\kappa_1}{q^T} \right) \left(1 - \frac{\bar{q}^R}{\bar{q}^T} \kappa_1 \Sigma - (1 + \Sigma) \bar{q}^R \right). \tag{A162}$$

Then, since for $\Sigma < 0$, (A162) is a decreasing function of $\kappa_1$, we have its smallest value for $\kappa_1 = 1$:

$$\left(1 + \frac{1}{q^T} \right) \left(1 - \frac{\bar{q}^R}{\bar{q}^T} \right) \left(1 + \Sigma \right). \tag{A163}$$

Given that $1 + \Sigma > 0$, and $Q^T > 1$, we have $(1 + \Sigma) Q^T - \Sigma > 1 > \bar{q}^T$, so that (A163) is an increasing function of $\bar{q}^R$. Taking the smallest possible value of $\bar{q}^R = 0$, we get a lower bound on (A163): \(\frac{Q^T}{(1 + \Sigma) Q^T - \Sigma}\). Since for $\Sigma < 0$ (A164) is an increasing function of $Q^T$, the smallest possible value of (A164) is obtained for $Q^T = 1$ and is equal to 1. Thus, the right-hand side of (A160) is greater than or equal to $\bar{q}^T$.

Under the second scenario, we have $1 \leq \bar{R} \leq \frac{\bar{q}^T}{q^T} \leq \bar{R}^*$, and (A153) and (A155) are satisfied for any $q_1$ and $q_2$. If $\frac{\bar{q}^T}{q^T} = \bar{R}^*$, then (A154) is also satisfied for any $q_2$. If $\frac{\bar{q}^T}{q^T} < \bar{R}^*$, then (A154) becomes

$$q_2 < \bar{q}^T \left( \frac{\bar{R}^* - 1}{\bar{R}^* - \frac{\bar{q}^T}{q^T}} \right), \tag{A165}$$

Using (A158), we have

$$\frac{\bar{R}^* - 1}{\bar{R}^* - \frac{\bar{q}^T}{q^T}} = \frac{\bar{R} - 1 - \frac{q_1}{q^T} \kappa_1 \left(Q^T - q_1 \right) \left(1 - \frac{\bar{q}^T}{q^T} \right)}{\bar{R} - \frac{\bar{q}^T}{q^T} - \kappa_1 \left(Q^T - q_1 \right) \left(1 - \frac{\bar{q}^T}{q^T} \right)}. \tag{A166}$$

If $\frac{\bar{q}^T}{q^T} = \bar{R}$, we get

$$\frac{\bar{R}^* - 1}{\bar{R}^* - \frac{\bar{q}^T}{q^T}} = \frac{\bar{q}^T - 1 - \frac{q_1}{q^T} \kappa_1 \left(\frac{Q^T}{Q^T - q_1} \right) \left(1 - \frac{\bar{q}^T}{q^T} \right)}{\bar{R}^* - \frac{q^T}{q^T} - \kappa_1 \left(\frac{Q^T}{Q^T - q_1} \right) \left(1 - \frac{\bar{q}^T}{q^T} \right)} = \frac{1 + \frac{q_1}{q^T} \kappa_1 \left(\frac{Q^T}{Q^T - q_1} \right)}{\left(\frac{Q^T}{Q^T - q_1} \right)}. \tag{A167}$$
Note that in this case, formally, $\Sigma = -1$. For $\bar{q}^T > R$, we have $\Sigma < -1$, but we can still use (A160):

$$q_2 < q^T \left( \frac{Q^T - q_1 \left( 1 + \frac{\kappa_1}{\bar{q}^T} \Sigma \right)}{(1 + \Sigma) Q^T - \kappa_1 \Sigma - q_1 (1 + \Sigma)} \right), \quad (A168)$$

which we can re-express as

$$q_2 < q^T \left( \frac{Q^T - q_1 \left( 1 - \frac{\kappa_1}{\bar{q}^T} \Sigma \right)}{(1 - |\Sigma|) Q^T + \kappa_1 |\Sigma| - q_1 (1 - |\Sigma|)} \right). \quad (A169)$$

As the right-hand side of (A169) is an increasing function of $Q^T$, its lowest value is achieved for $Q^T = 1$, and is given by

$$\frac{1 - q_1 \left( 1 - \frac{\kappa_1}{\bar{q}^T} |\Sigma| \right)}{(1 - |\Sigma|) + \kappa_1 |\Sigma| - q_1 (1 - |\Sigma|)}. \quad (A170)$$

The right-hand side of (A170) is a decreasing function of $\kappa_1$, and by setting $\kappa_1 = 1$, we get the lowest possible value

$$\frac{1 - q_1 \left( 1 - \frac{1}{\bar{q}^T} |\Sigma| \right)}{1 - q_1 (1 - |\Sigma|)}, \quad (A171)$$

which is an increasing function of $q_1$, reaching its minimum, $q^T$ at $q_1 = 0$. Thus, the right-hand side of (A168) is greater than or equal to $q^T$.

Finally, under the third scenario, $\bar{R} \leq \bar{R}^* < \frac{q^T}{\bar{q}^T}$, and (A153)-(A155) are satisfied for any $q_1$ and $q_2$. This is expressed using the max$(\cdot, 0) = (\cdot)^+$ operator in (27).

Case 10: $\bar{q}^T > \bar{q}^R$, $\bar{q}^R < q_1 < q_2 < \bar{q}^T$.

In this case, we have $\mathcal{R}_1, \mathcal{R}_2 > 0$, and $A_1, A_2 < 0$. Then,

$$\frac{\bar{R} + \mathcal{R}_1}{1 + A_1} = \frac{\bar{R} + |\mathcal{R}_1|}{1 - |A_1|}, \quad (A172)$$

$$\frac{\bar{R} + \mathcal{R}_2}{1 + A_2} = \frac{\bar{R} + |\mathcal{R}_2|}{1 - |A_2|}, \quad (A173)$$

$$\frac{\bar{R} + \mathcal{R}_1 + \mathcal{R}_2}{1 + A_1 + A_2} = \frac{\bar{R} + |\mathcal{R}_1| + |\mathcal{R}_2|}{1 - |A_1| - |A_2|}, \quad (A174)$$

and the optimal combination of $Y_1$ and $Y_2$ is $(1, 1)$, corresponding to the optimal RVI values

\[ \hat{r}_1 = T_h, \hat{r}_2 = T_h. \]

Case 11: $\bar{q}^T > \bar{q}^R$, $\bar{q}^R < q_1 < \bar{q}^T \leq q_2$.

In this case, we have $\mathcal{R}_1, \mathcal{R}_2, A_2 > 0, A_1 < 0$, and $|\mathcal{R}_2|/|A_2| > 1$. Then,

$$\frac{\bar{R} + \mathcal{R}_1}{1 + A_1} = \frac{\bar{R} + |\mathcal{R}_1|}{1 - |A_1|}, \quad (A175)$$
\[ \frac{\bar{R} + R_2}{1 + A_2} = \frac{\bar{R} + |R_2|}{1 + |A_2|}, \quad (A176) \]
\[ \frac{\bar{R} + R_1 + R_2}{1 + A_1 + A_2} = \frac{\bar{R} + |R_1| + |R_2|}{1 - |A_1| + |A_2|}, \quad (A177) \]

so that the optimal value for \( Y_1 \) is 1. The optimal value of \( Y_2 \) is determined by the relative values of \( \frac{\bar{R} + |R_1|}{1 - |A_1|} \) and \( \frac{\bar{R} + R_1 + |R_2|}{1 - |A_1| + |A_2|} \). Then, we have

\[ \frac{\bar{R} + |R_1|}{1 - |A_1|} - \frac{\bar{R} + |R_1| + |R_2|}{1 - |A_1| + |A_2|} = \frac{|A_2|}{1 - |A_1|} \left( \frac{\bar{R} + |R_1|}{1 - |A_1|} - \frac{|R_2|}{|A_2|} \right) \geq 0 \quad (A178) \]

if and only if

\[ \frac{|R_2|}{|A_2|} \leq \frac{\bar{R} + |R_1|}{1 - |A_1|}. \quad (A179) \]

Note that, for \( \tilde{q} < q_1 < \tilde{q} \leq q_2 \), we have \( \bar{R}^* \), defined in (A57), equal to

\[ \bar{R}^* = \frac{\bar{R} + R_1}{1 + A_1} = \frac{\bar{R} + |R_1|}{1 - |A_1|}. \quad (A180) \]

Thus we have the optimal combination of \( Y_1 \) and \( Y_2 \) to be \((1,0)\) (corresponding to the optimal RVI values \( \hat{r}_1 = T_h, \hat{r}_2 = T_i \)) for \( \frac{|R_2|}{|A_2|} \leq \bar{R}^* \), and \((1,1)\) (corresponding to the optimal RVI values \( \hat{r}_1 = \hat{r}_2 = T_h \)) for \( \frac{|R_2|}{|A_2|} > \bar{R}^* \). Note that in this case, \( \frac{|R_2|}{|A_2|} > \bar{R}^* \) is equivalent to

\[ \bar{R}^* - 1 > \frac{q_2}{\tilde{q}^*} \left( \frac{\bar{R}^* - 1}{\frac{\bar{R}^* - 1}{\tilde{q}^*}} \right) \], \quad (A181) \]

similar to (A154). (A181) is, in turn, equivalent to

\[ q_2 < \tilde{q}^* \left( \frac{\bar{R}^* - 1}{\frac{\bar{R}^* - 1}{\tilde{q}^*}} \right) \], \quad (A182) \]

which is the same as (27).

Case 12: \( \tilde{q}^* > \tilde{q}^R, \tilde{q}^R < \tilde{q}^* \leq q_1 < q_2 \).

In this case, we have \( R_1, R_2, A_1, A_2 > 0 \). Then,

\[ \frac{\bar{R} + R_1}{1 + A_1} = \frac{\bar{R} + |R_1|}{1 + |A_1|}, \quad (A183) \]
\[ \frac{\bar{R} + R_2}{1 + A_2} = \frac{\bar{R} + |R_2|}{1 + |A_2|}, \quad (A184) \]
\[ \frac{\bar{R} + R_1 + R_2}{1 + A_1 + A_2} = \frac{\bar{R} + |R_1| + |R_2|}{1 - |A_1| + |A_2|}, \quad (A185) \]

Note that for \( \tilde{q}^R < \tilde{q}^* \leq q_1 < q_2 \) we have \( \frac{|R_1|}{|A_1|} > \frac{|R_2|}{|A_2|} \geq 1. \)
Suppose that $\bar{R} \geq \left| \frac{\mathcal{R}_1}{\mathcal{A}_1} \right|$, which is equivalent to

$$\frac{\bar{q}_\tau - 1}{\bar{q}_\tau} - 1 \leq \bar{R},$$

(A186)

or

$$\frac{q_1}{\bar{q}_\tau} \left( \bar{R} - \frac{\bar{q}_\tau}{\bar{q}_\tau} \right) > \bar{R} - 1,$$

(A187)

which, in turn, implies $\bar{R} - \frac{\bar{q}_\tau}{\bar{q}_\tau} > 0$ and

$$q_1 > \bar{q}_\tau \left( \frac{\bar{R} - 1}{\bar{R} - \frac{\bar{q}_\tau}{\bar{q}_\tau}} \right) = \frac{\bar{q}_\tau}{1 + \Sigma},$$

(A188)

with $1 + \Sigma > 0$.

Then,

$$\bar{R} \geq \frac{\bar{R} + |\mathcal{R}_1|}{1 + |\mathcal{A}_1|},$$

(A189)

$$\bar{R} > \frac{\bar{R} + |\mathcal{R}_2|}{1 + |\mathcal{A}_2|},$$

(A190)

$$\bar{R} > \frac{\bar{R} + |\mathcal{R}_1| + |\mathcal{R}_2|}{1 + |\mathcal{A}_1| + |\mathcal{A}_2|},$$

(A191)

so that the optimal combination of $Y_1$ and $Y_2$ is $(0,0)$, corresponding to the optimal RVI values $\hat{r}_1 = \hat{r}_2 = T_1$.

Now, suppose that $\left| \frac{\mathcal{R}_2}{\mathcal{A}_2} \right| \leq \bar{R} < \left| \frac{\mathcal{R}_1}{\mathcal{A}_1} \right|$. Similar to (A187), this implies

$$q_1 > \frac{\bar{q}_\tau}{1 + \Sigma},$$

(A192)

with $1 + \Sigma > 0$, and

$$q_1 \leq \frac{\bar{q}_\tau}{1 + \Sigma}.$$

(A193)

Then,

$$\bar{R} < \frac{\bar{R} + |\mathcal{R}_1|}{1 + |\mathcal{A}_1|},$$

(A194)

$$\bar{R} \geq \frac{\bar{R} + |\mathcal{R}_2|}{1 + |\mathcal{A}_2|}.$$

(A195)
and
\[
\frac{\bar{R} + |R_1| + |R_2|}{1 + |A_1| + |A_2|} - \frac{\bar{R}_1 + |R_1|}{1 + |A_1|} \leq \frac{|A_2| \left( \frac{|R_2|}{A_2} - \frac{\bar{R}_2 + |R_1|}{1 + |A_1|} \right)}{1 + |A_1| + |A_2|} < 0, \quad (A197)
\]
so that the optimal combination of $Y_1$ and $Y_2$ is $(1, 0)$, corresponding to the optimal RVI values $\hat{r}_1 = T_h, \hat{r}_2 = T_l$.

Finally, suppose that $1 \leq \bar{R} < \frac{|R_2|}{A_2}$, which implies
\[
q_1 \leq \frac{\bar{q}}{(1 + \Sigma)^\tau}, \quad (A198)
\]
\[
q_2 \leq \frac{\bar{q}}{(1 + \Sigma)^\tau}. \quad (A199)
\]

Then,
\[
\bar{R} < \frac{\bar{R} + |R_1|}{1 + |A_1|}, \quad (A200)
\]
\[
\bar{R} < \frac{\bar{R} + |R_2|}{1 + |A_2|}. \quad (A201)
\]

Further,
\[
\frac{\bar{R} + |R_1| + |R_2|}{1 + |A_1| + |A_2|} - \frac{\bar{R} + |R_2|}{1 + |A_2|} \geq \frac{|A_1| \left( \frac{|R_1|}{A_1} - \frac{\bar{R} + |R_2|}{1 + |A_2|} \right)}{1 + |A_1| + |A_2|} \geq \frac{|A_1| \left( \frac{|R_2|}{A_2} - \bar{R} \right)}{1 + |A_1| + |A_2|} > 0, \quad (A202)
\]
and
\[
\frac{\bar{R} + |R_1| + |R_2|}{1 + |A_1| + |A_2|} - \frac{\bar{R} + |R_1|}{1 + |A_1|} = \frac{|A_2| \left( \frac{|R_2|}{A_2} - \frac{\bar{R} + |R_1|}{1 + |A_1|} \right)}{1 + |A_1| + |A_2|}. \quad (A203)
\]

This last expression is non-negative if and only if $\frac{|R_2|}{A_2} \geq \bar{R}^*$. Thus, the optimal combination of $Y_1$ and $Y_2$ is $(1, 1)$, and the optimal RVI values are $\hat{r}_1 = \hat{r}_2 = T_h$ for $\frac{|R_2|}{A_2} > \bar{R}^*$, and $(1, 0)$, and the
optimal RVI values are \( \hat{r}_1 = T_h, \hat{r}_2 = T_l \) for \( \frac{r_{21}}{A_{21}} \leq \bar{R}^* \). Note that in this case, \( \frac{r_{22}}{A_{22}} > \bar{R}^* \) is equivalent to

\[
\bar{R}^* - 1 > \frac{q_2}{\bar{q}} \left( \bar{R}^* - \frac{\bar{q}}{\bar{q}^\tau} \right),
\]

(A204)
similar to (A181). (A204) is, in turn, equivalent to

\[
q_2 < \bar{q}^\tau \left( \frac{\bar{R}^* - 1}{(\bar{R}^* - \frac{\bar{q}^\tau}{\bar{q}^\tau})^+} \right),
\]

(A205)
which is the same as (27).

\[\square\]

Proof of Corollary 1

In the setting with \( q^R = \bar{q}^\tau \), we have

\[
\frac{R_i}{A_i} = 1, i = 1, 2.
\]

(A206)

Note that \( \bar{R} = 1 + \frac{(1-\delta)R^T}{\delta \bar{q}^R} > 1 = \frac{r_{11}}{A_{11}}, i = 1, 2 \). Then, as it follows from (26) and (27), \( \hat{r}_1 = T_h \) whenever \( q_1 \leq \bar{q}^\tau \), and \( \hat{r}_1 = T_l \) otherwise, and \( \hat{r}_2 = T_h \) whenever \( q_2 \leq \bar{q}^\tau \), and \( \hat{r}_2 = T_l \) otherwise.

\[\square\]

Proof of Proposition 3

Under the proportional compensation, \( \Sigma = 0 \), and, as shown in Proposition 1, the setting where different RVIs can be applied to different patient groups and the setting where the same RVI is used result in different optimal choices, if

\[
q_1 \leq \bar{q}^\tau,
\]

(A207)
and

\[
q_2 > \bar{q}^\tau.
\]

(A208)

In particular, under (A207) and (A208), if the RVI value can be set individually for each patient groups, the optimal RVI for group 1 is \( \hat{r}_1 = T_h \), while the optimal value RVI value for group 2 is \( \hat{r}_2 = T_l \). On the other hand, the optimal RVI value for the setting where a single RVI is applied to both groups depends on the value of \( \kappa_1 \), resulting in two cases.

Case 1: \( \kappa_1 > \hat{\kappa}_1 \).
In the “uniform” RVI case, the optimal RVI value to apply to both patient groups is \( \hat{r} = T_h \), so that the physician’s revenue is given by

\[
R_s = \frac{(1 - \delta) R^d + \delta \left( \kappa_1 \left( \frac{(1-q_1)R^r + q_1 R^u}{(1-q_1)T_h + q_1 T_l} \right) + \kappa_2 \left( \frac{(1-q_2)R^r + q_2 R^u}{(1-q_2)T_h + q_2 T_l} \right) \right)}{\frac{1}{\tau^r} \left( \kappa_1 \left( \frac{(1-q_1)+q_1 \left( \frac{R^u}{R^r} \right)}{(1-q_1)T_h + q_1 T_l} \right) + \kappa_2 \left( \frac{(1-q_2)+q_2 \left( \frac{R^u}{R^r} \right)}{(1-q_2)T_h + q_2 T_l} \right) \right)}
\]

\( \frac{\delta R^r}{\tau^r} \left( 1 + \frac{(1 - \delta) R^d T_l}{\delta R^r} \right) \left( \frac{1}{\kappa_1 \left( \frac{(1-q_1)+q_1 \left( \frac{R^u}{R^r} \right)}{(1-q_1)T_h + q_1 T_l} \right) + \kappa_2 \left( \frac{(1-q_2)+q_2 \left( \frac{R^u}{R^r} \right)}{(1-q_2)T_h + q_2 T_l} \right) \right)
\]

\[
= \frac{\delta R^r}{\tau^r} \left( 1 + \frac{(1 - \delta) R^d T_l}{\delta R^r} \right) \left( \frac{1}{\kappa_1 \left( \frac{1+q_1 \left( \frac{1}{q_1} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right)}{1+q_1 \left( \frac{1}{q_1} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right)} \right) + \kappa_2 \left( \frac{1+q_2 \left( \frac{1}{q_2} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right)}{1+q_2 \left( \frac{1}{q_2} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right)} \right) \right)
\]

where we have used \( \frac{\tau^u}{\tau^r} = \frac{\hat{R}^u}{R^r} \) and

\[
\frac{\tau^u}{\tau^r} - 1 = \left( \frac{T_h}{T_l} - 1 \right) \left( \frac{1}{q^r} - 1 \right).
\]

Note that for \( q_1 \leq q^r < q_2 \) we have

\[
\frac{1 + q_1 \left( \frac{1}{q_1} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right)}{1 + q_1 \left( \frac{1}{q_1} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right)} \leq 1 < \frac{1 + q_2 \left( \frac{1}{q_2} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right)}{1 + q_2 \left( \frac{1}{q_2} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right)},
\]

In the setting where \( \hat{r}_1 = T_h \) and \( \hat{r}_2 = T_l \), the physician’s revenue is

\[
R_d = \frac{\delta R^r}{\tau^r} \left( 1 + \frac{(1 - \delta) R^d T_l}{\delta R^r} \right) \left( \frac{1}{1 + \kappa_1 \left( \frac{1+q_1 \left( \frac{1}{q_1} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right)}{1+q_1 \left( \frac{1}{q_1} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right)} - 1 \right)} \right).
\]

Therefore, the ratio of the two revenue values is
where $1 - \frac{R_s}{R_d}$ provides the expression in (33).

We would like to show that this ratio is an increasing function of $\kappa_1$ for $\kappa_1 \geq \hat{\kappa}_1$. Note that $R_s \leq R_d$, and

$$\frac{\partial R_s}{\partial \kappa_1} = \frac{\partial R_s}{\partial \kappa_1} \frac{R_d - \partial R_d}{R_d^2}$$ (A214)

will be positive as long as

$$\frac{\partial R_s}{\partial \kappa_1} > \frac{\partial R_d}{\partial \kappa_1}. \quad (A215)$$

Denoting

$$B(q) = \frac{1 + q \left( \frac{1}{q} - 1 \right) \left( \frac{T_l}{T_l} - 1 \right)}{1 + q \left( \frac{1}{q} - 1 \right) \left( \frac{T_l}{T_l} - 1 \right)}$$ (A216)

we get

$$\frac{\partial R_s}{\partial \kappa_1} = \left( \frac{1 - \delta}{\delta R_c} \right) \left( \frac{B(q_2) - B(q_1)}{(B(q_2) + \kappa_1 (B(q_1) - B(q_2)))^2} \right), \quad (A217)$$

$$\frac{\partial R_d}{\partial \kappa_1} = \left( \frac{1 - \delta}{\delta R_c} \right) \left( \frac{1 - B(q_1)}{(1 + \kappa_1 (B(q_1) - 1))^2} \right), \quad (A218)$$

where $B(q_2) > 1 \geq B(q_1)$. We observe that (A215) holds if and only if

$$\left( \frac{B(q_2) - B(q_1)}{(B(q_2) + \kappa_1 (B(q_1) - B(q_2)))^2} \right) > \left( \frac{1 - B(q_1)}{(1 + \kappa_1 (B(q_1) - 1))^2} \right), \quad (A219)$$

or

$$\frac{B(q_2) - \kappa_1 (B(q_2) - B(q_1))}{\sqrt{B(q_2) - B(q_1)}} < \frac{1 - \kappa_1 (1 - B(q_1))}{\sqrt{1 - B(q_1)}}. \quad (A220)$$

Note that (A220) can be expressed as

$$\kappa_1 > \frac{\frac{B(q_1)}{\sqrt{B(q_2) - B(q_1)}} - \frac{1}{\sqrt{1 - B(q_1)}}}{\sqrt{B(q_2) - B(q_1)} - \sqrt{1 - B(q_1)}}. \quad (A221)$$
Note that \( \hat{\kappa}_1 \) satisfies
\[
B(q_2) + \hat{\kappa}_1 (B(q_1) - B(q_2)) = 1,
\] (A222)
so that for any \( \kappa_1 > \hat{\kappa}_1 \), we have
\[
B(q_2) + \kappa_1 (B(q_1) - B(q_2)) < 1,
\] (A223)
or
\[
\kappa_1 > \frac{B(q_2) - 1}{B(q_2) - B(q_1)},
\] (A224)
Thus, for
\[
\frac{B(q_2) - 1}{B(q_2) - B(q_1)} \geq \frac{\frac{B(q_2)}{\sqrt{B(q_2)-B(q_1)}} - \frac{1}{\sqrt{1-B(q_1)}}}{\sqrt{B(q_2)-B(q_1)} - \sqrt{1-B(q_1)}} = \frac{B(q_2) - 1 + 1 - \sqrt{\frac{B(q_2)-B(q_1)}{1-B(q_1)}}}{B(q_2) - B(q_1) - \sqrt{B(q_2)-B(q_1)}\sqrt{1-B(q_1)}},
\] (A225)
the ratio of the two revenue values is an increasing function of \( \kappa_1 \). Defining
\[
A = B(q_2) - 1,
\] (A226)
\[
C = B(q_2) - B(q_1),
\] (A227)
\[
X = \sqrt{\frac{B(q_2)-B(q_1)}{1-B(q_1)}} - 1,
\] (A228)
\[
Y = \sqrt{(B(q_2)-B(q_1))(1-B(q_1))},
\] (A229)
we can re-express (A225) as
\[
\frac{A}{C} \geq \frac{A - X}{C - Y}
\] (A230)
that holds if and only if
\[
\frac{X}{Y} \geq \frac{A}{C},
\] (A231)
or
\[
\frac{B(q_2) - 1}{B(q_2) - B(q_1)} \leq \frac{\frac{B(q_2)-B(q_1)}{1-B(q_1)} - 1}{\sqrt{(B(q_2)-B(q_1))(1-B(q_1))}}.
\] (A232)
Using
\[
D = 1 - B(q_1),
\] (A233)
we have for (A232)

\[
\frac{A}{A+D} \leq \frac{\sqrt{\frac{A+D}{D}} - 1}{\sqrt{(A+D)(D)}},
\]

(A234)

or

\[
\frac{AD}{A+D} \leq 1 - \sqrt{\frac{D}{A+D}}.
\]

(A235)

Further, (A235) is equivalent to

\[
\frac{AD}{A+D} + \sqrt{\frac{D}{A+D}} \leq 1.
\]

(A236)

The left-hand side of (A236) is an increasing function of \(D\). Given that \(D = 1 - B(q_1)\), the maximum value of \(D\) is realized for the minimum value of \(B(q_1)\). Note that

\[
B(q_1) = \frac{1 + q_1 \left(\frac{1}{q_1} - 1\right) \left(\frac{T_h}{T_l} - 1\right)}{1 + (1 - q_1) \left(\frac{T_h}{T_l} - 1\right)},
\]

(A237)

is an increasing function of \(q_1\), reaching minimum at \(q_1 = 0\). The value of this minimum is \(\frac{T_h}{T_l}\), resulting in the maximum value of \(D\) to be \(D_m = 1 - \frac{T_h}{T_l}\). Then, if (A236) were to hold for any \(D \in [0, 1 - \frac{T_h}{T_l}]\), we will have

\[
\frac{AD_m}{A+D_m} + \sqrt{\frac{D_m}{A+D_m}} = D_m - D_m \left(\sqrt{\frac{D_m}{A+D_m}}\right)^2 + \sqrt{\frac{D_m}{A+D_m}} \leq 1.
\]

(A238)

Given that, for \(q_2 \in [\bar{q}, 1]\), the value of \(A = B(q_2) - 1\) is between 0 and

\[
A_m = \left(\frac{1}{q^2} - 1\right) \left(\frac{T_h}{T_l} - 1\right),
\]

(A239)

the maximum of

\[D_m - D_m t^2 + t\]

(A240)

with

\[
t = \sqrt{\frac{D_m}{A+D_m}} \leq 1,
\]

(A241)

is reached either at \(t = 1\) or at \(t = \frac{1}{2D_m}\), whichever is smaller. Note that the value of (A240) for \(t = 1\) is 1, so, in order for \(D_m - D_m t^2 + t \leq 1\) to hold we must require that

\[
\frac{1}{2D_m} \geq 1,
\]

(A242)

which is the same as \(T_l \geq \frac{1}{2} T_h\).
Case 2: $\kappa_1 \leq \hat{\kappa}_1$.

In the “uniform” RVI case, $\bar{r} = T_i$, and the physician’s revenue is given by

$$R_s = \frac{(1 - \delta)R^d + \delta R^c}{T_i} = \frac{\delta R^r}{T^r} \left( 1 + \left( \frac{(1 - \delta)R^d T_i}{\delta R^r} \right) \right).$$

(A243)

In the heterogeneous RVI case, $\bar{r}_1 = T_h$, $\bar{r}_2 = T_i$, and the physician’s revenue is given by (A212). The ratio of these two revenue values of revenue is

$$\frac{R_s}{R_d} = \frac{1 + \left( \frac{(1 - \delta)R^d T_i}{\delta R^r} \right)}{1 + \left( \frac{(1 - \delta)R^d T_i}{\delta R^r} \right)} \left( \frac{1}{1 + q (1 - \theta) \left( \frac{\delta}{\delta - 1} \right) (1 - \eta)} \right) \left( \frac{1}{1 + q (1 - \theta) \left( \frac{\delta}{\delta - 1} \right) (1 - \eta)} \right),$$

which, for $q_1 < q^*$ is a decreasing function of $\kappa_1$. Also, $1 - \frac{R_s}{R_d}$ provides the expression in (32).

As the results of both Case 1 and Case 2 imply, the ratio of the two revenue values is bound from below by the value achieved at $\kappa_1 = \hat{\kappa}_1$. Then the relative performance gap of the “uniform” RVI approach when applied to the two-patient-group setting cannot exceed

$$\epsilon^S = 1 - \frac{1 + \left( \frac{(1 - \delta)R^d T_i}{\delta R^r} \right)}{1 + \left( \frac{(1 - \delta)R^d T_i}{\delta R^r} \right)} \left( \frac{1}{1 + q (1 - \theta) \left( \frac{\delta}{\delta - 1} \right) (1 - \eta)} \right) \left( \frac{1}{1 + q (1 - \theta) \left( \frac{\delta}{\delta - 1} \right) (1 - \eta)} \right),$$

(A245)

Proof of Proposition 4

There are four possible solutions for $(\bar{\theta}_i, \bar{r}_i^+)$: $(0, T_i)$, $(0, T_h)$, $(1, T_i)$, and $(1, T_h)$. We derive the necessary and sufficient conditions for each of these four options to be the optimal solution. Based (7) and (43), the long-run average cost values for the patient at each of these solutions are

$$D(0, T_i) = \frac{1}{T_i},$$

(A246)

$$D(0, T_h) = \frac{1 + q \eta}{q_i T_i + (1 - q_i) T_h},$$

(A247)

$$D(1, T_i) = R^d_c + \frac{1 - \left( 1 - \frac{R^c}{C^c} \right) \alpha_c^r}{T_i},$$

(A248)
In what follows we derive the optimality conditions for each of the aforementioned solutions. For each solution, we derive conditions under which the patient’s long-run average cost is smaller under that solution compared to the other three.

Case 1: \((\bar{\theta}_i, \bar{r}_e^i) = (0, T_i)\)

For \(D(0, T_i) < D(0, T_h)\) to hold, based on Lemma 1, we need

\[
q_i > \frac{1}{1 + \frac{\eta r_e Th}{T_l - 1}}.
\]

Next, we derive conditions for \(D(0, T_l) < D(1, T_l)\) and \(D(0, T_h) < D(1, T_h)\) to hold. We first compare the values of \(D(1, T_l)\) and \(D(1, T_h)\). This problem is identical to seeking the optimal RVI value that minimizes (43). By Comparing \(D_e^i(T_l)\) and \(D_e^i(T_h)\), we see the following:

(a) \(D(1, T_l) < D(1, T_h)\) if

\[
q_i > \frac{1}{1 + \frac{\eta r_e Th}{T_l - 1}},
\]

(b) \(D(1, T_l) \geq D(1, T_h)\) if

\[
q_i \leq \frac{1}{1 + \frac{\eta r_e Th}{T_l - 1}},
\]

where \(\eta r_e\) is given by (47). Note that \(\eta r_e > \eta\) for \(\alpha r_e > 0\). Therefore, (A250) guarantees (A251), and we only need to find conditions under which \(D(0, T_l) < D(1, T_l)\):

\[
\frac{1}{T_l} < R_e^i + \frac{1 - \left(1 - \frac{R_e^i}{\alpha e^i}\right)}{T_l},
\]

which is simplified to

\[
R_e^i > \frac{\left(1 - \frac{R_e^i}{\alpha e^i}\right)}{T_l}.
\]

In summary, for Case 1 we need (A250) and (A254).

Case 2: \((\bar{\theta}_i, \bar{r}_e^i) = (0, T_h)\)

For \(D(0, T_h) \leq D(0, T_i)\) to hold, based on Lemma 1, we need

\[
q_i \leq \frac{1}{1 + \frac{\eta}{T_l - 1}}.
\]

For \(D(0, T_h) < D(1, T_i)\) and \(D(0, T_h) < D(1, T_h)\), there are two cases to consider as both (A251) and (A252) may hold.
If (A251) holds, we have
\[ \frac{1}{1 + \frac{q_i \eta}{\bar{r}_i}} < q_i \leq \frac{1}{1 + \frac{\eta}{\bar{r}_i}}. \]  
(A256)

Then, we need to find conditions for \( D(0, T_h) < D(1, T_i) \):
\[ \frac{1 + q_i \eta}{q_i T_i + (1 - q_i) T_h} < R^d_e + \frac{1 - \left(1 - \frac{R^r_i}{\bar{r}_i}\right) \alpha^r_e}{T_i}, \]  
(A257)

which is simplified to
\[ R^d_e > \frac{1 + q_i \eta}{q_i T_i + (1 - q_i) T_h} - \frac{1 - \left(1 - \frac{R^r_i}{\bar{r}_i}\right) \alpha^r_e}{T_i}. \]  
(A258)

If (A252) holds, then we need to find conditions for \( D(0, T_h) < D(1, T_h) \):
\[ \frac{1 + q_i \eta}{q_i T_i + (1 - q_i) T_h} < R^d_e + \frac{(1 - q_i) \left(1 - \left(1 - \frac{R^r_i}{\bar{r}_i}\right) \alpha^r_e + q_i (1 + \eta) \right)}{q_i T_i + (1 - q_i) T_h}, \]  
(A259)

which is simplified to
\[ R^d_e > \frac{(1 - q_i) \left(1 - \frac{R^r_i}{\bar{r}_i}\right) \alpha^r_e}{q_i T_i + (1 - q_i) T_h}. \]  
(A260)

In summary, for Case 2 we need either of the following two to hold: both (A256) and (A258), or both (A252) and (A260).

Case 3: \((\bar{\theta}_i, \bar{r}_i^r) = (1, T_i)\)

For \( D(1, T_i) < D(1, T_h) \) to hold, we need (A251) to hold.

For \( D(1, T_i) \leq D(0, T_i) \) and \( D(1, T_i) \leq D(0, T_h) \) to hold, we need to consider two cases as both (A250) and (A255) may hold.

If (A250) holds, then we need to find conditions for \( D(1, T_i) \leq D(0, T_i) \) which is guaranteed by (similar to (A253)-(A254))
\[ R^d_e \leq \frac{\left(1 - \frac{R^r_i}{\bar{r}_i}\right) \alpha^r_e}{T_i}. \]  
(A261)

If (A255) holds, combined with (A251), then (A256) holds. Therefore, we need to find conditions for \( D(1, T_i) \leq D(0, T_h) \). Similar to (A257)-(A258), we have \( D(1, T_i) \leq D(0, T_h) \) if
\[ R^d_e \leq \frac{1 + q_i \eta}{q_i T_i + (1 - q_i) T_h} - \frac{1 - \left(1 - \frac{R^r_i}{\bar{r}_i}\right) \alpha^r_e}{T_i}. \]  
(A262)

In summary, for Case 3 we need either of the following two to hold: both (A250) and (A261), or both (A256) and (A262).

Case 4: \((\bar{\theta}_i, \bar{r}_i^r) = (1, T_h)\)
For $D(1,T_h) \leq D(1,T_l)$, we need (A252) to hold. Also, if (A252) holds, we have $D(0,T_h) < D(0,T_l)$ because (A252) guarantees (A255). Therefore, we only need to provide conditions for $D(1,T_h) \leq D(0,T_h)$ which is guaranteed by (similar to (A259)-(A260))

$$R_e^d \leq \frac{(1-q_i) \left( 1 - \frac{R_e^c}{c_o} \right) \alpha_e^r}{q_i T_l + (1-q_i) T_h}.$$  \hspace{1cm} (A263)

In summary, for Case 4 we need (A252) and (A263).

\[ \square \]

**Proof of Proposition 5**

Suppose that we are in a setting where patients choose to adopt e-visits. Note that, for $\alpha_e^r > 0$, we have $q_e^+(c,\Delta,R_e^r,\alpha_e^r) < q^+(c,\Delta)$ and $q_e^-(c,\Delta,R_e^r,\alpha_e^r) < q^-(c,\Delta)$.

a) Consider a patient group $i$ that is flexible in the absence of e-visits, so that $q^-(c,\Delta) \leq q_i \leq q^+(c,\Delta)$. In order for a flexible group $i$ to remain flexible upon the introduction of e-visits, it is necessary to have $q_i \leq q_e^+(c,\Delta,R_e^r,\alpha_e^r)$ which is equivalent to $\alpha_e^r \leq \overline{\alpha_e^r}(q_i)$.

b) A flexible patient group $i$ becomes inflexible upon the introduction of e-visits if and only if $q_e^+(c,\Delta,R_e^r,\alpha_e^r) < q_i$:

$$\frac{1}{1 + \frac{c(1-\Delta) \alpha_e^r}{(1-(1-R_e^r/c_o)\alpha_e^r)(T_l/T_h-1)}} < q_i,$$ \hspace{1cm} (A264)

which is equivalent to $\alpha_e^r > \overline{\alpha_e^r}(q_i)$.

c) Given $q_e^+(c,\Delta,R_e^r,\alpha_e^r) < q^+(c,\Delta)$ and $q_e^-(c,\Delta,R_e^r,\alpha_e^r) < q^-(c,\Delta)$, the only possible scenario under which an inflexible patient group becomes flexible is when $q_i < q^-(c,\Delta)$ and $q_e^-(c,\Delta,R_e^r,\alpha_e^r) \leq q_i \leq q_e^+(c,\Delta,R_e^r,\alpha_e^r)$. Note that

$$q_i \leq q_e^+(c,\Delta,R_e^r,\alpha_e^r),$$ \hspace{1cm} (A265)

is equivalent to

$$\left( 1 - \frac{R_e^r}{c_o} \right) \alpha_e^r \leq \frac{\left( \frac{1}{q_i} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right) - c(1-\Delta)}{\left( \frac{1}{q_i} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right) + 1},$$ \hspace{1cm} (A266)

and

$$q_i \geq q_e^-(c,\Delta,R_e^r,\alpha_e^r),$$ \hspace{1cm} (A267)

is equivalent to

$$\left( 1 - \frac{R_e^r}{c_o} \right) \alpha_e^r \geq \frac{\left( \frac{1}{q_i} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right) - c(1+\Delta)}{\left( \frac{1}{q_i} - 1 \right) \left( \frac{T_h}{T_l} - 1 \right) + 1}.$$ \hspace{1cm} (A268)

Solve both of the above inequalities results in $\alpha_e^r(q_i) \leq \alpha_e^r \leq \overline{\alpha_e^r}(q_i)$.

\[ \square \]
Proof of Proposition 6

Suppose that we are in a setting where patients choose to adopt e-visits.

a) The result follows from the proof of Proposition 2 with \( q^+ (c, \Delta), q^- (c, \Delta), q^e, q^R, R, \Sigma, i = 1, 2 \) replaced by \( q^e_1 (c, \Delta, R_e, \alpha^e_1), q^e_2 (c, \Delta, R_e, \alpha^e_1), q^e_0, q^R_e, R_e, \Sigma_e, i = 1, 2 \), respectively.

b) Note that \( \bar{\alpha}^e(q_2) < \alpha^e \) implies, according to the result of part b) of Proposition 5, that the patient group 2 is inflexible. In particular, \( q_2 > q^e_1 (c, \Delta, R_e, \alpha^e_1) \) and \( \bar{\rho}_e = T_e \). On the other hand, \( \alpha^e \leq \bar{\alpha}^e(q_1) \), the patient group 1 remains flexible, since \( q_1 < q^e_2 (c, \Delta, R_e, \alpha^e) \). The choice of the RVI value for the patient group 1 is dictated by the following version of (38)-(40):

\[
\max_{N, r_1} \left( N \left( (1 - \delta) \bar{R}^d_e + \delta \kappa_1 \left( \frac{\rho^e_i (r_1) \bar{R}^e_e + (1 - \rho^e_i (r_1)) R^u}{T_i (r_1)} \right) \right) + \delta \kappa_2 \left( \frac{\bar{R}^e_e}{T_i} \right) \right) \tag{A269}
\]

s.t. \( N \left( \kappa_1 \left( \frac{\rho^e_i (r_1) \bar{\tau}^e_e + (1 - \rho^e_i (r_1)) \tau^u_e}{T_i (r_1)} \right) + \kappa_2 \left( \frac{\bar{\tau}^e_e}{T_i} \right) \right) \leq A \), \tag{A270}

\( r_1 \in \{T_e, T_h\} \). \tag{A271}

Then, introducing

\[
R^e_i = \kappa_i \left( \frac{q_i - q^R_e}{q^R_e (Q^T - q_i)} \right), \tag{A272}
\]

\[
A^e_i = \kappa_i \left( \frac{q_i - q^e_i}{q^e_i (Q^T - q_i)} \right), \tag{A273}
\]

we can re-express (A269)-(A271) as

\[
\max_{Y_i} \left( \frac{\bar{R}^e_e + R^e_i Y_i}{1 + A^e_i Y_i} \right) \tag{A274}
\]

s.t. \( Y_i \in \{0, 1\} \), \tag{A275}

so that the best RVI value for the patient group 1 is determined by the relative values of \( \bar{R}^e_e \) and \( \frac{\bar{R}^e_e + R^e_i}{1 + A^e_i} \). Since \( 1 + A^e_i > 0 \),

\[
\bar{R}^e_e \leq \frac{\bar{R}^e_e + R^e_i}{1 + A^e_i} \iff \bar{R}^e A^e_i \leq R^e_e \left( \frac{q_i}{q^e_i} - 1 \right) \leq \frac{q_i}{q^e_i} - 1. \tag{A276}
\]

Suppose that \( \bar{q}^e_i \leq q^R_e \), so that \( \Sigma_e > 0 \), and consider three possible cases: \( q_1 \leq \bar{q}^e_i, \bar{q}^e_i < q_1 \leq \bar{q}^R_e \), and \( \bar{q}^R_e \leq q_1 \).

In the first case, (A276) is equivalent to

\[
q_1 \leq \bar{q}^e_i \left( \frac{1}{1 + \left( \frac{\bar{q}^e_i - q^R_e}{\bar{R}^e_e - 1} \right)} \right) = \bar{q}^e_i \left( \frac{1}{1 + \left( \frac{\delta R^e_e}{(1 - \delta) R^e_e T_i} \right) \left( \frac{q^e_i}{1 - \bar{q}^R_e} \right)} \right) = \bar{q}^e_i \left( \frac{1}{1 + \Sigma_e} \right). \tag{A277}
\]

Note that the expression on the right-hand side of (A277) is less or equal to \( \bar{q}^e_i \). Thus, the optimal value of \( r_1 \) is equal to \( T_h \) if and only if (A277) holds.
Now, consider the case of $\bar{q}_c^* \leq \bar{q}_e^R$ and $\bar{q}_e^c < q_1 \leq \bar{q}_e^R$. In this case, we have to compare $\bar{R}^e$ and $\frac{R^e + R_1^e}{1 + A_1^e}$, and, given that $R_1^e < 0$ and $A_1^e > 0$, we have $\bar{R}^e > \frac{R^e + R_1^e}{1 + A_1^e}$, and the optimal value of $r_1$ is equal to $T_1$.

Finally, for $\bar{q}_c^* \leq \bar{q}_e^R$ and $\bar{q}_c^R < q_1$, (A276) becomes

$$\bar{R}^e \left( \frac{q_1}{\bar{q}_c^*} - 1 \right) \leq \frac{q_1}{\bar{q}_e^R} - 1 \iff \bar{q}_c^* \left( 1 - \frac{q_1}{\bar{q}_e^R} \right) \geq 1 - \frac{q_1}{\bar{q}_c^*},$$

which does not hold for $\bar{q}_e^R \leq \bar{q}_c^* < q_1$. Thus, the optimal value of $r_1$ is equal to $T_1$.

Suppose now that $\bar{q}_c^* > \bar{q}_e^R$, so that $\Sigma_c < 0$, and consider three possible cases: $q_1 \leq \bar{q}_c^R$, $\bar{q}_e^c < q_1 \leq \bar{q}_e^R$, and $\bar{q}_e^c \leq q_1$.

In the first case, we have

$$\bar{R}^e \left( \frac{q_1}{\bar{q}_c^*} - 1 \right) \leq \frac{q_1}{\bar{q}_e^R} - 1 \iff \bar{R}^e \left( 1 - \frac{q_1}{\bar{q}_e^R} \right) \geq 1 - \frac{q_1}{\bar{q}_c^*},$$

which is the same as

$$\bar{R}^e - 1 \geq \frac{q_1}{\bar{q}_e^R} \left( \bar{R}^e - \frac{\bar{q}_c^R}{\bar{q}_e^R} \right).$$

Then, for $\bar{R}^e \leq \frac{\bar{q}_c^R}{\bar{q}_e^R}$, (A280) holds for any $q_1$. On the other hand, for $\bar{R}^e > \frac{\bar{q}_c^R}{\bar{q}_e^R}$, which is equivalent to

$$\left( \frac{1}{(1 - \delta)^R_{eT_1}} \right) \left( \frac{\bar{q}_c^R}{\bar{q}_e^R} - 1 \right) < 1,$$

(A280) holds if and only if

$$q_1 \leq \bar{q}_c^R \left( 1 - \frac{1}{\frac{\delta R^e}{(1 - \delta)^R_{eT_1}} \left( \frac{\bar{q}_e^R}{\bar{q}_e^R} - 1 \right)} \right).$$

Note, however, that

$$\bar{q}_c^R \left( \frac{1}{1 - \frac{\delta R^e}{(1 - \delta)^R_{eT_1}} \left( \frac{\bar{q}_e^R}{\bar{q}_e^R} - 1 \right)} \right) \bar{q}_e^R = \frac{\bar{q}_c^R}{\bar{q}_e^R}$$

$$= \bar{q}_c^R \left( \frac{\bar{q}_c^R}{\bar{q}_e^R} - 1 \right) \left( \frac{\delta R^e}{(1 - \delta)^R_{eT_1}} + 1 \right)$$

$$= \bar{q}_c^R \left( \frac{\bar{q}_e^R}{\bar{q}_e^R} - 1 \right) \left( \frac{\delta R^e}{(1 - \delta)^R_{eT_1}} \right) > 0,$$

so that (A282) holds for any $q_1 < \bar{q}_c^R$. Thus, (A280) holds for any $q_1 < \bar{q}_c^R$ and the optimal value of $r_1$ is equal to $T_h$. 

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Next, consider $\bar{q}_e^r > \bar{q}_e^R$ and $\bar{q}_e^R < q_1 \leq \bar{q}_e^c$. In this case, we have
\[
\bar{R}_e^c \left( \frac{q_1}{q_e^c} - 1 \right) \leq \frac{q_1}{q_e^R} - 1, \tag{A284}
\]
for any $q_1$, and the optimal value of $r_1$ is equal to $T_h$.

Finally, for $\bar{q}_e^r > \bar{q}_e^R$ and $\bar{q}_e^R < q_1$, (A276) is equivalent to
\[
\frac{q_1}{q_e^c} \left( \bar{R}_e - \frac{\bar{q}_e^r}{\bar{q}_e^R} \right) \leq \bar{R}_e - 1. \tag{A285}
\]
This conditions holds for any $q_1$ if $\bar{R}_e \leq \frac{\bar{q}_e^c}{\bar{q}_e^R}$. Note that $\bar{R}_e \leq \frac{\bar{q}_e^c}{\bar{q}_e^R}$ guarantees that $\Sigma_e \leq -1$.

On the other hand, if $\bar{R}_e > \frac{\bar{q}_e^c}{\bar{q}_e^R}$, then (A285) holds if and only if
\[
q_1 \leq \bar{q}_e^c \left( 1 + \left( \frac{1}{1 - \left( \frac{\delta R_e^c}{(1-\delta)R_e^R T_e} \right) \left( \frac{\bar{q}_e^c}{\bar{q}_e^R} - 1 \right) \right) \right) = \frac{\bar{q}_e^c}{1 + \Sigma_e}. \tag{A286}
\]
Note that the right-hand side of (A286) is greater than or equal to $\bar{q}_e^c$ because $\bar{R}_e > \frac{\bar{q}_e^c}{\bar{q}_e^R}$ guarantees that $\Sigma_e > -1$. We can combine the result for both cases ($\bar{R}_e \leq \frac{\bar{q}_e^c}{\bar{q}_e^R}$ and $\bar{R}_e > \frac{\bar{q}_e^c}{\bar{q}_e^R}$) by using the notation $x^+ = \max(x, 0)$ and requiring that
\[
q_1 \leq \frac{\bar{q}_e^c}{(1 + \Sigma_e)^+}, \tag{A287}
\]
as a condition for setting the optimal $r_1$ value to $T_h$.

We conclude by observing that (A287) is equivalent to (A277) when $\bar{q}_e^c \leq \bar{q}_e^R$.

c) Note that, as follows from the result in part b) of Proposition 5, if $\alpha_e^c > \bar{\alpha}_e^c (q_1)$, both patient groups become inflexible. In particular, we have $q_1 > q_1^c (c, \Delta, R_e^c, \alpha_e^c)$ and $q_2 > q_2^c (c, \Delta, R_e^c, \alpha_e^c)$. Then, both patient groups insist on the shortest possible revisit interval, and $\hat{r}_1 = \hat{r}_2 = T_i$.

\[\square\]

**Proof of Corollary 2**

In the “proportional” setting we have $\bar{q}_e^R = \bar{q}_e^c$, so that
\[
\frac{R_e^c}{A_i^c} = 1, i = 1, 2. \tag{A288}
\]
Then, $\bar{R}_e = 1 + \frac{(1-\delta)R_e^R T_e}{\delta R_e^c} > 1 = \frac{R_e^c}{A_i^c}$, $i = 1, 2$.

Then, if $\alpha_e^c \leq \bar{\alpha}_e^c (q_2)$, then, as (56) and (57) imply, $\hat{r}_1 = T_h$ whenever $q_1 \leq \bar{q}_e^c$, and $\hat{r}_2 = T_i$ otherwise, while $\hat{r}_2 = T_h$ whenever $q_2 \leq \bar{q}_e^c$, and $\hat{r}_2 = T_i$ otherwise. Also, if $\alpha_e^r (q_1) \geq \alpha_e^r (q_2)$ holds, then $\hat{r}_2 = T_i$ and, as (58) implies, $\hat{r}_1 = T_h$ if and only if $q_1 \leq \bar{q}_e^c$. Finally, if $\alpha_e^r > \bar{\alpha}_e^r (q_1)$, both $\hat{r}_1$ and $\hat{r}_2$ are set at $T_i$.

\[\square\]
Proof of Proposition 7

Note that in this case \( \bar{q}\tau > \bar{q}\tau^* \).

a) Using Propositions 2 and 6, we know that, before e-visits are introduced, \( \hat{r} = T_i \) if \( q > \bar{q}\tau \), and given that \( \bar{q}\tau > \bar{q}^* \), the RVIs stay at \( T_i \) for \( q > \bar{q}\tau \) upon the introduction of e-visits. Similarly, \( \hat{r} = T_h \) if \( q \leq \bar{q}\tau \), and, given that \( \bar{q}\tau > \bar{q}^* \), the RVIs stay at \( T_h \) for \( q \leq \bar{q}^* \) after e-visits are introduced. If \( \bar{q}\tau \geq q > \bar{q}^* \), however, the value of RVI changes from \( T_h \) to \( T_i \).

b) Note that from (39) we have

\[
\hat{N} = \frac{A}{\rho'(\tau^*) + (1-\rho'(\tau^*))\tau^u}.
\]

(A289)

Also, \( \bar{r}\tau < \tau^r \). Therefore, if \( T_i(r_i) \) does not change after e-visits are introduced, \( \hat{N} > \hat{N} \). That is, if RVI does not change upon the introduction of e-visits, panel size is guaranteed to increase. Therefore, panel size increases if \( q \leq \bar{q}^* \), or if \( q \geq \bar{q}^* \) because \( \bar{r}\tau = \hat{r}\tau \).

From part a), \( \bar{r}\tau < \hat{r}\tau \) if \( \bar{q}^* \leq q < \bar{q}\tau \), and we want to find the conditions that ensure \( \hat{N} \leq \hat{N} \):

\[
\hat{N} \leq \hat{N} \iff \frac{A}{T_i} \leq \frac{A}{(1-q)\tau^r + q\tau^u} \iff \frac{\bar{r}\tau}{T_i} \geq (1-q)\tau^r + q\tau^u \iff q \leq \bar{q}\tau.
\]

(A290)

Note that

\[
\bar{q}\tau \leq \bar{q}^* \leq \bar{q}^* \leq \bar{q}\tau,
\]

because

\[
\frac{(1-\bar{q}^*)\bar{r}\tau + \bar{q}^*\tau^u}{\bar{q}^* T_i + (1-\bar{q}^*) T_h} = \frac{\bar{r}\tau}{T_i} \implies \frac{(1-\bar{q}^*)\tau^r + \bar{q}^*\tau^u}{\bar{q}^* T_i + (1-\bar{q}^*) T_h} > \frac{\bar{r}\tau}{T_i}.
\]

(A292)

c) We want to establish necessary and sufficient conditions for \( \Pi_\delta(\hat{N}, \bar{r}\tau) \leq \Pi_\delta(\hat{N}, \hat{r}\tau) \).

If \( \hat{r} = \bar{r}\tau = T_i \), we need the following:

\[
\frac{(1-\bar{r}\tau)R^d + \delta \bar{r}\tau}{\bar{r}\tau} \leq \frac{(1-\bar{r}\tau)R^d + \delta \bar{r}\tau}{\bar{r}\tau} \iff \frac{\bar{r}\tau}{\bar{r}\tau} \leq \frac{\bar{r}\tau}{\bar{r}\tau} \iff \bar{r}\tau \geq \tau^r,
\]

(A293)

which contradicts \( \bar{r}\tau < \tau^r \).

If \( \hat{r} = \bar{r}\tau = T_h \), we need the following:

\[
\frac{(1-\bar{r}\tau)R^d + \delta qR^u + (1-q)\bar{r}\tau}{qT_i + (1-q)T_h} \leq \frac{(1-\bar{r}\tau)R^d + \delta qR^u + (1-q)\bar{r}\tau}{qT_i + (1-q)T_h} \iff \tau \geq \tau^r,
\]

(A294)

which contradicts \( \tau^r < \tau^r \).

If \( \hat{r} > \bar{r}\tau \), we need the following:

\[
\frac{(1-\bar{r}\tau)R^d + \delta \bar{r}\tau}{\bar{r}\tau} \leq \frac{(1-\bar{r}\tau)R^d + \delta 2qR^u + (1-q)\bar{r}\tau}{qT_i + (1-q)T_h} \iff \frac{\bar{r}\tau}{\bar{r}\tau} \geq \frac{(1-\bar{r}\tau)R^d + \delta qR^u + (1-q)\bar{r}\tau}{qT_i + (1-q)T_h} \iff q \leq \overline{\bar{r}\tau},
\]

(A295)

which contradicts the fact that \( \bar{r}\tau < \hat{r} \) if \( \frac{\bar{r}\tau}{T_i} \leq (1-q)\tau^r + q\tau^u \). Note that we showed \( \bar{q}\tau \leq \bar{q}^* \) in (A291).

□
Proof of Proposition 8

Suppose that we are in a setting where patients choose to adopt e-visits.

First, we show conditions for \( \frac{q^*}{(1+\Sigma_c)^+} > \bar{q}^* \). We know that \( q^* < \bar{q}^* \), so to have \( \frac{q^*}{(1+\Sigma_c)^+} > \bar{q}^* \), we need \( \Sigma_c < 0 \) which is guaranteed if \( \bar{q}^* \leq q_e^R \). Also, note that if \( \Sigma_c \leq -1 \), then \( \frac{q^*}{(1+\Sigma_c)^+} > \bar{q}^* \). Therefore, we focus on \( -1 < \Sigma_c < 0 \), and provide conditions for \( \frac{q^*}{(1+\Sigma_c)^+} > \bar{q}^* \):

\[
\frac{q^*}{1+\Sigma_c} > \bar{q}^* \iff \Sigma_c < \frac{q^*}{\bar{q}^*} - 1 \iff R_e^d \leq R_e^d < \bar{R}_e^d. \tag{A296}
\]

Therefore, if \( \frac{R_e^d}{R_e^d} < \bar{R}_e^d \), then \( \frac{q^*}{(1+\Sigma_c)^+} > \bar{q}^* \).

a) Using Propositions 2 and 6, we know that, prior to the introduction of e-visits, \( \hat{\imath} = T_1 \) if \( q > \frac{q^*}{(1+\Sigma_c)^+} \). Therefore, if \( \frac{q^*}{(1+\Sigma_c)^+} > \bar{q}^* \), the RVI values increase for \( q < \frac{q^*}{(1+\Sigma_c)^+} \). Also, when \( \frac{q^*}{(1+\Sigma_c)^+} \leq \bar{q}^* \), the RVI values decrease for \( \frac{q^*}{(1+\Sigma_c)^+} \leq q < \bar{q}^* \).

b) From part a), \( \hat{\imath} \geq \hat{\imath} \) if \( \frac{q^*}{(1+\Sigma_c)^+} \leq q < \bar{q}^* \). Under this condition, we want to find the additional conditions ensuring that \( \hat{N}^c \leq \hat{N} \). From (A290), we only need \( q \leq \bar{q}^a \). Note, however, that this interval has no overlap with \( \frac{q^*}{(1+\Sigma_c)^+} \leq q < \bar{q}^* \), based on (A291).

Also, \( \hat{\imath} \geq \hat{\imath} \) if \( \bar{q}^* < q \leq \frac{q^*}{(1+\Sigma_c)^+} \). Under this condition, we want to find the additional conditions ensuring that \( \hat{N}^c \leq \hat{N} \):

\[
\hat{N}^c \leq \hat{N} \iff \frac{A}{(1-q^*+q^+u)} \leq \frac{A}{q^*} \iff q \geq \bar{q}^a, \tag{A297}
\]

So, panel size decreases if \( \bar{q}^a < q \leq \frac{q^*}{(1+\Sigma_c)^+} \). Next, we need to ensure that this interval is not empty. First, note that

\[
\bar{q}^a \geq \bar{q}^*, \tag{A298}
\]

because

\[
\frac{(1-\bar{q}^*)\tau^r + \bar{q}^*\tau^u}{\bar{q}^*T_1 + (1-\bar{q}^*)T_h} = \frac{\tau^r}{T_1} \Rightarrow \frac{(1-\bar{q}^*)\bar{\imath}^c + \bar{q}^*\tau^u}{\bar{q}^*T_1 + (1-\bar{q}^*)T_h} < \frac{\tau^r}{T_1}. \tag{A299}
\]

Second, we need to have \( \bar{q}^a \leq \frac{q^*}{(1+\Sigma_c)^+} \). That is,

\[
\frac{q_e^c}{1+\Sigma_c} \geq \bar{q}^* \left( \frac{1 - \left(1 - Q^T\right) \alpha_e^c (1 - \frac{\bar{q}^*}{\bar{q}^c})}{1 - \left(1 - Q^T\right) \alpha_e^c (1 - \frac{\bar{q}^*}{\bar{q}^c})} \right), \tag{A300}
\]

which is equivalent to

\[
(1+\Sigma_c)^+ \leq \frac{1 - \left(1 - Q^T\right) \alpha_e^c (1 - \frac{\bar{q}^*}{\bar{q}^c})}{1 - \left(1 - Q^T\right) \alpha_e^c (1 - \frac{\bar{q}^*}{\bar{q}^c})}. \tag{A301}
\]

c) There are four cases to consider, \( \hat{\imath} = T_1, \hat{\imath} = T_h, \hat{\imath} > \hat{\imath} \), and \( \hat{\imath} < \hat{\imath} \). Under each of these cases, we look for conditions that guarantee \( \Pi_\delta(\hat{N}, \hat{\imath}) \leq \Pi_\delta(\hat{N}, \hat{\imath}) \). Similar to (A30)

\[
\Pi_\delta(\hat{N}, \hat{\imath}) = \frac{\hat{R} + \left( \frac{q^* - q^R}{q^R (Q^2 - q)} \right) I}{1 + \left( \frac{q^* - q^R}{q^R (Q^2 - q)} \right) I}. \tag{A302}
\]
and

\[
\Pi_\epsilon^e \left( \hat{N}^e, \hat{r}^e \right) = \frac{\hat{R}_\epsilon + \left( \frac{q - \bar{q}^R}{\bar{q}^R (Q^T - q)} \right) I_\epsilon}{1 + \left( \frac{q - \bar{q}^e}{\bar{q}^e (Q^T - q)} \right) I_\epsilon},
\]

(A303)

where \( I = 1 \) if \( \hat{r} = T_h \), and \( I = 0 \) otherwise. Similarly, \( I_\epsilon = 1 \) if \( \hat{r}^e = T_h \), and \( I_\epsilon = 0 \) otherwise. The difference between the two expressions in (A302) and (A303) is \( G \), so \( G < 0 \) means lower revenue for the physician under e-visits compared to the case without e-visits.

The four cases mentioned above (i.e., \( \hat{r} = \hat{r}^e = T_l \), \( \hat{r} = \hat{r}^e = T_h \), \( \hat{r} > \hat{r}^e \), and \( \hat{r} < \hat{r}^e \)) can be described in the following way: (1) if \( q < \bar{q}^\alpha \left\{ \frac{\bar{q}^T}{(1 + \Sigma_e)\tau}, \bar{q}^T \right\} \), we have \( \hat{r} = \hat{r}^e = T_l \); (2) if \( q > \max \left\{ \frac{\bar{q}^T}{(1 + \Sigma_e)^e}, \bar{q}^T \right\} \), we have \( \hat{r} = \hat{r}^e = T_h \); (3) if \( (q, R_c^l) \in \Xi \), we have \( \hat{r} = T_h, \hat{r}^e = T_l \), and (4) if \( (q, R_c^r) \in \Xi \), we have \( \hat{r} = T_l, \hat{r}^e = T_h \).

\[\square\]

**Proof of Proposition 9**

We assume that we are in a setting where patients choose to adopt e-visits. Note that in the setting described by the proposition, \( \alpha^e_\epsilon > \alpha^e_\epsilon \left( q \right) \), so \( \hat{r}^e = T_l \).

a) RVIs decrease if \( q < \bar{q}^\tau \) since in this case \( \hat{r} = T_h \).

b) If \( \hat{r}^e < \hat{r} \), then, as it follows from (A290), panel size decreases upon the introduction of e-visits if \( q \leq \bar{q}^\alpha \). Note that from (A291) we have \( \bar{q}^\alpha < \bar{q}^\tau \), so that \( q \leq \bar{q}^\alpha \) is a necessary and sufficient condition for panel size to decrease after e-visits are introduced.

c) For the proportional fee-for-service e-visit compensation, similar to (A295), we have \( q \leq \bar{q}^\alpha \). For the capitation e-visit compensation, we need to consider two separate cases, (1) \( \hat{r} = T_h \), and (2) \( \hat{r} = T_l \). The first case occurs when \( q < \bar{q}^\tau \), so that for revenue to decrease we need \( G(1, 0) < 0 \). The second case occurs when \( q > \bar{q}^\tau \), so that for revenue to decrease we need \( G(0, 0) < 0 \).

\[\square\]
Appendix B: Combined Impact of RVI and Care Channel Customization

In this section, we numerically evaluate the joint impact of RVI and care channel customization. In particular, we focus on a heterogeneous patient panel with two patient groups and use as the base case the setting without e-visits or RVI customization.

We compare this base case to two cases in which the physician utilizes both RVI and care channel customization. In the first case, e-visits result in exclusively fee-for-service compensation for the physician: the patient pays $30 to the physician for each e-visit, which is in the $20-$50 range currently used in practice (MedInfoTech 2012). In the second case, e-visit compensation is capitation-based: there is no “per e-visit” revenue for the physician or payment from the patient, but the physician is compensated for providing e-visits at a daily rate of $0.0025 for each patient on her panel, irrespective of the actual number of e-visits. Reijonsaari et al. (2005) study a health system that charges a $60 annual fee for e-visits with 10% patient adoption. The daily capitation payment for such a system is about $0.02: assuming a year has 260 working days, we have \( \frac{360 \times 0.1}{260} = 0.023 \). Note that we use \( R_{de} = 0.0025 \) instead of this estimated value of 0.02 because for \( \alpha_r \) patients do not adopt e-visits for any value of \( \alpha_r \). Thus, for e-visit adoption to materialize, we lowered the e-visit capitation fee to 0.0025.

Figure B.1 shows the changes in system outcomes, as compared to the base case that does not include e-visits or RVI customization, when e-visits are compensated on a fee-for-service basis. The variable on the x-axis is \( \kappa_1 \), the fraction of patients on the panel who belong to the healthier group, and the variable on the y-axis is \( \alpha_r \), the fraction of routine visits that can be safely handled using e-visit care. In this setting, e-visits generate less revenue per unit of time as compared to in-office routine and urgent visits, i.e., \( \frac{R_r}{\tau_r} > \frac{R_u}{\tau_u} > \frac{R_e}{\tau_e} \). We chose \( \tau_e \) such that e-visit compensation is compensated less proportionally compared to routine and urgent visits because we have shown before that proportional e-visit compensation is guaranteed to increase physician revenue. Also, recall that since there is no e-visit capitation fee in this setting, patients choose to adopt e-visits for all \( \alpha_r \) values.

Figure B.1a shows that upon the introduction of e-visits, physician revenue decreases only if e-visits replace a large fraction of routine visits and most of the patients on the panel are relatively healthy. The physician rejects e-visits in this region (identified by hatched shading). Note that in this region the use of e-visits saves time for the physician, and, thus, leads to additional revenue by increasing the panel size. However, this increase in revenue cannot keep up with the revenue loss caused by e-visits replacing the routine visits that generate the highest revenue per unit of time. Also, as expected, RVI customization by patient group increases physician revenue relative to a baseline of no customization, but increased substitutability of office visits by e-visits countervails this effect and dominates for high enough levels of substitutability.
Figure B.1: Fee-for-service e-visit compensation: changes in system outcomes upon the introduction of e-visits as a function of (1) fraction of routine office visits that can be handled remotely, $\alpha_r^c$, and (2) fraction of patients on the physician’s panel that belong to the healthier group, $\kappa_1$ ($q_1 = 0.3, q_2 = 0.7, \delta = 0.25, c = 6, c_0 = 50, \Delta = 0.95, T_h = 360, T_l = 60, \tau^r = 1, \tau^u = 2, \tau_r^c = 0.25, R^r = 200, R^u = 350, R^d = 0.1, R^d_0 = 0, R^e_c = 30$).

Physician panel size decreases only if $\kappa_1$ is sufficiently large, and, in addition, $\alpha_r^c$ is sufficiently small. In this region, the small values of $\alpha_r^c$ imply that the physician time savings associated with e-visits are limited. Additionally, as stated in Proposition 1, for $\kappa_1 > \hat{\kappa}_1$ the physician chooses the RVI of $T_h$ for both patient groups in the base case. With RVI customization, however, the optimal RVI for patients in group 2 changes to $T_l$ (unless $\kappa_1$ is close to 1 and $\alpha_r^c$ is small; we discuss this case later). Given that $q_2$ is not too large, panel size is larger with $r_2 = T_h$ compared to the case with $r_2 = T_l$. Outside of this particular region, however, time savings resulting from the use of e-visits are substantial enough to increase the size of patient panel.

Turning to panel health (defined in (29)), we observe that it diminishes for $\kappa_1 < \hat{\kappa}_1$. The reason for this drop is that, for low values of $\kappa_1$, the optimal RVI in the base case is $T_l$ for both patient
groups, but RVI customization leads to the physician picking the RVI of \( T_h \) for the patients in

\[ \kappa_1 > \hat{\kappa}_1, \] 

panel health either stays constant or improves. In the interval of \( \kappa_1 > \hat{\kappa}_1, \) panel health improves because the RVI value for patients in group 2 change to \( T_l \) under RVI customization. The only exception to this is the area where \( \kappa_1 \) is close to 1 and \( \alpha^r \) is small; in this area panel health does not change compared to the base case because both patient groups are assigned the RVI of \( T_h \) which is the same as their RVI values in the base case. Recall that we showed it is possible for the physician to assign the RVI of \( T_h \) to both patient groups in equation (57) of Proposition 6. Also, note that both patient groups remain flexible for all value of \( \alpha^r \) in Figure B.1, and, hence, the RVI changes to \( T_l \) for group 2 patients in the \( \kappa_1 > \hat{\kappa}_1 \) interval only because of RVI customization by the physician.

Figure B.2 shows the changes in system outcomes upon the introduction of e-visits compensated on a capitation basis. On the patient side, e-visit adoption depends on \( \alpha^r \): neither of the patient groups adopts e-visits if \( \alpha^r \leq 0.15 \), and both patient groups adopt e-visits if \( \alpha^r > 0.15 \). Also, group 1 and 2 patients become inflexible with the RVI of \( T_l \) for \( \alpha^r > \bar{\alpha}^r(q_1) \) and \( \alpha^r > \bar{\alpha}^r(q_2) \), respectively. All the critical values of \( \alpha^r \) are marked with horizontal dotted lines in Figure B.2. Note that in Figure B.2, patients pay no per e-visit fee, so their flexibility as a function of \( \alpha^r \) changes at a much faster pace as compared to the fee-for-service e-visit case. Therefore, for sufficiently large values of \( \alpha^r \), even group 1 patients become inflexible with an RVI of \( T_l \).

We now turn to the system outcomes. Figure B.2a shows changes in physician revenue as a function of \( \alpha^r \) and \( \kappa_1 \). Changes in revenue for \( \alpha^r < 0.15 \) are only due to RVI customization because patients do not adopt e-visit in that area. We observe that RVI customization increases physician revenue for all value of \( \kappa_1 \leq 0.93 \). Also, similar to Figure B.2, RVI customization does not change RVI values for \( \kappa_1 > 0.93 \); given that there is no e-visit adoption for \( \alpha^r < 0.15 \), we see no change in revenue in the area where \( \alpha^r < 0.15 \) and \( \kappa_1 > 0.93 \). The physician rejects e-visits for most of the areas in which \( \alpha^r \) is large because she does not get paid per e-visit, and, hence, her revenue decreases if e-visits replace a large fraction of routine visits. These areas are identified by hatched shading in Figure B.2.

Under capitation e-visit compensation, patient panel size increases if \( \kappa_1 \leq \hat{\kappa}_1 \) mostly because of RVI customization: while the RVI of patients in group 2 is \( T_l \) (same as the base case), the RVI of group 1 patients increases to \( T_h \). In the area where \( \alpha^r \geq 0.15 \) and \( \kappa_1 \leq \hat{\kappa}_1 \), patients and the physician choose to adopt e-visits and the time savings of e-visits also contributes to increasing panel size. If \( \kappa_1 > \hat{\kappa}_1 \), panel size decreases, stays the same, and increases in areas A, B, and C, respectively. Panel size decreases in the area marked as A because the RVI of group 2 patients changes from \( T_h \) in the base case to \( T_l \) under e-visits and RVI customization. For \( \alpha^r < 0.15 \) and \( \kappa_1 > 0.93 \), marked as B, patients do not adopt e-visits and the physician assigns an RVI of \( T_h \) to
Figure B.2: Capitation e-visit compensation: changes in system outcomes upon the introduction of e-visits as a function of (1) fraction of routine office visits that can be handled remotely, \( \alpha_r \), and (2) fraction of patients on the physician’s panel that belong to the healthier group, \( \kappa_1 \) \( (q_1 = 0.3, q_2 = 0.7, \delta = 0.25, c = 6, c_o = 50, \Delta = 0.95, T_h = 360, T_l = 60, \tau^r = 1, \tau^u = 2, \tau^e = 0.2, R^r = 200, R^u = 350, R^d = 0.1, R^e_d = 0.0025, R^e_e = 0) \).

both patient groups. This leads to no change in panel size because nothing (neither RVIs nor the mode of care) changes compared to the base case. Panel size increases in area C because e-visits save the physician enough time to expand panel size.

Changes in panel health under capitation e-visit compensation are shown in Figure B.2c. First, we focus on the area where \( \kappa_1 \leq \hat{\kappa}_1 \). In this area, panel health decreases due to RVI customization: the RVI for patients in group 1 increases from \( T_l \) in the base case to \( T_h \). We divide the area where \( \kappa_1 > \hat{\kappa}_1 \) into three regions: \( D \), \( E \), and \( F \). Panel health improves in the region marked as \( D \) because under RVI customization the physician assigns the RVI of \( T_l \) to patients of groups 2 which is lower than \( T_h \) in the base case, and the RVI of group 1 patients stays constant. Panel health is constant in area \( E \) because the RVI values are the same as the ones in the base case for both patient groups.
Note that the border of area $E$ moves to the left after patients adopt e-visits ($\alpha_r^e > 0.15$). This is consistent with our results in Proposition 6: the $q_2$ threshold for the physician to assign the RVI of $T_h$ to group 2 patients in equation (57) is a function of $\alpha_r^e$. Patient health improves in area $F$ only because of patient response. While the physician prefers the RVI of $T_h$ for group 2 patients, these patients are inflexible with $T_i$ for $\alpha_r^e > \bar{\alpha}_r^e(q_2)$.

Overall, we observe that RVI customization and e-visits can enhance as well as negate each other’s effects on system outcomes. RVI customization is either revenue-neutral or revenue-increasing for the physician, so it may compensate for some of the revenue loss due to e-visit adoption. This pattern is clear in Figure B.1a, where the joint revenue impact of RVI customization and e-visits is positive for a large set of $\alpha_r^e$ and $\kappa_1$ values. We also observe this compensating effect with regards to panel size. In the area located on the right-hand-side of the $\kappa_1 = \hat{\kappa}_1$ line, where panel size decreases in both Figures B.1b and B.2b, e-visits and RVI customization act in opposite directions: RVI customization decreases panel size, and e-visits increase it, meaning that without the introduction of e-visits, panel size would decrease for all $\kappa_1 > \hat{\kappa}_1$ (except when $\kappa_1$ is close to 1 because in that case panel size stays constant, e.g., area $B$ in Figure B.2b). By contrast, e-visits and RVI customization both increase panel size in the area located on the left-hand-side of the $\kappa_1 = \hat{\kappa}_1$ line in Figures B.1b and B.2b. In terms of panel health, RVI customization and e-visits can also act hand-in-hand or against each other. Consider the areas of no change in panel health on the right-hand-side of $\kappa_1 = \hat{\kappa}_1$ in Figure B.1c (colored in white). In this area, increases in $\alpha_r^e$ decrease the area in which panel health stays constant, and for large enough values of $\alpha_r^e$ panel health improves for all $\kappa_1$ values. These effects are reversed in area $E$ of Figure B.2c: as $\alpha_r^e$ increases, the area in which panel health stays constant expands. On the other hand, for large enough values of $\alpha_r^e$, e-visits cause patients in group 2 to become inflexible with $T_i$; this leads to improvements in patient health in area $F$ of Figure B.2c.