# Essays on Environmental Economics and Regional Economics

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# Abstract of Dissertation

## Essays on Environmental Economics and Regional Economics

The first two essays of this dissertation study individual (household) and government adaptation to sea-level rise (SLR). The form of government adaptation is assumed to be construction of a seawall, and the form of household adaptation is migration across locations (regions). The first essay investigates the socially optimal adaptation outcome, and examines whether adaptation decisions made by local governments are efficient. In a two-region setting, I construct a spatial model in which the probability of damage due to SLR risk decreases as the distance from the shoreline increases. Equalization of wage rates across locations is the driving force for migration. I demonstrate that in contrast to efficient provision of a local public good under free migration, the provision of local adaptation is inefficient in general.

The second essay examines the nature of the interaction between household and government adaptation. I model household and government adaptation as a sequential game. For the two levels of government (local and central), I separately investigate how the sequence of adaptation decision-making affects adaptation outcomes. Using a simulation, I show that households should move first (second) when the local (central) government chooses seawall height.

The third essay studies travel time use over five decades in the United States. Over the period from 1965 to 2013, we examine travel time allocation in the U.S. for the aggregate economy and for subgroups of different age, gender and work status, education, and whether there are children in the household. We use the Blinder-Oaxaca method to decompose changes in the unconditional mean of total travel time into the portion that can be explained by demographic shifts and the portion that can be explained by changes within demographic groups.

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# Chapter 1: Introduction

This dissertation consists of two different topics: one in environmental economics and the other in regional economics. The first two essays are applied theoretical studies that focus on the topic of climate change and adaptation. The third essay[1] is an empirical study that documents travel time use over the past five decades in the United States.

Climate change is now considered to be inevitable. It increases the severity of natural hazards, including destructive storms, erosion, and sea-level rise that may inundate a whole region. Climate policies have been mostly focused on mitigation. However, regardless of how much mitigation is achieved or will be achieved, climate is already changing, and will continue to change due to past emissions. As a result, there are growing concerns about how societies should respond or adapt to climate change efficiently.

The first two essays study individual (household) and government adaptation to sea-level rise (SLR). The form of government adaptation is assumed to be the construction of a seawall, and the form of individual adaptation is costless migration from at-risk locations to risk-free locations. Extending the existing adaptation literature, which usually assumes individual and government adaptation are independent, I treat them as being substitutes, i.e., a higher seawall results in less migration. I also assume that governments are aware of the impact of their seawall height decisions on migration.

The first essay (Chapter 2) investigates the socially optimal adaptation outcome theoretically, and examines whether adaptation decisions made by local governments are efficient, in other words, whether the local public good (the seawall) can be provided locally without any loss in social welfare. Although the specific illustration involves a flooding hazard, the model can be adapted to any other productivity shocks

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[1] This is a joint work with Professor Chao Wei.

that are spatial in nature and can be mitigated by providing a local public good. In this essay, I consider a two-region setting in which a coastal region borders an inland region. Each region has a local government that makes seawall height decisions for its own region.[2] Alternatively, there is a central government that makes seawall height decisions for both regions as a whole. I examine whether decisions on seawall height made by the local governments of these two regions can achieve the social optimum. I construct a spatial model in which the probability of damage due to SLR risk decreases as the distance from the shoreline increases, and equalization of wage rates across locations is the driving force for migration. The analysis demonstrates that in general, local governments will build a seawall that is either too high or too low compared to the socially optimal height. Therefore, I conclude that in contrast to efficient provision of a local public good under free mobility, the provision of local adaptation is inefficient in general.

The second essay (Chapter 3) studies the efficiency of adaptation from the perspective of a sequential game, and investigates how the sequence of decision-making by households and the government affects adaptation outcomes. The two main issues addressed are: social welfare comparisons based on first-mover status (government vs. households), and based on the level of government (local or central) making the adaptation decisions. The model in this essay also uses a two-region setting, and assumes that both regions are overpopulated. The model is grounded in the public economics literature, which assumes that the local government provides a local public good in its local region. However, the decision on seawall height can be made by either the local government in the coastal region or a central government that governs both regions. Unlike the first essay, the local government in the inland region in this model is assumed to be passive, i.e., it does not participate in the seawall decision-making. For simplicity, I assume that SLR only affects and causes damages

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[2] The local government of the inland region is assumed to be able to finance for the seawall if it has an incentive to build a seawall in order to achieve its welfare objective for its own region.

to the coastal region. Equalization of utility between the two regions is the driving force for household migration. Using a simulation, I show that society is better off when households move first (second) if the local (central) government chooses seawall height. However, as long as free migration is allowed, in no case is the first-best outcome achieved.

The third essay (Chapter 4) studies travel time use over five decades in the United States. We examine travel time allocation in the U.S. for the aggregate economy and for subgroups of different age, gender and work status, education levels, and whether there are children in the household over the period from 1965 to 2013. We show that travel time increased significantly in the U.S between 1965 and 1993, reached a peak sometime between 1993 and 2003, and declined over the following decade. We use the Blinder-Oaxaca method to decompose changes in the unconditional mean of total travel time into the portion that can be explained by demographic shifts and the portion that can be explained by changes within demographic groups. We find that changes in education composition play a prominent role in the increase in total travel time from 1975 to 1993. Shifts across work-gender groups also play a dominant role among demographic shifts when we focus on variations in work travel for the 1975 -1993 period. After 1993, demographic shifts play a small role in the evolution of total travel time; this even more true for the 2003 - 2013 period. We find that a shift of time allocation from more travel-intensive market and non-market work to less travel-intensive leisure is the main driving force behind the decline in travel time from 2003 to 2013.

# Chapter 2: Free Migration and the Inefficiency of Local Adaptation

## 2.1 Introduction

Sea-level rise (SLR) is one of the salient effects of climate change. The Intergovernmental Panel on Climate Change (IPCC) predicts global SLR of 28-61 cm by the year 2100, even with aggressive emissions reductions (IPCC, 2013). Rising sea levels expose coastal populations to the risk of increasing flooding events, erosion, and inundation. Anthoff et al. (2006) estimate that there will be 145 million people at risk from a 1 meter SLR scenario, 41% of whom will be in South Asia, and 32% in East Asia.

Migration has been observed as a significant individual response to climate change.[3] The estimate of 200 million climate migrants by 2050 from Myers (2005) is a widely accepted figure.[4] Construction of coastal defenses, such as a seawall, is a common form of government adaptation to SLR. This essay considers the relationship between individual and government adaptation, which can be viewed as substitutes. I investigate optimal adaptation outcomes theoretically given this linkage and examine the efficiency of adaptation decisions made by decentralized levels of government. Three central questions are addressed. First, what migration patterns are produced under a laissez-faire response to SLR risk? Second, what is the optimal social response (the central government makes seawall decisions) in a system with free migration? Third, are local government decisions on seawall height likely to achieve this social optimum?

In this essay, I assume there are two adjacent regions in a nation, a coastal region, which is vulnerable to SLR, and an inland region. Each region has a local government that makes seawall height decisions for its own region. Alternatively, there is a central government that makes seawall height decisions for both regions. I construct a one-

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[3] According to the IPCC (1990a), "The greatest single impact of climate change might be on human migration, with millions of people displaced by shoreline erosion, coastal flooding and agricultural disruption."

[4] For example, it was cited in Stern (2007).

dimensional spatial model in which flooding caused by SLR destroys output with certainty. The probability of flooding (damage) for a location decreases as the distance between the location and the shoreline increases. Workers are able to migrate freely across locations in order to pursue higher wages. In other words, equalization of wage rates across locations is the consequence of the no-arbitrage equilibrium produced by free migration. Both central and local governments are aware of the impact of seawall height on migration, and take it into account when making seawall height decisions.

This essay makes two contributions. First, it modifies a well-established result in public economics to the adaptation setting. It demonstrates that in contrast to efficient local public good provision, local adaptation provision under free migration is inefficient. Second, it extends the existing adaptation literature by providing a formal spatial analysis of the optimal mix of individual and government adaptation.

Lecocq and Shalizi (2007) state that mitigation provides a clear global public good, while adaptation mostly provides a private good, or a local public good. Buob and Stephan (2011) also point out that adaptation in a region can independently provide benefits that accrue only to residents of that region, whereas benefits from mitigation are globally public and depend on the decisions of other regions. Obviously, a seawall is a local public good, and the provision of seawall under free migration resembles local public good provision under free mobility. An immediate question is which level of government, central or local, should make the seawall decision.

Oates (1972) analyzes the trade-off between centralized and decentralized provision of local public goods. The Oates' *Decentralization Theorem* states that without spillovers, a decentralized system is preferred. With spillovers, the outcome depends on the extent of heterogeneity in tastes and the degree of spillovers. This is because a one-size-fits-all outcome produced by a central government does not cater to local needs, whereas local governments fail to internalize spillover effects. Lockwood (2002) and Besley and Coate (2003) relax the assumption of uniform federal policies and state that public goods can be provided unequally across jurisdictions by a central government. Oates and Schwab (1988) and Wellisch (2000) bring in the issue of interjurisdictional economic competition to discuss the efficiency of decentralization. They assume jurisdictions compete for mobile firms to increase local wages and expand the local tax base, and show that competition among governments induces efficient local choices.

However, Oates' framework does not allow for migration across jurisdictions. Besley and Coate (2003) and Janeba and Wilson (2011) mention that household mobility is an important issue in the study of Oates' theorem. Oates (2008) also states that the *Decentralization Theorem* is restrictive in that there is no mobility in response to changes in fiscal parameters. The assumptions made about mobility and about the nature of the public good interact in important ways for outcome determination. Bloch and Zenginobuz (2014) incorporate imperfect mobility in Oates' framework. Agents are assumed to be heterogeneous in their model. In particular, only a fraction of the residents in each jurisdiction are able to move to the other jurisdiction in response to differences in public good provision or taxation of the two jurisdictions.

Different from Oates' framework, there is another large literature on the efficiency properties of local public good provision under free mobility, but this literature does not allow for spillovers across jurisdictions, unlike Oates. Tiebout (1956) first proposes that if consumer-voters are fully mobile, they will move to the community where their preference patterns are best satisfied. Local governments would compete for households by their choice of fiscal packages. This "vote with one's feet" process would lead to an optimal level of local public good expenditure. Some subsequent research does not agree with this view. For example, Starrett (1980) argues that free migration yields externalities, so there will be an incentive for local governments to overspend or underspend. Musgrave (1971), Buchanan and Goetz (1972), and Wildasin (1991) also argue that decentralization of government activities leads to an inefficient allocation, because regional governments neglect the well being of individuals living in other regions and thus cause interregional externalities. However, in response to Starrett, Boadway (1982) shows that if local governments take into account migration responses to their expenditure decisions, local public good provision will be socially optimal. Wellisch (2000) shows that when governments take into account migration responses to governments' actions, interregional household mobility is an incentive mechanism for regional governments to choose an efficient local public good provision. The counterintuitive result is that a Nash equilibrium of decentralized and uncoordinated local public good provision can result in a socially efficient outcome. Hoel (2004) shows this result is valid for a very general class of economies with interregional interactions. Similar results have been shown in the context of public goods with spillovers by Wildasin (1991), and in the context of an environmental externality by Hoel and Shapiro (2003).

The logic behind this argument is that when considering migration responses, regional governments take into account the effects of their actions not only on their own residents' utility but also on the welfare of nonresidents. Therefore, interregional household mobility provides an incentive for regional governments to choose an efficient allocation. However, no research has been done to show whether this result holds when local public good provision and free mobility are adaptive responses to climate risk. This essay shows that although the government takes migration into account when making adaptation decisions, local adaptation provision is inefficient. Migration as a form of adaptation can obstruct rather than promote efficiency for decentralized adaptation.

In this essay, individuals are assumed to be homogeneous and a seawall is the only local public good that is provided in response to SLR. Also, local governments and the central government are assumed to possess identical information about the probability that hazards occur. Therefore, local governments do not have advantages in terms of local tastes or local information. Whether there are spillover effects of the seawall depends on whether the inland region incurs any damages. Free migration is the key characteristic of the first two essays. Hence, these two essays are closer to the literature on local public good provision under free mobility stemming from Tiebout (1956).

As for the adaptation literature, there has been little theoretical work on efficient adaptation. Mendelsohn (2000) presents a benefit-cost framework in which agents maximize net benefits of adaptation, to examine efficient adaptation. The model presented in this essay applies a similar benefit-cost analysis framework. Mendelsohn (2000) claims that as long as the costs and rewards are borne by the decision-maker, private adaptation will be efficient. However, government intervention is required for "joint adaptation" to be efficient. Adaptation is joint only when an action affects the benefits that other individuals receive. The government would choose the efficient level of adaptation that maximizes the group's net benefits.

It should be noted that migration as a form of autonomous adaptation, which is adaptation undertaken by households, firms, or collections of these (Malik and Smith, 2012), generates externalities in both migration-sending and migration-receiving regions. When there is strong demand for labor in the migration-receiving region, migrants play a positive role in wealth creation. In fact, migration is a proven development strategy that can help migrants, their families, and the communities from which they come, and to which they move, adapt to climate change (Agrawal, 2010). However, migration can create conflicts in migration-receiving regions too. Reuveny (2007) shows that people living in less-developed countries may be more likely to leave affected areas, which may cause conflict in migration-receiving areas. Therefore, whether the impact of migration is largely positive or largely negative for a region depends on the specific economic and social circumstances in that region. In this essay, migrants benefit the migration-receiving region by raising output, whereas they make native workers worse off because they drive down the wage rate.

McLeman and Smit (2006) propose a conceptual model, based upon the concepts of vulnerability, exposure to risk and adaptive capacity, to investigate migration as an adaptive response to risks associated with climate change. However, their study only examines household adaptation and does not take into account government adaptation. Malik and Smith (2012) argue that there is an interplay between autonomous (household) adaptation and planned (government) adaptation. This essay builds a model that considers an interplay between these two forms of adaptation.

This essay has several distinguishing features. First, it introduces a spatial model assuming that the damage probability varies continuously over space. This provides insights on the pattern of migration and population distribution from hazard-prone to hazard-free locations. Second, it considers individual and government adaptation as substitutes, rather than being independent. Finally, it considers externalities caused by migration in both migration-sending and migration-receiving regions and examines adaptation incentives for the local governments of both regions.

The analysis shows that decisions made by the local governments result in a seawall that is either too high or too low compared to a welfare-maximizing choice, because local governments neglect the effects of a seawall on neighboring regions. The simulation results show that the central and local government decisions can also differ as to when the corner solution of "no seawall" is optimal. Therefore, local provision of adaptation in general cannot achieve the socially optimal level, and the decision on seawall height is better made by a central government.

The essay is organized as follows. Section 2.2 investigates the equilibrium in the baseline where the government does nothing regarding SLR, and then examines the impact of a seawall. Section 2.3 discusses the central government's problem and its optimal choice of seawall height. Section 2.4 discusses the optimal choices of seawall height by the two local governments under two different damage scenarios as well as two different government objectives. Section 2.5 presents a simulation to determine optimal adaptation under eight different scenarios and illustrates the results obtained in the previous sections. Section 2.6 investigates an extension of the model. The final section contains the conclusions.

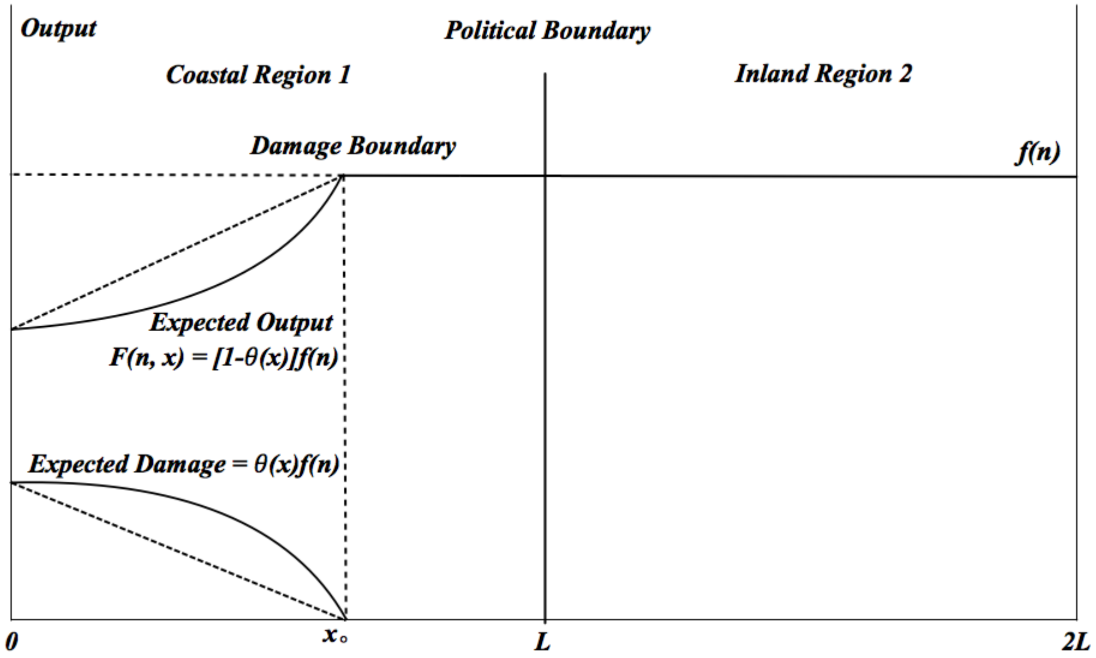
## 2.2 The Model

In this section I first characterize the laissez-faire baseline solution in which the government does nothing about SLR risk, while individuals can migrate freely in order to avoid expected losses. Then in Section 2.2.2, I assume a seawall can be built to protect the land at risk, and I investigate its impact on migration and output. The risk of SLR can be modeled in different ways. Frame (1998) constructs a model of housing markets in which locations are differentiated by both risk of loss due to natural hazards and distance from a central business district (CBD). In his model, all production takes place in the CBD. In my model, in contrast, I assume an agricultural economy and that all land is equally productive without SLR. Therefore, locations are only differentiated by the probability of damage due to SLR risk. The closer a location is to the shoreline, the higher the probability that it is damaged.

### 2.2.1 The Baseline

Suppose a nation consists of two regions, a coastal region 1, which borders an inland region 2. Each region has the same length of land $L$, which is collectively owned by a group of external (absentee) landlords. Specifically, referring to Figure 2.1, on the horizontal $x$ axis, region 1 governs the portion from 0 to $L$, while region 2 governs the portion from $L$ to $2L$. 0 is the shoreline, and $L$ is the political boundary. In period 0, which is the initial period, there is no SLR risk. However, SLR is anticipated to occur in period 1.

Figure 2.1: Expected Damage and Expected Output under SLR



There are $2N$ workers in the nation, who are hired by the landowners to produce crops. Initially, without SLR risk, all land is equally productive, and workers are evenly distributed over the land. The population per unit of land, denoted by $n$, is equal to $2N/2L$. However, workers are able to migrate freely among locations in order to pursue higher wages. This free migration condition ensures that the wage rate is equal everywhere in equilibrium. Production is assumed to have constant returns to scale. For simplicity, production is characterized by the Cobb-Douglas production function $f(N,L) = AN^{\alpha}L^{1-\alpha}$, where $A > 0$ is total factor productivity, and $\alpha \in (0,1)$ is the elasticity of output with respect to labor. The production function per unit of land is thus $f(n) = An^{\alpha}$. Each worker receives a wage income $w$, which is equal to the marginal product of labor

$$w = f'(n) = \alpha A n^{\alpha-1} = \frac{\alpha f(n)}{n}. \tag{2.1}$$

The landowners receive a unit land rent $r(n)$, which is equal to the residual

$$r(n) = f(n) - nw = (1-\alpha)f(n). \tag{2.2}$$

Suppose that flooding caused by SLR is anticipated to occur in period 1, and can destroy output in the interval $[0, x_0)$, but has no impact on output in the interval $[x_0, 2L]$. In other words, the interval $[0, x_0)$ is the at-risk interval of land, and the interval $[x_0, 2L]$ is the risk-free interval of land. For the rest of the essay, I will use at-risk (risk-free) land to refer to all land in the at-risk (risk-free) interval and at-risk (risk-free) location to refer to a location in the at-risk (risk-free) interval.

I further assume that the probability of damage rises with proximity to the shoreline, i.e., output produced at $x = 0$ has the highest probability of destruction. $x_0$ is called the "damage boundary" where the probability of damage falls to zero. $x_0$ can be located in region 1, in region 2, or right at the political boundary $L$. Formally, the probability of damage as a function of location is defined as follow.

**Definition 2.1** *$\theta(x; x_0)$, or simply $\theta(x)$,*[5] *is a decreasing and concave function, which captures the damage probability at location $x$, given the damage boundary $x_0$. Specifically, $\theta(x; x_0) \in (0, 1)$, with $\theta(0; x_0) > 0$, $\theta'(x) < 0$, and $\theta''(x) \leq 0$ for $x \in [0, x_0)$, and $\theta(x; x_0) = 0$, for $x \in [x_0, 2L]$. In addition, $\frac{\partial \theta(x)}{\partial x_0} > 0$, for $x \in [0, x_0)$.*

According to this definition, the larger the damage boundary, the higher the probability of damage for a given at-risk location. The probability that damage occurs at the shoreline is $\theta(0; x_0)$, which might be dependent or independent of the damage boundary.[6]

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[5] Because $x_0$ is exogenous in the model, I simply use $\theta(x)$ to represent $\theta(x; x_0)$ for the following discussions.

[6] The probability that damage occurs at the shoreline and the length of the at-risk land might be related. The larger the probability at the shoreline, the larger the potential impact, and so the larger the at-risk interval.

Figure 2.1 depicts a scenario where the damage boundary does not overlap the political boundary and is located in region 1. Expected damage can either be linear or strictly concave. Recall that $f(n)$ is the initial output per unit of land in period 0, which is identical everywhere. However, when SLR is anticipated to affect the interval $[0, x_0)$, the expected amount of output destroyed in period 1 is $\theta(x)f(n)$, which varies with location. Let $F(n, x)$ be the expected production function at location $x$ given the probability of damage due to SLR, and let $w^s$ be the expected wage rate, then

$$F(n, x) = [1 - \theta(x)]f(n); \tag{2.3}$$

$$w^s = F_n(n, x) = [1 - \theta(x)]f'(n). \tag{2.4}$$

Clearly, for the at-risk land, the expected wage rate depends on $\theta(x)$, which is different across locations. Therefore, the initial distribution of population is no longer an equilibrium, and there is an incentive for migration from lower-wage locations to higher-wage locations. The new distribution of population in equilibrium is summarized in the following proposition.

**Proposition 2.1** *Given the risk of SLR, population is an increasing and convex function of distance from the shoreline in the at-risk interval, while it is evenly distributed in the risk-free interval. Formally, we have*

$$n(x) = \begin{cases} n_{x_0}[1 - \theta(x)]^{\frac{1}{1-\alpha}}, & \text{if } x \in [0, x_0) \\ n_{x_0}, & \text{if } x \in [x_0, 2L] \end{cases}, \tag{2.5a}$$

$$n_{x_0} = \frac{2N}{M}; \tag{2.5b}$$

*where* $M = (2L - x_0) + \int_0^{x_0} [1 - \theta(x)]^{\frac{1}{1-\alpha}} dx$. $n_{x_0}$ *is population at the damage boundary, and* $M$ *is the effective length of land.*

The "effective length of land" $M$ is the length of land corresponding to the labor-land ratio with full productivity (population density on the risk-free land) under SLR. In other words, total population can only fill in a length, $M < 2L$, of land such that every location has the same population density $n_{x_0}$. Specifically, total population is equal to

$$n_{x_0} M = n_{x_0}(2L - x_0) + n_{x_0} \int_0^{x_0} [1 - \theta(x)]^{\frac{1}{1-\alpha}} dx.$$

The term $2L - x_0$ is the length of risk-free land, which has full productivity with a population density $n_{x_0}$ everywhere in the interval $[x_0, 2L]$. As we will see later, $n_{x_0}$ is greater than $n$, because there is migration from at-risk locations to risk-free locations. $x_0$ is the length of at-risk land, which has lower productivity due to damages. The population density for every at-risk location is lower than $n_{x_0}$. However, the term $n_{x_0} \int_0^{x_0} [1 - \theta(x)]^{\frac{1}{1-\alpha}} dx$ indicates that total population in the interval $[0, x_0]$ can be distributed evenly with the population density $n_{x_0}$ but at a shorter length than $x_0$. Therefore, the effective length $M$ is shorter than the physical length $2L$.

The derivation of Proposition 2.1 is straightforward. Due to free migration, the wage rate must be equal everywhere in equilibrium. Let $\overline{w^s}$ be the identical wage rate across locations. Recall that $\theta(x) = 0$, for $x \in [x_0, 2L]$, therefore, population at each risk-free location is $n_{x_0} = [\frac{\alpha A}{\overline{w^s}}]^{\frac{1}{1-\alpha}}$. According to (2.4), given the identical wage rate $\overline{w^s}$, marginal product of labor, and thus population on the at-risk land, has to adjust with $\theta(x)$, the location-indexed probability of damage. Thus, population becomes a function of $x$ in the at-risk interval.

$$n(x) = \left\{ \frac{\alpha A [1 - \theta(x)]}{\overline{w^s}} \right\}^{\frac{1}{1-\alpha}} = n_{x_0} [1 - \theta(x)]^{\frac{1}{1-\alpha}}, \quad \text{for } x \in [0, x_0). \tag{2.6}$$

We thus obtain the expression for $n(x)$ in (2.5a). It is easy to verify that for $x \in [0, x_0)$, $\frac{\partial n(x)}{\partial x} > 0$, and $\frac{\partial^2 n(x)}{\partial x^2} > 0$.[7] Hence, $n(x)$ is an increasing and convex function of

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[7] $\frac{\partial n(x)}{\partial x} = -\frac{n_{x_0} \theta'(x) [1-\theta(x)]^{\frac{\alpha}{1-\alpha}}}{1-\alpha} > 0$, $\frac{\partial^2 n(x)}{\partial x^2} = \frac{\alpha n_{x_0} [\theta'(x)]^2 [1-\theta(x)]^{\frac{2\alpha-1}{1-\alpha}}}{(1-\alpha)^2} - \frac{n_{x_0} \theta''(x) [1-\theta(x)]^{\frac{\alpha}{1-\alpha}}}{1-\alpha} > 0$.

location $x$ in the at-risk interval.

A second equilibrium condition is that total population is equal to $2N$:

$$(2L - x_0)n_{x_0} + \int_0^{x_0} n(x)dx = 2N. \tag{2.7}$$

The first term is total population in the risk-free interval, while the second term is total population in the at-risk interval. Using (2.5a), this yields

$$n_{x_0}\left\{(2L - x_0) + \int_0^{x_0} [1 - \theta(x)]^{\frac{1}{1-\alpha}} dx\right\} = 2N. \tag{2.8}$$

Let $M$ denote the expression in the braces, one can solve for $n_{x_0}$ as shown in (2.5b). Obviously, $(2L - x_0) < M < 2L$. Therefore, we have $n_{x_0} > \frac{N}{L}$, or $n_{x_0} > n$, which indicates that population at each risk-free location rises above the initial population.

Clearly, the effective length of land $M$ is shorter than the physical length $2L$. Under SLR risk, population moves from high-risk locations to lower risk and risk-free locations. Population is no longer evenly distributed on the at-risk land; instead, it decreases as one moves closer to the shoreline. As explained earlier, one can think equivalently as if population is still distributed evenly everywhere but over a shorter length of land $M$. That is, under SLR, population at each location is $n_{x_0}$, which is more than initial population $n$, but the total length of land becomes $M$, which is shorter than $2L$. In other words, population density becomes higher due to the shorter "effective length" of land.

Figure 2.2 shows the population distribution for both the without and with SLR risk cases. Initially, the population is $n$ at every location over the length of land $2L$. When SLR is anticipated, location 0, which is at the highest risk, has the least population and population then increases at an increasing rate as one moves farther

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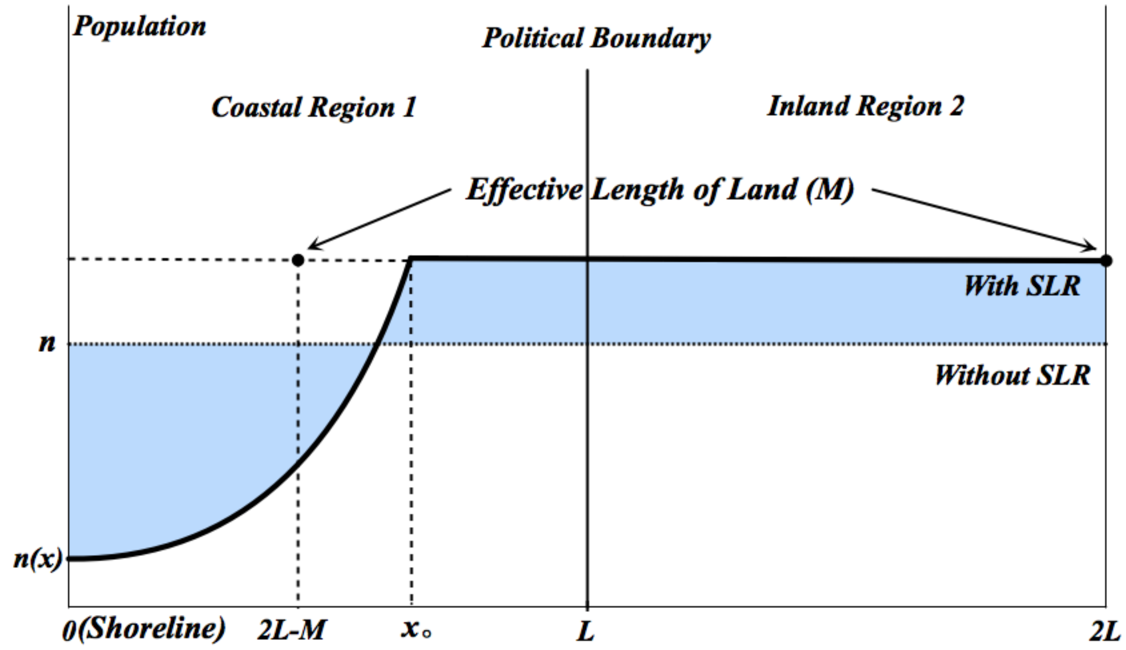
As shown in Definition 2.1, provided $0 < \theta(x) < 1$, and $\theta'(x) < 0$, the positive sign for the first derivative is proved. Also, given $\theta''(x) \geq 0$, the second derivative is positive.

Figure 2.2: Distribution of Population



away from the shoreline, until the damage boundary $x_0$. Every risk-free location then has the same population $n_{x_0}$. Notice that the two shaded sections in Figure 2.2 have the same area, which shows that the number of individuals who emigrate is equal to the number that immigrate. Although the actual population on the at-risk land is not evenly distributed, it can be seen as though it is evenly distributed with $n_{x_0}$ at each location but over a shorter length $x_0 - (2L - M)$ rather than $x_0$. Moreover, one can verify that $\frac{\partial M}{\partial x_0} < 0$, and $\frac{\partial n_{x_0}}{\partial x_0} > 0$, which indicates that as the damage boundary moves away from the shoreline, i.e., the length of at-risk land increases, the effective length becomes shorter, and population density becomes higher.[8]

Having characterized migration due to the risk of SLR, I turn to the effect of migration on the wage rate, output, and land rents. The wage rate under SLR is $\overline{w^s} = \alpha A n_{x_0}^{\alpha-1}$. Recall that $n_{x_0} > n$, thus $\overline{w^s} < w$, i.e., the new wage rate is lower than the initial wage rate. Obviously, $\frac{\partial \overline{w^s}}{\partial n_{x_0}} < 0$, which means more migration results in a lower (identical) wage rate everywhere. The expected distribution of output

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[8] $\frac{\partial M}{\partial x_0} = -\frac{1}{1-\alpha}\int_0^{x_0} \theta_{x_0}[1-\theta(x)]^{\frac{\alpha}{1-\alpha}} dx < 0; \frac{\partial n_{x_0}}{\partial x_0} = -\frac{2N}{M^2}\frac{\partial M}{\partial x_0} > 0.$

across locations shares the same pattern as population distribution. One can easily establish the following corollary to Proposition 2.1.

**Corollary 2.1.1** *Given the risk of SLR, the expected level of total output of both regions is lower than the initial level; output is an increasing and strictly convex function of distance from the shoreline in the at-risk interval, while it is identical at each location in the risk-free interval. Formally, we have*

$$F[n(x)] = \begin{cases} [1-\theta(x)]^{\frac{1}{1-\alpha}} F(n_{x_0}), & \text{if } x \in [0, x_0) \\ F(n_{x_0}), & \text{if } x \in [x_0, 2L] \end{cases}, \tag{2.9a}$$

$$Y^s = F(n_{x_0})M < Y; \tag{2.9b}$$

*where $Y^s$ is expected total output under SLR, and $Y$ is total output without SLR.*

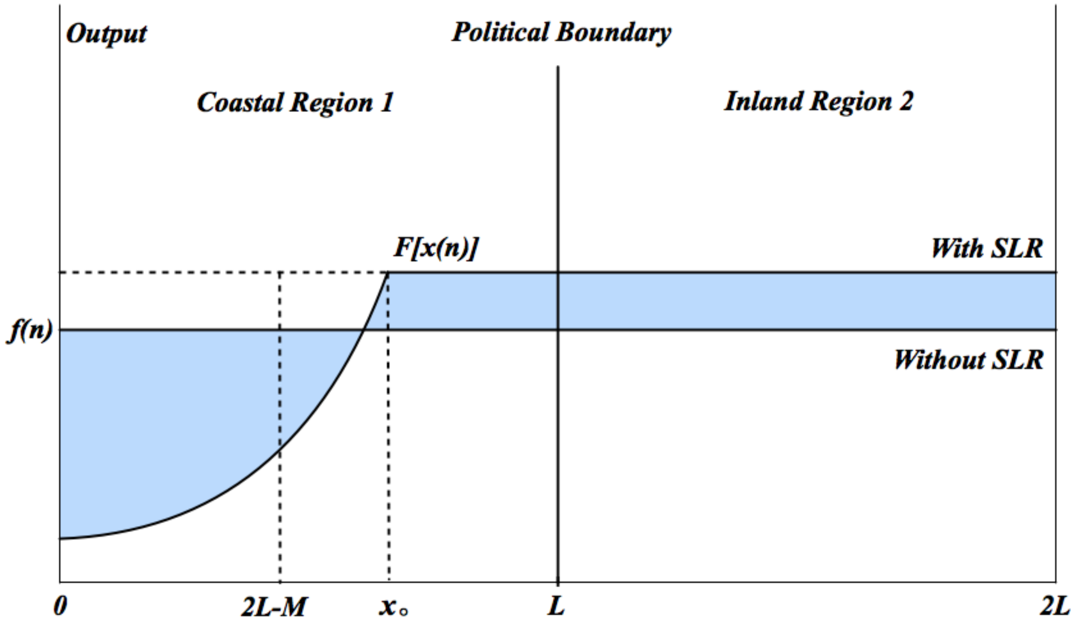
Using (2.5a), one can easily derive (2.9a) and verify that $\frac{\partial F[n(x)]}{\partial x} > 0$, and $\frac{\partial^2 F[n(x)]}{\partial x^2} > 0$. Initially, total output of both regions is $Y = 2Lf(n) = 2LAn^{\alpha}$. With SLR, using (2.5b), expected total output becomes

$$Y^s = (2L - x_0)F(n_{x_0}) + \int_0^{x_0} F[n(x)]dx = F(n_{x_0})M = MA(n_{x_0})^{\alpha}. \tag{2.10}$$

The expression above shows that total output is equal to the output on the risk-free land, $(2L - x_0)F(n_{x_0})$, plus the output on the at-risk land, $\int_0^{x_0} F[n(x)]dx$. Equivalently, this is equal to the output at the damage boundary $F(n_{x_0})$, multiplied by the effective length of land $M$. Notice that $M < 2L$ and $(n_{x_0})^{\alpha} < n^{\alpha}$, hence, $Y^s < Y$, the expected level of total output under SLR is lower than the initial level. This is intuitive, because the damage risk results in population being evenly distributed over a shorter length $M$, which increases density at each location and thus reduces the marginal product of labor. Figure 2.3 shows the distribution pattern of output. Notice here the shaded sections do not have the same area. The section below $f(n)$

is larger, because the initial total output level in period 0 is higher.

Figure 2.3: Distribution of Output



Finally, I examine how land rents change. Recall that land rents are the residual after deducting total wages at each location, $r^s(x) = (1-\alpha)F[n(x)]$. Therefore, land rents have the same distribution pattern as output, and it is simply a fixed fraction $(1-\alpha)$ of output. Total wages take up the remaining fraction, which means total wages at each at-risk location become smaller due to lower expected output. However, because of migration, the at-risk land has less labor in the new equilibrium, so that the wage rate is equal everywhere (at a lower level).

### 2.2.2 Building a Seawall

In this section, I add a seawall to the baseline scenario, and examine its impact on expected damages as well as population distribution. As stated in the previous section, without seawall protection, all crops on the at-risk land will be destroyed if flooding occurs, i.e., the damage rate is 100 percent. However, a seawall is able to reduce the damage rate. Let $g \geq 0$ be seawall height. $k(g) \in (0, 1]$ is the damage reduction function of $g$, with $k(0) = 1$, $k'(g) < 0$, $k''(g) > 0$. This indicates that the higher the seawall is, the lower the damage rate will be, but the seawall cannot reduce the damage rate to zero.[9] The migration pattern and population distribution in equilibrium still follow Proposition 2.1 except that they are now affected by seawall height. Similar to (2.5a) and (2.5b), population distribution with a seawall can be expressed as

$$n(x) = \begin{cases} n_{x_0}[1-\theta(x)k(g)]^{\frac{1}{1-\alpha}}, & \text{if } x \in [0, x_0) \\ n_{x_0}, & \text{if } x \in [x_0, 2L] \end{cases}, \tag{2.11a}$$

$$n_{x_0} = \frac{2N}{M(g)}; \tag{2.11b}$$

where $M(g) = (2L - x_0) + \int_0^{x_0} [1 - \theta(x)k(g)]^{\frac{1}{1-\alpha}} dx$, with $2L - x_0 < M(g) < 2L$. $M(g)$ is the effective length of land, which is a function of seawall height $g$. The following proposition summarizes the impact of seawall height on the effective length of land.

**Proposition 2.2** *A higher seawall increases the effective length of land but at a decreasing rate; and it reduces migration (population density) in equilibrium. Formally,*

$$\frac{\partial M(g)}{\partial g} > 0, \frac{\partial^2 M(g)}{\partial g^2} < 0, \frac{\partial n_{x_0}(g)}{\partial g} < 0, \frac{\partial^2 n_{x_0}(g)}{\partial g^2} > 0.$$

The signs of the two first-order derivatives are straightforward to determine. The derivative of effective length $M(g)$ with respect to seawall height is

$$\frac{\partial M(g)}{\partial g} = -\frac{k'(g)}{1-\alpha} \int_0^{x_0} [1 - \theta(x)k(g)]^{\frac{\alpha}{1-\alpha}} \theta(x) dx.$$

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[9] The seawall can only prevent damages caused by inundation. However, there are other associated hazards, for example, storms, which can also causes damages. The seawall cannot prevent damages caused by other types of hazards.

Recall that $k'(g) < 0$, and $k''(g) > 0$, therefore $\frac{\partial M(g)}{\partial g} > 0$. Furthermore,

$$\frac{\partial n_{x_0}(g)}{\partial g} = -\frac{2N}{M(g)^2}\frac{\partial M(g)}{\partial g} = -\frac{n_{x_0}(g)}{M(g)}\frac{\partial M(g)}{\partial g} < 0.$$

However, the sign of the second-order derivatives cannot be determined without specific functional forms.[10] With appropriate functional specifications, we can prove that $\frac{\partial^2 M(g)}{\partial g^2} < 0$ and $\frac{\partial^2 n_{x_0}(g)}{\partial g^2} > 0$ are likely to hold. The detailed proof is presented in Appendix A.1. Intuitively, a higher seawall reduces the expected damage rate and raises the expected output level on the at-risk land. Therefore, the wage rate falls less and there is less incentive for migration. However, since a seawall reduces the damage rate at a decreasing rate, it increases the effective length of land at a decreasing rate.

Similar to (2.9a) and (2.9b), the expected output when there is a seawall becomes

$$F[n(x)] = \begin{cases} [1-\theta(x)k(g)]^{\frac{1}{1-\alpha}} F(n_{x_0}), & \text{if } x \in [0, x_0) \\ F(n_{x_0}), & \text{if } x \in [x_0, 2L] \end{cases}, \tag{2.12a}$$

$$Y^s(g) = F(n_{x_0})M(g) < Y; \tag{2.12b}$$

Recall that the wage rate in equilibrium is equal everywhere. We can simply use the wage rate at the damage boundary $\overline{w^s}(g) = \alpha A[n_{x_0}(g)]^{\alpha-1}$ to establish the following corollary to Proposition 2.2.

**Corollary 2.2.1** *A higher seawall results in a higher level of expected total output and a higher wage rate. Specifically, the marginal increase in output is equal to unit land rent at the damage boundary multiplied by the marginal increase of effective length. The marginal increase of the wage rate is a fraction of the marginal increase*

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[10] $\frac{\partial^2 M(g)}{\partial g^2} = -\frac{k''(g)}{1-\alpha}\int_0^{x_0}[1-\theta(x)k(g)]^{\frac{\alpha}{1-\alpha}}\theta(x)dx + \frac{\alpha[k''(g)]^2}{(1-\alpha)^2}\int_0^{x_0}[1-\theta(x)k(g)]^{\frac{2\alpha-1}{1-\alpha}}\theta^2(x)dx$. The first term is negative and the second term is positive.

*in output.*

$$\begin{aligned}\frac{\partial Y^s(g)}{\partial g} &= (1-\alpha)F(n_{x_0})\frac{\partial M(g)}{\partial g} > 0;\\ \frac{\partial \overline{w^s}(g)}{\partial g} &= \frac{\alpha}{2N}(1-\alpha)F(n_{x_0})\frac{\partial M(g)}{\partial g} > 0.\end{aligned}$$

The derivation of the first expression will be presented in the next section. Given the first expression, the second expression follows directly, due to the relationship $\overline{w^s}(g) = \frac{\alpha Y^s(g)}{2N}$.

Finally, from the baseline, we know that $\frac{\partial M}{\partial x_0} < 0$, the effective length diminishes as the damage boundary moves farther away from the shoreline, i.e., the length of the at-risk land increases. Here with a seawall, we have a parallel result and an extension of it by applying Proposition 2.2, which shows how changes in the damage boundary affect the marginal effect of seawall height on effective length.

**Corollary 2.2.2** *As the length of at-risk land increases (i.e., $x_0$ increases), the effective length decreases while the marginal effect of seawall height on effective length increases. That is,*

$$\frac{\partial M(g)}{\partial x_0} < 0, \textit{ and } \frac{\partial M^2(g)}{\partial g \partial x_0} > 0.$$

One can obtain this result by applying the proof of Proposition 2.2. It is straightforward that a smaller at-risk interval results in a larger effective length. The second inequality above shows that the marginal effect of the seawall is smaller when the at-risk interval is smaller. It is clear that for the same seawall height, the benefit it yields is larger when the at-risk interval is larger, because it reduces more damages.

## 2.3 Central Government's Problem

In the previous section, I investigated the effect of seawall height on population distribution, expected output, the wage rate, and land rents. I now address the problem of optimal seawall height. This depends on who makes the decision and what the objective is. In this section, I assume that a central government chooses seawall height to maximize expected total output of the nation for both periods less the construction cost of the seawall. Notice that for a central government, maximizing total output is equivalent to maximizing output per capita or maximizing the wage rate, because the share of land in output is constant and the total population in the nation is fixed.

Let $C(g)$ be the construction cost of a seawall, with $C(0) = C_0 > 0$, $C'(g) \geq 0$, $C'(0) = 0$, and $C''(g) > 0$. The central government has to finance the seawall from the initial total output $Y$ in period 0. Obviously, the total cost of the seawall cannot exceed total output, and I assume this constraint is not binding. For simplicity, I assume the discount rate is zero.[11]

The central government's problem is to

$$\max_{g} Y^s(g) + Y - C(g) = F[n_{x0}(g)]M(g) + Y - C(g). \tag{2.13}$$

Recall that $Y^s(g) = F[n_{x0}(g)]M(g)$ is the expected total output under SLR risk in period 1, while $Y = 2Lf(n)$ is the total output in period 0 without SLR risk. The first-order condition for (2.13) yields

$$F'_{n_{x0}} \frac{\partial n_{x0}(g)}{\partial g} M(g) + F[n_{x0}(g)] \frac{\partial M(g)}{\partial g} = C'(g). \tag{2.14}$$

The RHS is the marginal construction cost of the seawall. The LHS is the marginal benefit of seawall height, which is equal to $\frac{\partial Y^s(g)}{\partial g}$, the marginal increase of expected total output in period 1. This marginal benefit comprises two terms. The first term is negative and reflects the migration effect. Because $\frac{\partial n_{x0}}{\partial g} < 0$, a higher seawall lowers migration and hence output for locations with low or zero damage probability. The second term is positive and reflects the productivity effect. Since $\frac{\partial M(g)}{\partial g} > 0$, a higher

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[11] The assumption of the zero discount rate is not essential to the analysis in this model.

seawall increases the effective length of land for production, thus increasing output. In other words, a higher seawall reduces the damage rate and yields output gain for locations with high damage probability. Using 2.11b,

$$\frac{\partial n_{x_0}(g)}{\partial g} = \frac{\partial n_{x_0}(g)}{\partial M(g)} \frac{\partial M(g)}{\partial g} = -\frac{n_{x_0}(g)}{M(g)} \frac{\partial M(g)}{\partial g}. \tag{2.15}$$

Using (2.15), equation (2.14) can be rewritten as

$$(1-\alpha) F[n_{x_0}(g)] \frac{\partial M(g)}{\partial g} = C'(g). \tag{2.16}$$

This establishes the first expression in Corollary 2.2.1. Let $B_g$ denote the LHS of (2.16), which is the marginal benefit of seawall height for both regions as a whole from the perspective of the central government. Using Corollary 2.2.2, one can show that $\frac{\partial B_g}{\partial g} < 0$, the marginal benefit is decreasing with seawall height.[12] Given $C'(0) = 0$, and $C''(g) > 0$, this ensures that the solution defined by (2.16) is a unique local maximum (given that the corner solution is excluded in this section and will be considered later in the simulation section). By again applying Corollary 2.2.2, one can show that $\frac{\partial B_g}{\partial x_0} > 0$, namely, as the length of at-risk land increases, the marginal benefit of seawall height increases.[13] Clearly, since the central government will build a seawall whose height is determined by (2.16), there will be less migration than in the baseline due to seawall protection. After examining the central government's problem, the next section will examine the local government's problem.

## 2.4 Local Government's Problem

One might posit that the local government knows local climate conditions better than a central government, and can thus adapt more efficiently. In this essay, however, I

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[12] $\frac{\partial B_g}{\partial g} = (1-\alpha) F'_{n_{x_0}} \frac{\partial n_{x_0}(g)}{\partial g} \frac{\partial M(g)}{\partial g} + (1-\alpha) F[n_{x_0}(g)] \frac{\partial M^2(g)}{\partial g^2} < 0.$

[13] $\frac{\partial B_g}{\partial x_0} = (1-\alpha) F'_{n_{x_0}} \frac{\partial n_{x_0}(g)}{\partial g} \frac{\partial M(g)}{\partial g} + (1-\alpha) F[n_{x_0}(g)] \frac{\partial M^2(g)}{\partial g \partial x_0} > 0.$

assume that the central government and the local governments of both regions possess the same information, and investigate whether the decentralized level of government can achieve the same outcome as the central government. In this section, I examine whether the two local governments have an incentive to build a seawall and what their choices of seawall height will be in terms of maximizing either net output in their own regions or maximizing the (uniform) wage rate. Note that although the local government of the inland region 2 is not able to build a seawall in the coastal region 1 directly, because it is beyond its jurisdiction, it can still "build a seawall" in the sense of funding seawall construction.

I assume that the local governments in both regions are aware of free migration and the influence of seawall height on the distribution of population under SLR risk, as captured by (2.11a) and (2.11b). Because the damage boundary might not coincide with the political boundary–it could be located in the coastal region 1 or in the inland region 2–its location might influence the local government's decisions regarding seawall height. I thus investigate the two possible locations separately in Sections 2.4.1 and 2.4.2, respectively. Finally in Section 2.4.3, I consider the case in which the local government only considers the welfare of workers and its objective is to maximize the wage rate instead of output. Throughout, I assume that the local government faces the same cost function for seawall construction as the central government, and that it finances the cost by imposing an output tax on period-0 total output $\frac{1}{2}Y$ in each region, so that landlords and workers bear the same percentage of tax burden. Obviously, the total cost $C(g)$ cannot exceed $\frac{1}{2}Y$, and I assume this constraint is not binding.

### 2.4.1 Damage Boundary Located in the Coastal Region

I first consider the case in which the damage boundary is located in the coastal region 1, i.e., $x_0 \in [0, L]$, which means the at-risk land lies only in the coastal region 1; the inland region 2 is completely risk-free. Also, the local government in each region maximizes net expected total output, which is expected total output for both periods in its own region less the construction cost of the seawall, which is financed by an output tax in its own region.

### The Coastal Region

Let $Y_1(g)$ be the expected output in region 1 given SLR risk in period 1. Recall that $[0, x_0)$ is the at-risk interval in region 1, therefore,

$$Y_1(g) = (L - x_0)F[n_{x_0}(g)] + \int_0^{x_0} F[n(x)]dx = F[n_{x_0}(g)][M(g) - L]. \tag{2.17}$$

Formally, the objective of the local government in region 1 is

$$\max_g Y_1(g) + \frac{Y}{2} - C(g) = F[n_{x_0}(g)][M(g) - L] + \frac{Y}{2} - C(g), \tag{2.18}$$

where $Y_1(g)$ is the expected total output of region 1 in period 1, and $\frac{Y}{2} - C(g)$ is the net total output in period 0. The first-order condition for (2.18) yields

$$F'_{n_{x_0}} \frac{\partial n_{x_0}(g)}{\partial g}[M(g) - L] + F[n_{x_0}(g)]\frac{\partial M(g)}{\partial g} = C'(g). \tag{2.19}$$

As in the central government's problem, the RHS is the marginal construction cost of the seawall. The LHS is the marginal benefit of seawall height for region 1 alone, which is $\frac{\partial Y_1(g)}{\partial g}$, the marginal increase of expected output in region 1. The second term on the LHS is positive as usual and is the same as that in (2.14). It captures the marginal increase of the effective length caused by a higher seawall. The first term on the LHS is still negative, given $M(g) > L > x_0$, and it reflects the migration effect in region 1. Because all land ($L$) in region 2 is risk-free in this case, $M(g) - L$ is the length of effective land in region 1. There is a marginal loss of potential opportunity of increasing output for risk-free locations from migration due to a higher seawall. Comparing the first term on the LHS of (2.19) with the corresponding term in (2.14), the absolute value of this term for region 1 in (2.19) is smaller. The opportunity loss for the local government of region 1 is smaller, because $2L - x_0 > L - x_0$, the local government faces a smaller length of risk-free land to attract migrants and raise output. Therefore, the opportunity loss from less migration induced by a higher seawall is smaller. By applying (2.15), (2.19) can be rewritten as

$$B_g + \frac{\alpha F[n_{x_0}(g)]L}{M(g)} \frac{\partial M(g)}{\partial g} = C'(g). \tag{2.20}$$

where, as before, $B_g$ is the LHS of (2.16), and captures the marginal benefit of seawall height from the perspective of the central government. Let $B_{1g}$ denote the LHS of (2.20), the marginal benefit of seawall height from the perspective of the local government of region 1. We can conclude that $B_{1g} > B_g$. Furthermore, by using Corollary 2.2.2, one can verify that $\frac{\partial B_{1g}}{\partial x_0} > 0$, namely, as the at-risk land increases, the marginal benefit of seawall height for region 1 increases.[14] However, one must keep in mind that this only applies to the situation where $x_0$ is located in region 1.

### The Inland Region

Now let us turn to the inland region 2 and examine whether the local government of region 2 has an incentive to build (finance) a seawall. The local government of region 2 also finances the seawall from an output tax in its own region. Let $Y_2(g)$ be the expected output in region 2 in period 1. Because the damage boundary is located in region 1, $Y_2(g) = F[n_{x_0}(g)]L$. Let $B_{2g}$ be the marginal benefit of seawall height for

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[14] $\frac{\partial B_{1g}}{\partial x_0} = \frac{\partial B_g}{\partial x_0} + \alpha L\Big\{ - \frac{(1+\alpha)F[n_{x_0}(g)]}{[M(g)]^2} \frac{\partial M(g)}{\partial x_0} \frac{\partial M(g)}{\partial g} + \frac{F[n_{x_0}(g)]}{M(g)} \frac{\partial M(g)}{\partial g \partial x_0} \Big\} > 0$, given $\frac{\partial M(g)}{\partial x_0} < 0$, $\frac{\partial M(g)}{\partial g} > 0$, and $\frac{\partial M^2(g)}{\partial g \partial x_0} > 0$.

region 2. Notice that

$$B_{2g} = \frac{\partial Y_2(g)}{\partial g} = F'_{n_{x0}} \frac{\partial n_{x_0}(g)}{\partial g} L = -\frac{\alpha F[n_{x_0}(g)] L}{M(g)} \frac{\partial M(g)}{\partial g}. \tag{2.21}$$

Clearly, $B_{2g} < 0$, which indicates that a higher seawall always results in a marginal loss for region 2. This is because region 2 is completely risk-free, and it will receive the most migration from region 1 when there is no seawall. Since more labor leads to more output, region 2 always benefits from immigration in terms of total output. Therefore, the local government of region 2 has no incentive to build a seawall under this situation. Notice that the second term of the LHS in (2.20) is equal to $-B_{2g}$, which means that unlike the central government, the local government of region 1 does not take into account the marginal loss of region 2. We conclude this section with the following proposition.

**Proposition 2.3** *When the damage boundary is located in the coastal region 1, the local government of region 1 will build a higher seawall than the central government, inducing less than social optimal migration to region 2, due to a larger marginal benefit of seawall height for region 1. The local government of region 2 has no incentive to build a seawall due to a negative marginal benefit. Specifically,*

$$B_g = B_{1g} + B_{2g}, \textit{ with } B_{2g} < 0, \;\; B_{1g} > B_g > 0;$$

*where $B_g$, $B_{1g}$, and $B_{2g}$ are the marginal benefit of seawall height from the perspective of the central government, the local government of region 1, and the local government of region 2 respectively.*

Therefore, in terms of maximizing total output, if it is the local governments that decide seawall height, the seawall will be higher than the socially optimal level while migration will be lower than the socially optimal level.

### 2.4.2 Damage Boundary Located in the Inland Region

Let us turn to the case in which the damage boundary crosses over the political boundary and is located in the inland region 2, i.e., $x_0 \in (L, 2L]$. Some locations in region 2 are now at risk. The local government of each region still maximizes net expected total output in its own region. I examine whether the local government of region 2 has an incentive to build a seawall in this case and how seawall height decisions made by local governments differ from that by the central government.

Because both regions are exposed to the risk of damage, I break down the effective length to facilitate analysis. The total effective length $M(g)$ can be rewritten as

$$\begin{aligned} M(g) &= m_1(g) + m_2(g) \\ &= \int_0^L [1-\theta(x)k(g)]^{\frac{1}{1-\alpha}}dx + \int_L^{x_0} [1-\theta(x)k(g)]^{\frac{1}{1-\alpha}}dx + (2L - x_0). \end{aligned} \tag{2.22}$$

Let $m_1(g)$ denote the effective length of region 1, which is the first term in (2.22). Let $m_2(g)$ denote the effective length of region 2, which is the sum of the second and third terms in (2.22). It is clear that all land in region 1 is at risk, while region 2 still has some risk-free land if $x_0 < 2L$. The following lemma summarizes the relationship between the effective length of region 1 and that of region 2.

**Lemma 2.4** *When the damage boundary $x_0$ is located in the inland region 2, then*

$$M(g) = m_1(g) + m_2(g), \textit{ with } m_2(g) > m_1(g) > 0;$$

$$\frac{\partial m_1(g)}{\partial g} > 0, \frac{\partial m_2(g)}{\partial g} > 0, \textit{ and } \frac{\partial m_1(g)}{\partial g} \gtreqless \frac{\partial m_2(g)}{\partial g}.$$

Obviously, the effective length of region 2 is longer than that of region 1 even when $x_0 = 2L$, because the function $[1-\theta(x)k(g)]^{\frac{1}{1-\alpha}}$ is increasing in $x$. Also, the derivative of effective length with respect to seawall height for each region is positive.[15] However, the relationship between these two derivatives for the two regions is ambiguous.[16]

Using the effective length of each region, the expected total output for period 1 of each region can be written as

$$Y_1(g) = \int_0^L F[n(x)]dx = F[n_{x_0}(g)]m_1(g); \tag{2.23a}$$

$$Y_2(g) = \int_L^{x_0} F[n(x)]dx + F[n_{x_0}(g)](2L - x_0) = F[n_{x_0}(g)]m_2(g). \tag{2.23b}$$

Therefore, the marginal benefits of seawall height for region 1 and region 2 are

$$B_{1g} = \frac{\partial Y_1(g)}{\partial g} = F'_{n_{x_0}} \frac{\partial n_{x_0}(g)}{\partial g} m_1(g) + F[n_{x_0}(g)] \frac{\partial m_1(g)}{\partial g}; \tag{2.24a}$$

$$B_{2g} = \frac{\partial Y_2(g)}{\partial g} = F'_{n_{x_0}} \frac{\partial n_{x_0}(g)}{\partial g} m_2(g) + F[n_{x_0}(g)] \frac{\partial m_2(g)}{\partial g}. \tag{2.24b}$$

Expressions (2.24a) and (2.24b) have the same economic interpretation as the LHS of (2.14), except that here the effective length is specific to each region, i.e., $m_1(g)$ in (2.24a), and $m_2(g)$ in (2.24b), rather than the total effective length $M(g)$ in (2.14).

To facilitate the analysis, I define the elasticity that measures the percentage change of effective length caused by a one percent change of seawall height.

**Definition 2.2** *Let $\eta_1, \eta_2$, and $\eta$ be the seawall height elasticity of effective length for region 1, region 2, and both regions respectively. Specifically, we have*

$$\eta_1 = \frac{\partial m_1(g)}{\partial g} \frac{g}{m_1(g)}, \ \eta_2 = \frac{\partial m_2(g)}{\partial g} \frac{g}{m_2(g)}, \ \textit{and } \eta = \frac{\partial M(g)}{\partial g} \frac{g}{M(g)}.$$

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[15] $\frac{\partial m_1(g)}{\partial g} = \frac{-k'(g)}{1-\alpha} \int_0^L [1-\theta(x)k(g)]^{\frac{\alpha}{1-\alpha}} \theta(x)dx > 0$; $\frac{\partial m_2(g)}{\partial g} = \frac{-k'(g)}{1-\alpha} \int_L^{x_0} [1-\theta(x)k(g)]^{\frac{\alpha}{1-\alpha}} \theta(x)dx > 0$.

[16] This is partly because the function $[1-\theta(x)k(g)]^{\frac{\alpha}{1-\alpha}}\theta(x)$ is not monotonically decreasing. More details are provided in Appendix A.2.

*Furthermore, define the elasticity ratio of each region relative to both regions:*

$$\rho_1 = \frac{\eta_1}{\eta} = \frac{\dfrac{\partial m_1(g)}{\partial g}/m_1(g)}{\dfrac{\partial M(g)}{\partial g}/M(g)}, \text{ and } \rho_2 = \frac{\eta_2}{\eta} = \frac{\dfrac{\partial m_2(g)}{\partial g}/m_2(g)}{\dfrac{\partial M(g)}{\partial g}/M(g)}.$$

Applying the definitions above, (2.24a) and (2.24b) can be rewritten as

$$B_{1g} = F[n_{x_0}(g)](1 - \frac{\alpha}{\rho_1})\frac{\partial m_1(g)}{\partial g}; \tag{2.25a}$$

$$B_{2g} = F[n_{x_0}(g)](1 - \frac{\alpha}{\rho_2})\frac{\partial m_2(g)}{\partial g}. \tag{2.25b}$$

Using Lemma 2.4, it is clear that $B_g = B_{1g} + B_{2g}$, but due to the ambiguous relationship between $\frac{\partial m_1(g)}{\partial g}$ and $\frac{\partial m_2(g)}{\partial g}$, the relationship between $B_{1g}$ and $B_{2g}$ is ambiguous. However, a simulation conducted in Section 2.5 provides some insights into their relative magnitudes. Specifically, if $x_0$ is not very large or $\alpha$ is relatively large, then $B_{1g} > B_g > 0$, and $B_{2g} < 0$ is likely to hold. Only when $x_0$ is very large and $\alpha$ is small, is $0 < B_{2g} < B_{1g} < B_g$ likely to hold.[17] In other words, in most cases, the relationships among $B_g$, $B_{1g}$, and $B_{2g}$ are consistent with those showed in Proposition 2.3, and only under rare circumstances are they different. Intuitively, if $x_0$ is large, the length of at-risk land is large, which increases the marginal benefit of seawall height for region 2. Moreover, if $\alpha$ is small, the contribution of labor to output is small, so that the increase of output due to migration is small, which also increases the marginal benefit of seawall height for region 2. The following proposition summarizes these results.

**Proposition 2.5** *When the damage boundary is located in the inland region 2, the local government of region 2 has either no incentive to build a seawall or a smaller incentive than the local government of region 1, inducing it to free ride. The local*

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[17] Please refer to Appendix A.2 for numerical results and explanations.

*government of region 1 will build a seawall that is in general higher than the central government's choice, but could be lower under some circumstances.*

The figures below, based on the simulation in Section 2.5, illustrate these two possibilities.[18] Figure 2.4 shows that when $x_0$ is large, and $\alpha$ is relatively large, the marginal benefit of seawall height for region 2 is negative, $B_{2g} < 0$. The local government of region 2 thus has no incentive to build a seawall and the local government of region 1 chooses a higher seawall than the central government.

Figure 2.5 shows that when $x_0$ is large but $\alpha$ is relatively small, the marginal benefit of seawall height for region 2 is positive, $B_{2g} > 0$. The local government of region 2 has an incentive to build a seawall, but it is likely to free ride, because the local government of region 1 will choose a higher seawall, but one that is lower than the central government's choice.

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[18] Please refer to Section 2.5 and the Appendix A.2 for specification details.

Figure 2.4: Marginal Benefit and Marginal Cost When $x_0$ Is Large and $\alpha$ Is Large

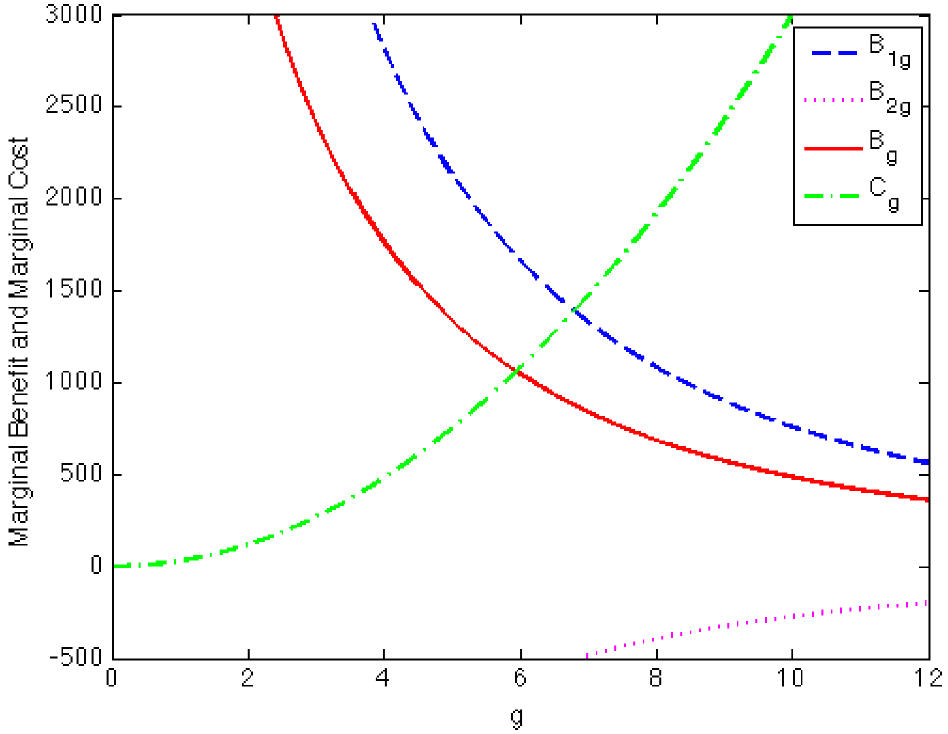
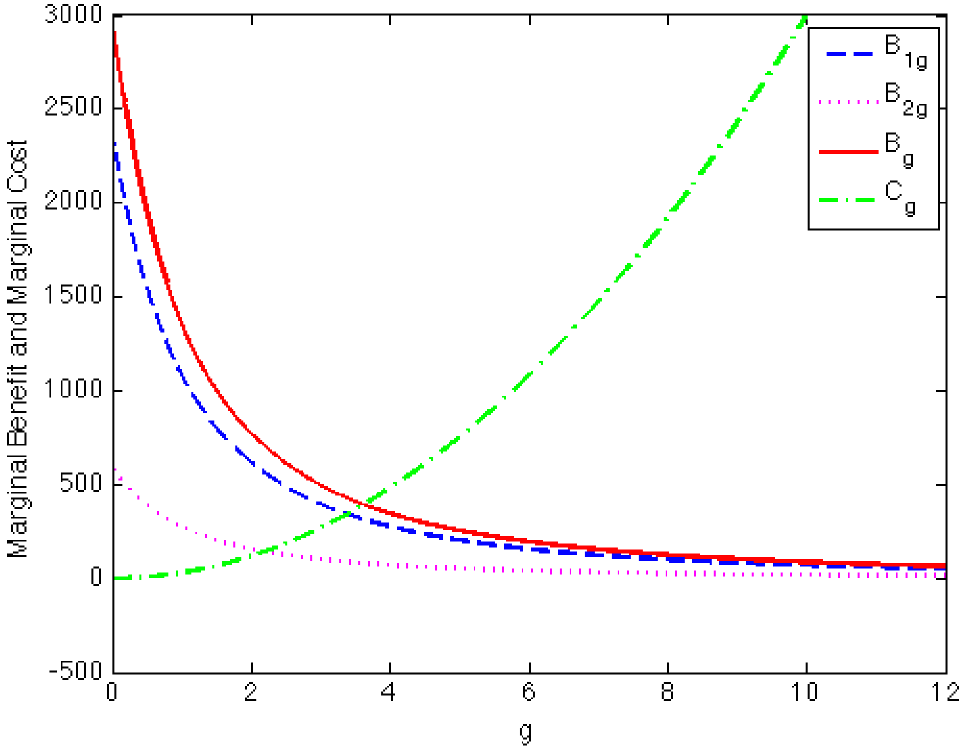


Figure 2.5: Marginal Benefit and Marginal Cost When $x_0$ Is Large and $\alpha$ Is Small



### 2.4.3 Wage Rate Objective

In this section, I consider an alternative objective for the local governments. Each local government might only care about the welfare of local residents, who are workers in the model. Therefore, in this section I assume that the local government maximizes the after-tax wage rate for both periods, which in this model is equivalent to maximizing output per capita. Since more labor results in a lower marginal product of labor and hence a lower wage rate, migration is now undesirable for the receiving region. One might think that the local government of region 2 will choose to build a higher seawall to prevent migration, while the local government of region 1 will choose to build a lower seawall to encourage emigration. However, the following proposition shows this is not the case.

**Proposition 2.6** *When the objective of the local government is to maximize the after-tax wage rate, the two local governments will choose the same seawall height and thus it is plausible that the two local governments will cooperate and share the cost of the seawall. However, the seawall height chosen by the local governments is lower than that chosen by the central government.*

The fundamental reason for this result is the identical wage rate across locations in equilibrium. The local governments of the two regions have the same objective function, and the location of the damage boundary is irrelevant. Because in equilibrium, locations are identical in terms of the wage rate, therefore, the location of the damage boundary does not influence the objective function of the local governments. The purpose of building a seawall for the local government of region 2 is to deter migrants, while for the local government of region 1 it is to reduce the damage rate, because damages result in a lower marginal product of labor. Free migration balances out these two factors and ensures an equal wage rate. Therefore, the two local governments have the same maximization problem:

$$\max_{g} \left[1 - \frac{C(g)}{Y/2}\right] f'(n) + F'[n_{x_0}(g)]. \tag{2.26}$$

The first term is the after-tax wage rate in period 0, where $\frac{C(g)}{Y/2}$ is the output tax rate. The second term is the expected wage rate in period 1. The first-order condition for (2.26) is

$$\frac{1}{2}(1-\alpha)F[n_{x_0}(g)]\frac{\partial M(g)}{\partial g} = C'(g). \tag{2.27}$$

Let $B_g^w$ denote the LHS of (2.27); it is the marginal benefit of seawall height. Comparing the LHS of (2.27) with the LHS of (2.16), it is clear that $B_g^w$ is only equal to half of $B_g$, which indicates that the local government will choose to build a lower seawall.

Finally, the following proposition summarizes the findings of Sections 2.3 and 2.4.

**Proposition 2.7** *Compared to the optimal seawall height chosen by a central government, when the local government maximizes net total output in its own region, the seawall is too high in most cases, whereas when the local government maximizes the after-tax wage rate, the seawall is too low. Thus, in general, the seawall decision made by the local government does not match the decision made by the central government.*[19]

Figure 2.6, again based on the simulation in Section 2.5, illustrates this conclusion. Now we know that the socially optimal interior solution cannot be achieved when the local governments decide seawall height. However, without specification of the cost function of the seawall, we are not able to know whether the corner solution, no seawall in the baseline, can be more preferable than the interior solutions. I conduct a simulation in the next section to investigate this issue.

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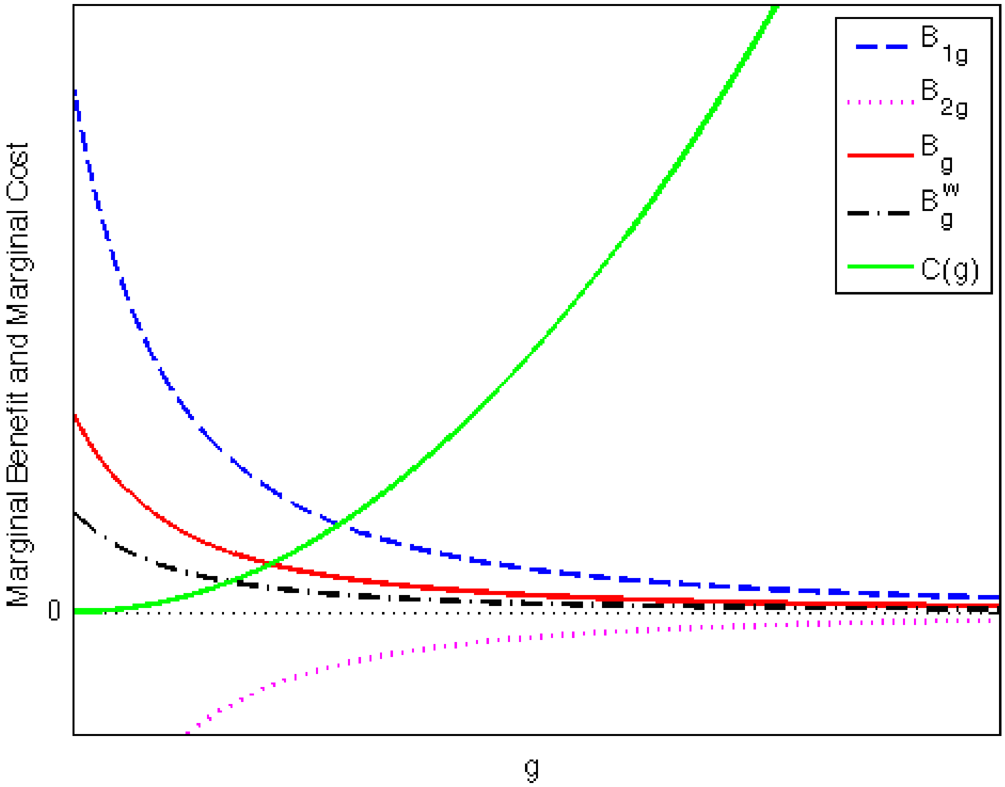
[19] This excludes the rare circumstances that $x_0$ is very large and $\alpha$ is small.

Figure 2.6: Marginal Benefit and Marginal Cost



## 2.5 Simulation Results

In this section, I use a simulation to examine different scenarios in order to illustrate the results obtained in previous sections, and to incorporate the corner solution in the baseline so that we can characterize optimal adaptation for each scenario.

### 2.5.1 Parameters and Scenarios

First, I describe the specific functional forms and parameter values I use for the simulation. For the Cobb-Douglas production function $f(N, L) = AN^{\alpha}L^{1-\alpha}$, $A = 100$, and $\alpha = 0.75$, which is the empirically estimated exponent of labor (Cobb and Douglas, 1928; Felipe and Adams, 2005). I set $N = 1000$ and $L = 50$ as the initial state. Next, the cost function for seawall construction is $C(g) = \delta Y + cg^3$, where $\delta \in (0, 1)$, is the fraction of total output that comprises the fixed cost of building a seawall. Because the adaptation cost relative to GDP is estimated to range from 0.05% to 0.5% (Stern et al., 2006), and for some low-lying countries or regions, could reach about 1% of GPD (Nicholls and Tol, 2006), I set $\delta = 1\%$ and 0.1% respectively for simulating high-cost and low-cost scenarios. Moreover, I set $c = 10$, therefore, the marginal cost of seawall construction is $C'(g) = 30g^2$.

For simplicity, suppose the probability of damage is a linear function, $\theta(x) = (x_0 - x)\theta_0 = \overline{\theta} - x\theta_0$, where $\theta_0 \in (0, \frac{1}{2L})$, or $(0, 0.01)$, given $L = 50$, and $\overline{\theta} = x_0\theta_0$, is the damage probability at the shoreline. I set $\theta_0 = 0.008$ and 0.002 respectively for high and low damage probability scenarios. Finally, the damage rate as a function of seawall height takes the form $k(g) = \frac{1}{0.5g+1}$. Obviously, this function satisfies the properties $k(0) = 1, k(g) > 0, k'(g) < 0$, and $k''(g) > 0$.

I simulate eight scenarios, based on the damage boundary $x_0$ (located in region 1 or region 2), the fixed cost coefficient $\delta$ (high or low), and the damage probability parameter $\overline{\theta}$ (high or low). I set $x_0 = 25$ if the damage boundary is located in the coastal region 1, and set $x_0 = 75$ if the damage boundary is located in the coastal region 2. Table 2.1 shows the parameter values for each scenario.

Table 2.1: Parameter Values for Eight Scenarios

| Scenario | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $\delta$ | 1% | 1% | 0.1% | 0.1% | 1% | 1% | 0.1% | 0.1% |
| $\overline{\theta}$ | 0.2 | 0.05 | 0.2 | 0.05 | 0.6 | 0.15 | 0.6 | 0.15 |
| $x_0$ | 25 | 25 | 25 | 25 | 75 | 75 | 75 | 75 |

For each scenario, I calculate seawall height, seawall cost, output, wage rate and loss rate for the corner solution (baseline), the central government's interior solution, the local government of region 1's interior solution based on output maximization, and the two local governments' interior solution based on wage rate maximization. The next section presents the simulation results.

### 2.5.2 Results

Table 2.2 shows two scenarios which assume $\delta = 1\%$, and $x_0 = 25$. The net total output is the total output for both regions for both periods less the seawall costs. "Net Output in R1" is net total output for both periods of region 1. "Wage Rate (P1)" is the expected equilibrium wage of period 1, and the after-tax wage rate is the wage rate after paying tax for financing the seawall in period 0. I do not calculate the average wage of both periods for the case of the local government of region 1 maximizing output, because only workers in region 1 pay tax in this case.

The central government chooses the higher level of net total output between its interior solution in the second column (Central Government) and the corner solution in the first column (Baseline). For the output objective, the local government in region 1 maximizes net output by selecting the larger of the interior solution with a sea wall in the third column [Local (Output)] and the corner solution with $g = 0$ (Baseline). For the wage rate objective, both local governments choose the higher average wage between the interior solution in the fourth column [Local (Wage)] and the corner solution. Finally, the loss rate is computed as the (absolute) loss of output plus the cost of seawall divided by total output in period 0 without SLR risk. The seawall height associated with the lowest loss rate for each scenario is the socially optimal choice.

From Table 2.2, we can see that in Scenario 1, the baseline yields a higher net total output level than the central government's interior solution, and a higher average wage rate than the two local governments' interior solution. This indicates that the central government and two local governments will choose the corner solution of no seawall protection. However, the baseline yields a lower net total output level for region 1 than the local government of region 1's interior solution. Therefore, the local government of region 1 will choose the interior solution to build a seawall with height of 3.46. For Scenario 2, the corner solution is preferred to all three interior

Table 2.2: Damage Boundary in Region 1 and High Fixed Cost

| | Scenario 1 | | | |
|---|---|---|---|---|
| $\overline{\theta} = 0.2$ | Baseline (1) | Central Govt. (2) | Local (Output) (3) | Local (Wage) (4) |
| Seawall Height | 0 | 2.56 | 3.46 | 2.03 |
| Seawall Cost | 0 | 1113.01 | 1358.69 | 1028.92 |
| Wage Rate (P1) | 34.7155 | 35.1034 | 35.1594 | 35.0596 |
| After-tax Wage | 35.4653 | 35.0479 | | 35.0795 |
| Net Total Output | 187149.16 | 187070.2 | 186973.74 | 187037.48 |
| Net Output in R1 | 89444.08 | 91018.32 | **91154.34** | 90802.59 |
| Average Wage | 35.0904 | 35.0757 | | 35.0695 |
| Loss Rate | **2.11%** | 2.20% | 2.30% | 2.23% |
| | Scenario 2 | | | |
| $\overline{\theta} = 0.05$ | Baseline (1) | Central Govt. (2) | Local (Output) (3) | Local (Wage) (4) |
| Seawall Height | 0 | 1.67 | 2.28 | 1.31 |
| Seawall Cost | 0 | 992.46 | 1064.55 | 968.15 |
| Wage Rate (P1) | 35.2526 | 35.3472 | 35.3637 | 35.3346 |
| After-tax Wage | 35.4653 | 35.0931 | | 35.1023 |
| Net Total Output | 188580.16 | 187840.97 | 187812.89 | 187831.58 |
| Net Output in R1 | **93145.08** | 92791.33 | 92830.07 | 92730.65 |
| Average Wage | 35.359 | 35.2202 | | 35.2184 |
| Loss Rate | **0.60%** | 1.38% | 1.41% | 1.39% |

solutions. When the corner solution of no seawall is preferred to interior solutions, it implies that it is not worth incurring the high fixed cost of building a seawall, given the length of at-risk land is relatively small. Figure A.6 in the Appendix A.3 depicts this situation.

Table 2.3 shows the results of Scenarios 7 and 8, in which the damage boundary is located in region 2 ($x_0 = 75$) and the fixed cost of seawall is low ($\delta = 0.1\%$). One can verify that the interior solutions are more preferred than the corner solutions. The

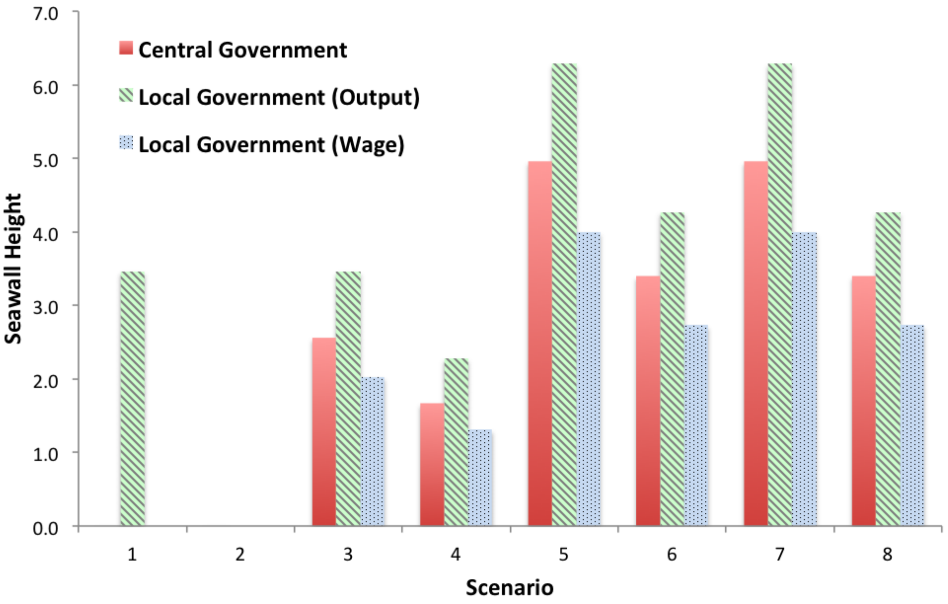
Table 2.3: Damage Boundary in Region 2 and Low Fixed Cost

| | | Scenario 7 | | |
|---|---|---|---|---|
| $\overline{\theta} = 0.6$ | Baseline (1) | Central Govt. (2) | Local (Output) (3) | Local (Wage) (4) |
| Seawall Height | 0 | 4.96 | 6.29 | 4 |
| Seawall Cost | 0 | 1313.13 | 2587.42 | 734.17 |
| Wage Rate (P1) | 29.7844 | 33.3529 | 33.6678 | 33.0504 |
| After-tax Wage | 35.4653 | 34.9729 | | 35.19 |
| Net Total Output | 173999.16 | 182201.98 | 181767.47 | 181974.49 |
| Net Output in R1 | 59958.08 | 81147.65 | 81747.99 | 79903.79 |
| Average Wage | 32.6249 | 34.1629 | | 34.1202 |
| Loss Rate | 16.02% | **7.34%** | 7.80% | 7.59% |
| | | Scenario 8 | | |
| $\overline{\theta} = 0.15$ | Baseline (1) | Central Govt. (2) | Local (Output) (3) | Local (Wage) (4) |
| Seawall Height | 0 | 3.4 | 4.27 | 2.73 |
| Seawall Cost | 0 | 487.51 | 872.89 | 298.59 |
| Wage Rate (P1) | 33.6068 | 34.7447 | 34.8424 | 34.646 |
| After-tax Wage | 35.4653 | 35.2825 | | 35.3533 |
| Net Total Output | 184192.16 | 186739.09 | 186614.44 | 186665.03 |
| Net Output in R1 | 83974.08 | 90075.38 | 90241.48 | 89705.76 |
| Average Wage | 34.5361 | 35.0136 | | 34.9997 |
| Loss Rate | 5.24% | **2.55%** | 2.68% | 2.63% |

baseline of no seawall yields a significantly higher loss rate than all other cases. Also, the central government's interior solution of seawall height yields the lowest loss rate. Tables A.1 and A.2 in the Appendix A.3 show the results of other four scenarios, which exhibit a pattern similar to those shown in Scenarios 7 and 8.

Figure 2.7 shows under all eight scenarios, the optimal seawall height chosen by the central government, by the local government of region 1 (maximizing the output), and by two local governments (maximizing wage rate). It is clear that both central and local governments choose to build a seawall in Scenarios 3 to 8. Seawall height chosen by the central government is always in the middle. The local government of region 1 always chooses too high a seawall when maximizing total output in its own region, and the two local governments always choose too low a seawall when maximizing the wage rate. These observations confirm the result stated in Proposition 2.7. For Scenario 2, both the central and the local governments choose not to build a seawall. For Scenario 1, the central government and two local governments maximizing wage rate choose not to build a seawall. However, the local government of region 1 maximizing net output in region 1 chooses to build a seawall. The corresponding migration rate for each scenario is shown in Figure 2.8.

Figure 2.7: Seawall Height Comparison



Furthermore, Figure 2.9 shows the loss rate difference between the outcomes of local and central governments. Only when both central and local governments choose the corner solution of no seawall protection (Scenario 2), do they yield the same social loss rate. In general, the local governments' choices yield a higher loss rate than the central government's choice. Except for Scenario 2, a higher seawall chosen by the local government of region 1 when maximizing total output in region 1 yields

Figure 2.8: Migration Rate Comparison

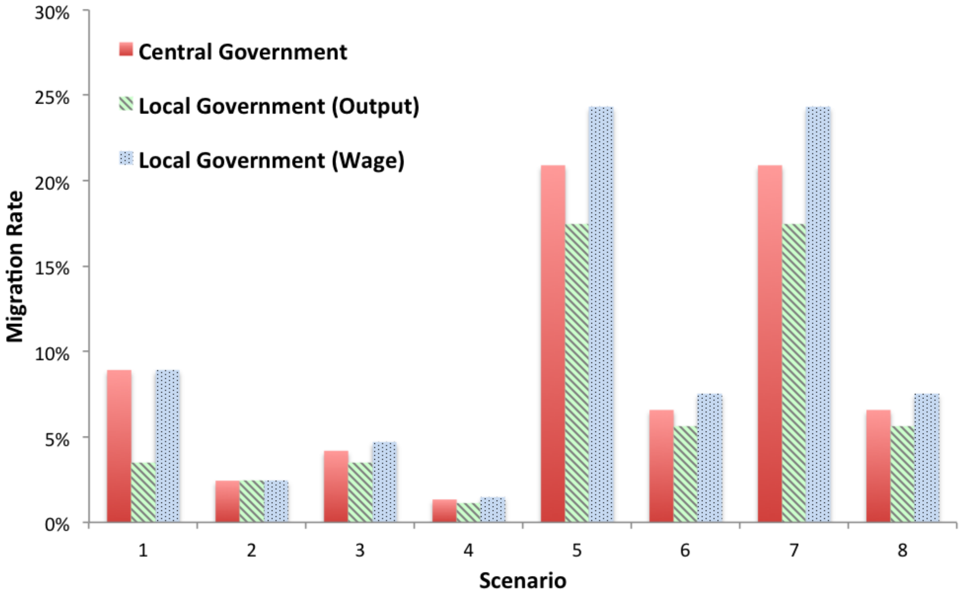
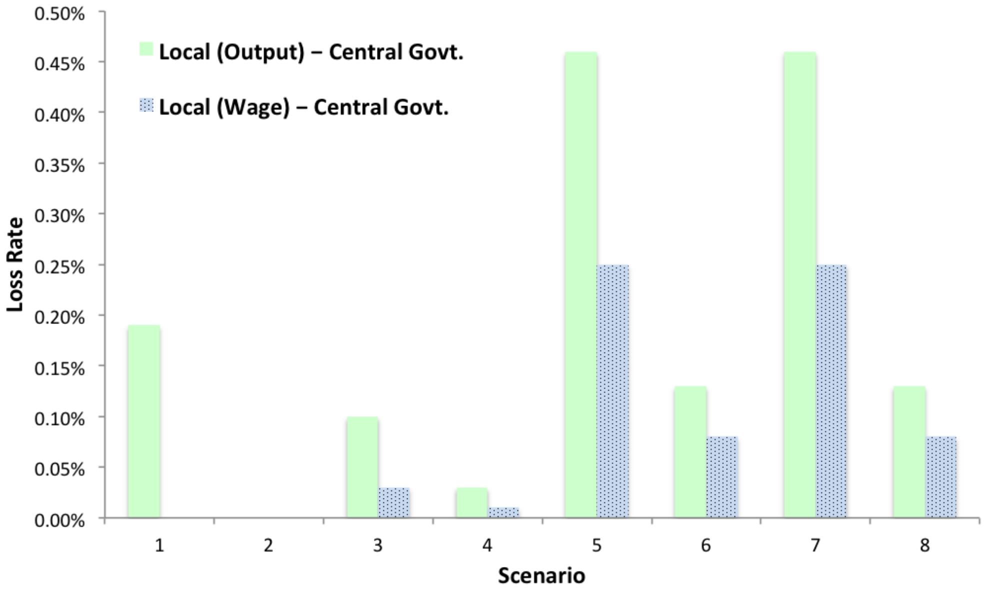


Figure 2.9: Loss Rate Difference



a higher loss rate than a lower seawall chosen by both local governments maximizing wage rate. This implies that in these scenarios, over protection (less migration) makes society worse off than under protection (more migration). Finally, Table 2.4 presents the optimal mix outcomes of central government adaptation (seawall height) and individual adaptation (migration rate) for all eight scenarios.

Table 2.4: Optimal Adaptation Outcomes

| Scenario | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| $\delta$ | 1% | 1% | 0.1% | 0.1% | 1% | 1% | 0.1% | 0.1% |
| $\overline{\theta}$ | 0.2 | 0.05 | 0.2 | 0.05 | 0.6 | 0.15 | 0.6 | 0.15 |
| $x_0$ | 25 | 25 | 25 | 25 | 75 | 75 | 75 | 75 |
| Population | | | | | | | | |
| Region 1 | 911 | 976 | 958 | 987 | 791 | 934 | 791 | 934 |
| Region 2 | 1089 | 1024 | 1042 | 1013 | 1209 | 1066 | 1209 | 1066 |
| Seawall Height | 0 | 0 | 2.56 | 1.67 | 4.96 | 3.4 | 4.96 | 3.4 |
| Migration Rate | 8.9% | 2.4% | 4.2% | 1.3% | 20.9% | 6.6% | 20.9% | 6.6% |
| Loss Rate | -2.11% | -0.6% | -1.3% | -0.48% | -8.24% | -3.45% | -7.34% | -2.55% |

## 2.6 An Extension

In this section, I examine an extension of the model. The structure of the model presented in previous sections implies that more labor always results in more output, thus migration always benefits the receiving region in terms of output level. One possible extension is to introduce a negative effect on output caused by more labor. In reality, migration creates congestion on public goods and services for the receiving region, which can even cause social conflicts. Therefore, I assume there is a congestion cost, which is increasing with labor, and examine how the previous results are altered.

For simplicity, I assume a linear congestion cost function $H(n) = \pi n$, where $\pi > 0$.[20] Net output for each location is $F[n(x)] - \pi n$. I assume that workers and landlords share this cost.[21] Specifically, total wages are $\alpha\{F[n(x)] - \pi n\}$, and total land rents are $(1-\alpha)\{F[n(x)] - \pi n\}$. Since net output must be non-negative, there

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[20] While congestion costs are more likely to be nonlinear in reality, the linear specification here is able to provide a simple benchmark to explore this extension.

[21] One can also assume that only landlords bear this cost, and workers are paid their marginal product of total output $F[n(x)]$. However, this imposes the constraint that the congestion costs cannot exceed land rents, which yields a maximum population capacity. One can prove that for $\alpha > 0.5$, which is usually the case in reality, more labor always results in higher net output within the population capacity. Therefore, the result will be the same as in the original model.

is a maximum population capacity $\overline{n}$, defined by $F(\overline{n}) = \pi\overline{n}$. Furthermore, I assume that the initial population $n$ satisfies $F'(n) \leq \pi$, which means each region either has optimal population or is over-populated. Net output reaches a maximum when $F'(n) = \pi$, and is decreasing when $F'(n) < \pi$. By assuming this, it is clear that migration causes declines of net output for the receiving region. Formally, together with the population capacity constraint, the initial population is assumed to satisfy $\alpha F(n) \leq \pi n < F(n)$, or $(\frac{\alpha A}{\pi})^{\frac{1}{1-\alpha}} \leq n < (\frac{A}{\pi})^{\frac{1}{1-\alpha}}$. Because the marginal congestion cost is constant, the expressions for population and total output distributions across locations are still captured by (2.5a), (2.5b), (2.9a), and (2.9b).

As before, the central government's problem is to maximize net total output of the two regions for both periods

$$\max_{g}\{F[n_{x_0}(g)] - \pi n_{x_0}(g)\}M(g) + [Y - 2N\pi - C(g)]. \tag{2.28}$$

The first-order condition for (2.28) yields

$$(1-\alpha)F[n_{x_0}(g)]\frac{\partial M(g)}{\partial g} = C'(g). \tag{2.29}$$

which is the same as (2.16). This implies that the congestion cost does not alter the central government's optimal choice. This is because marginal congestion cost is constant, so that the cost induced by more labor in some locations is perfectly offset by the benefit due to less labor in other locations. However, from the perspective of a local government, this is not true. The coastal region 1 always ends up with net emigration, while the inland region 2 always ends up with net immigration, hence, the cost and benefit are not completely offset within a region.

Suppose that the damage boundary is located in region 1. The objective of the local government of region 1 is

$$\max_g \{F[n_{x0}(g)] - \pi n_{x0}(g)\}[M(g) - L] + \Big[\frac{Y}{2} - N\pi - C(g)\Big]. \tag{2.30}$$

The first-order condition for (2.30) yields

$$B_g + \frac{\{\alpha F[n_{x0}(g)] - \pi n_{x0}(g)\}L}{M(g)} \frac{\partial M(g)}{\partial g} = C'(g). \tag{2.31}$$

For $n_{x0}(g) < \overline{n}$, $\alpha F[n_{x0}(g)] < \pi n_{x0}(g) < F[n_{x0}(g)]$, thus $0 < B_{1g} < B_g$. The second term on the LHS of (2.31) is negative, because a higher seawall prevents emigration, and thus eliminates the benefit of less labor resulting in lower congestion costs. Therefore, the local government of region 1 will build a lower seawall than the central government when there is a congestion cost. It is then easy to show that the marginal benefit for region 2 is

$$B_{2g} = -\frac{\{\alpha F[n_{x0}(g)] - \pi n_{x0}(g)\}L}{M(g)} \frac{\partial M(g)}{\partial g}, \tag{2.32}$$

which satisfies $0 < B_{2g} < B_g$. This implies that when there is a congestion cost, the local government of region 2 has an incentive to build a seawall to prevent migration, but the seawall height will be lower than the central government's choice. Note that the relationship between $B_{1g}$ and $B_{2g}$ is uncertain–it depends on $n_{x0}(g)$. We can show $B_{1g} > B_{2g}$, if

$$\frac{F[n_{x0}(g)]}{n_{x0}(g)} - \pi > \Big[\frac{n_{x0}(g)}{n} - 1\Big](\pi - F'_{n_{x0}}). \tag{2.33}$$

Notice that the LHS of (2.33) is decreasing in $n_{x0}(g)$, while the RHS of (2.33) is increasing in $n_{x0}(g)$. Therefore, we can conclude that when $g$ is small, so $n_{x0}(g)$ is large, $B_{1g} < B_{2g}$ is more likely to hold; when $g$ is large, so $n_{x0}(g)$ is small, $B_{1g} > B_{2g}$ is more likely to hold. Intuitively, when the seawall is low, the marginal effect of seawall height on migration is large, and thus region 2 has more incentive to raise seawall height to prevent migration and avoid additional congestion costs. However, one cannot analytically solve for the critical value of $g$ that yields $B_{1g} = B_{2g}$.

Figure 2.10: Marginal Benefit Comparisons under Congestion Costs

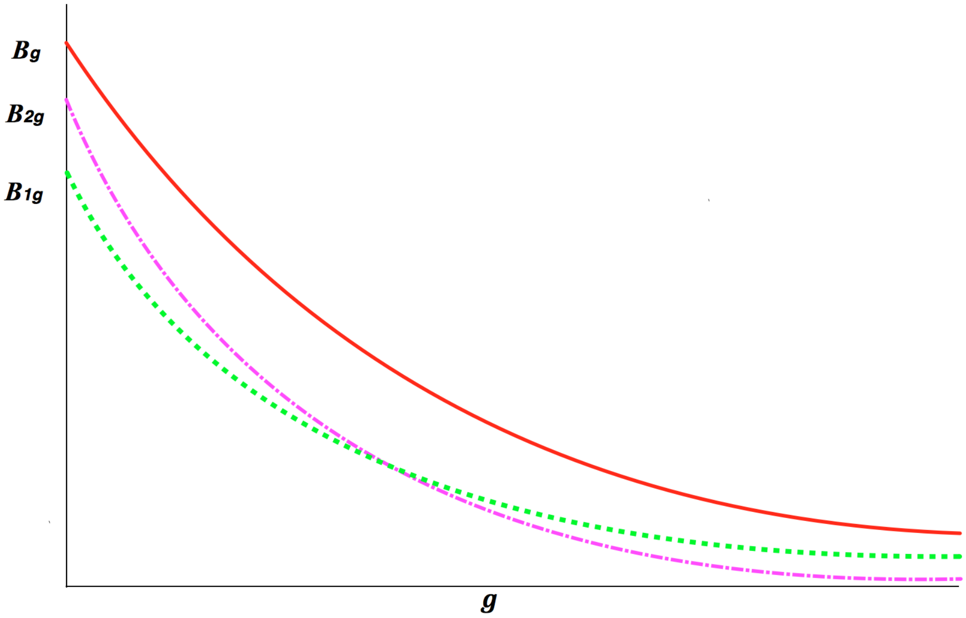

Figure 2.10 sketches the relationship among $B_{1g}, B_{2g}$ and $B_g$. Without a seawall cost functional form, one cannot determine which local government will choose a higher seawall and which local government will be the free rider. We can only say that if the marginal cost increases quickly with seawall height, it is more likely that the local government of region 1 will be the free rider. On the other hand, if the marginal cost increases slowly with seawall height, it is more likely that the local government of region 2 will be the free rider. However, it is clear that the local government will always choose a lower seawall than the central government. Keep in mind that this is under the assumption that the initial state is one of optimal or over population; hence, migration unambiguously reduces net output for migration-receiving region 2 and raises net output for migration-sending region 1.

## 2.7 Conclusions

Under the risk of SLR, migration and seawall protection are two major adaptation actions undertaken by individuals and governments, respectively. This essay considers the linkage between these two adaptation actions. It builds a model to theoretically investigate the optimal adaptation outcome, and examines the efficiency of decentralized government adaptation outcome. The model assumes that the probability of damage due to SLR risk decreases as the distance from the shoreline increases, and that equalization of wage rates across locations is the driving force for migration. I show that population distribution is altered by SLR risk. Specifically, the shoreline faces the highest damage probability, and thus has the smallest population. Population then increases at an increasing rate as one moves farther away from the shoreline, until the damage boundary is reached.

I examine government adaptation decisions made at both the centralized and decentralized levels. A seawall protects at-risk land and reduces migration, which implies that migration and protection are substitutes. By analyzing the impacts of migration and a seawall on both the coastal (migration-sending) region the inland (migration-receiving) region, I show that the incentives facing the two local governments and the central government for building a seawall differ. If the government's objective is to maximize output, then in most cases, the local government of the coastal region will choose to build a higher seawall than the central government. In contrast, the local government of the inland region has no incentive to build a seawall because the inland region always benefits from migration. Only when the length of at-risk land is very large, and the elasticity of output with respective to labor is low, does the local government of the coastal region build a lower seawall than the central government.

If the government's objective is to maximize the wage rate, the two local governments have the same incentive to build a seawall. Hence, it is plausible that they will cooperate and share the construction cost of a seawall. However, they will choose a lower seawall height than the central government.

Thus, in general, the seawall height determined by the local governments will be either too high or too low compared to the socially optimal level. The simulation results confirm this conclusion–the local governments' decisions in general yield higher loss rates, and show that the central and local government decisions can also differ as to when the corner solution of "no seawall" is optimal.

Finally, I extend the model by assuming a linear congestion cost caused by migration, which gives the local government of the inland region more incentive to build a seawall. Under certain circumstances, the local government of the coastal region now can be a free rider. The seawall height chosen by the local government in this case is lower than the central government's choice. However, this extension does not alter the conclusion that seawall height chosen by local governments is not the socially optimal one.

Therefore, I conclude that, with free migration, local provision of adaptation in general cannot achieve the socially optimal level, and that externalities caused by migration must be corrected for by a central government. This conclusion is different from the result presented in the public economics literature, namely, that with perfect household mobility, local public good provision is efficient. The fundamental reason for this difference is that the negative shock of sea-level rise is spatially asymmetric. The coastal region has a spatial disadvantage due to this shock, which triggers immigration to the inland region. The shock makes the inland region either better off by raising output or worse off by reducing the wage rate.

For the objective of maximizing output, the two regions are no longer in an equal position–the inland region does not need to do anything to enjoy benefits from the shock. Migration does not create an incentive for the local government in the inland region to provide adaptation, whereas it creates much incentive for the local government in the coastal region to over-provide adaptation to respond to the negative shock. For the objective of maximizing wage rate, the two regions have the same objective under migration equilibrium. However, the benefits of a seawall cannot be fully borne by each region, which results in under-provision of local adaptation. A higher seawall results in a lower damage rate and less migration at the same time. For the coastal region, when it builds a seawall to obtain the benefit from a lower damage rate, it loses some benefit from emigration. For the inland region, when it builds a seawall to obtain the benefit from less immigration, it also gives some benefit to the coastal region by reducing the damage rate. Therefore, the externality associated with migration cannot be resolved without other institutional arrangements.

# Chapter 3: Modeling Adaptation as a Sequential Game

## 3.1 Introduction

The first essay modifies a well-established result in public economics to the adaptation setting. It demonstrates the inefficiency of local adaptation provision under free migration, in contrast to efficient local public good provision under free migration. It should be noted that in the public economics literature, discussions of local public good provision implicitly assume that governments make decisions first, and that households respond to the governments' decisions via migration (i.e., vote with their feet). However, facing climate change, it is plausible that households make adaptation decisions before governments.[22] The second essay explores this scenario, and shows that the decision-making sequence matters.

There have been some studies examining the interplay between adaptation and mitigation, (e.g. Kane and Shogren, 2000; Klein et al., 2005; Tol, 2005). In particular, Buob and Stephan (2011) consider adaptation and mitigation as policy responses to global climate change within a game-theoretic framework. However, unlike mitigation policies that are usually made by governments, adaptation decisions are usually made by both governments and individuals (households or firms). There might also be interplay between these different forms of adaptation. Current adaptation research usually examines planned adaptation and autonomous adaptation separately. For example, Titus et al. (1991) and Fankhauser (1995) study planned adaptation, which often takes the form of public coastal protection programs, such as levees. Yohe et al. (1996) show that autonomous adaptation to coastal hazards may be reflected through market mechanisms, and study how the real estate market might react to long-term SLR. However, Malik and Smith (2012) propose that facing climate change threats, both households and governments will undertake adaptation, and they will

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[22] This might occur if adaptation costs for households are not high, or if the governments' policy-making procedures are rather long or uncertain.

each perceive and respond to the other's adaptation choices. This motivates the main innovation of this essay: I treat household adaptation and government adaptation as a sequential game to investigate their interaction.

The two main issues addressed are: social welfare comparisons based on: (1) first-mover status (government vs. households); (2) the level of government (local or central) making adaptation decisions. I show that households moving first could be better than the government moving first. Also, adaptation decisions made by a central government do not necessarily yield higher social welfare than those made by a local government.

As in the first essay, the model in this essay also adopts a two-region setting, a coastal region and an inland region, and assumes that each region has a local government. Households are able to migrate freely between the two regions. Recall that in the first essay the two local governments both participate in seawall decision-making, because SLR might cause damages in the inland region. Since the focus of this essay is to examine different decision-making sequences between households and the government, it is necessary to simplify the spatial pattern of damages by assuming that SLR causes damages in the coastal region alone. Therefore, the local government in the inland region in this essay is assumed to be passive about SLR, i.e., it does not participate in the seawall decision-making.

Unlike the model in the previous essay, the model in this essay is grounded in the public economics literature. The basic function of a local government is to provide a local public good in its local region. The decision on seawall height can be made by either the local government in the coastal region or a central government that governs both regions. Households' utility functions include both private and local public good consumption. Equalization of utility between the two regions is the driving force for household migration. By again assuming that the construction cost of a seawall is financed by a direct tax (an output tax), I examine the adaptation behaviors of both a local government in the coastal region and a central government for both regions.

Although the model setup resembles an agriculture economy, it incorporates the features of, and can be adapted to, an urban setting. Following Henderson (1982), I introduce a disamenity function in households' utility, namely, amenity in a region decreases with population size. Also, to ensure the existence of a stable two-region equilibrium (i.e., no region is depleted), both regions are assumed to be "over-populated",[23] which is consistent with the fact that many coastal cities possess high population densities.[24]

This essay first examines two extreme cases as the benchmarks. The first one is the baseline, in which the government does nothing about SLR, i.e., does not build a seawall, and household migration is the only form of adaptation. The second one is the social optimum, in which migration is not allowed, and there is a central planner who determines seawall height and allocates population between the two regions. Next, four cases for the interaction of household and government adaptation are examined. The two types of government are discussed separately, local and central government. The implications of alternative first movers (government vs. households) are explored for each government type. In particular, households moving first yields higher social welfare if and only if local government is responsible for making seawall decisions. However, the case where the central government makes the seawall decision and moves first yields the highest social welfare given free migration. In contrast, the case where the local government makes the seawall decision and moves first yields the lowest social welfare.

The essay is organized as follows. Section 3.2 describes the basic model setup, the equilibrium without SLR, and the effect of SLR shock. Section 3.3 examines the

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[23] I use "over-populated" to refer to a larger than optimal population size that yields the highest per capita utility in a region.

[24] According to Hanson et al. (2011), port cities are important concentrations for population with 13 out of the 20 most populated cities in the world in 2005 being port cities.

baseline and social optimum. Section 3.4 applies the concept of sequential games to investigate household and government adaptation behavior. Section 3.5 presents simulation results that compare social welfare across all cases.

## 3.2 The Model

### 3.2.1 General Features of the Economy

A hypothetical nation is assumed to consist of two regions, a coastal region (region 1) and an inland region (region 2), each with the same area of land $L$ available for production. The land in each region is collectively owned by all households in that region.[25] Households in the nation are alike. Households are able to move freely between the two regions in order to pursue higher utility. The total number of households in the nation is fixed and equal to $2n$. The number of households residing in region $i$ is $n_i$ $(i = 1, 2)$, and $n_1 + n_2 = 2n$. Assume $n_i > \underline{n}$, where $\underline{\text{n}}$ is a lower bound on population in each region. Household utility is defined by $U = \psi(n_i)u(z_i, P_i)$. $\psi(n_i)$ is a disamenity function, with $\psi'(n_i) < 0$ given $n_i > \underline{n}$, which indicates that increases in population cause decreases in amenity when population exceeds the lower bound.[26] $u(z_i, P_i)$ is a strictly quasi-concave utility function, where $z_i$ is the consumption of the private good, and $P_i$ denotes the consumption of the local public good provided in region $i$.

Each region has an identical aggregate production function $f(n_i)$, with $f'(n_i) > 0$ and $f''(n_i) < 0$. The fixed-land input $L$ from the production function is suppressed.[27]

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[25] This assumption follows Boadway and Flatters (1982), where they assume that all people are identical in tastes and land ownership. Also, the basic analysis of a local public good in Stiglitz and Atkinson (1980) assumes that all individuals have identical claims. They model a state in which land is publicly owned and all migrants have equal access to the rents (after paying for the public goods), see pp. 536.

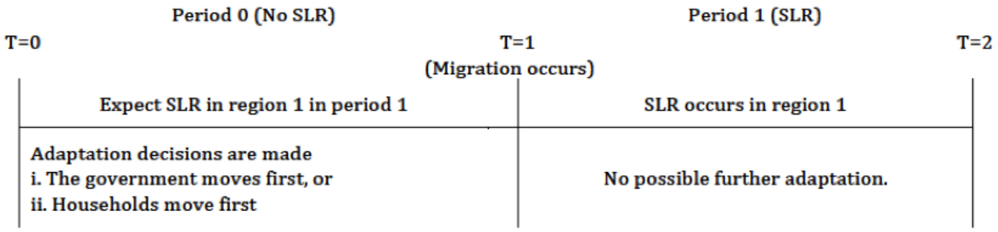
[26] That amenity decreases with population can be understood as that immigration causes a congestion cost. This is usually the case in an urban setting. An alternative specification is to assume the local public good is congestible, as in Boadway and Flatters (1982).

[27] See Boadway (1982)

Each household supplies 1 unit of labor given that household utility functions do not incorporate leisure. Output is available either as a private consumption good or a local public good. For simplicity, suppose that the local public good is "pure",[28] and the marginal rate of transformation of the private good to the public good is equal to one.

There are two periods in the model, period 0 and period 1. Figure 3.1 shows the timeline of the model. Time 0 (T=0) is the initial equilibrium state of the economy. At T=0, SLR is anticipated to occur in period 1 in region 1 alone. In other words, region 1 is the at-risk region, and region 2 is the risk-free region. Households in region 1 and the government are able to take adaptation actions during period 0. Households in region 1 decide whether to migrate to region 2, and the government chooses whether to build a seawall and determines its height. Adaptation decisions must be made in period 0, and they cannot be revised in period 1. Both households and the government are assumed to commit to their decisions.

Figure 3.1: Timeline of the Model



Migration does not occur at the moment that migration decisions are made.[29] In period 0, households in region 1 who decide to move only make commitments to move (for example, gain ownership of land in region 2 for period 1). They actually move at the end of period 0, or Time 1 (T=1), so they still contribute production in region 1 in

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[28] Pure public goods are goods that are perfectly non-rivalrous in consumption and are non-excludable.

[29] Households "moving" in this essay means that households "make migration decisions" rather than they actually migrating

period 0. The seawall decision can be made either by the local government in region 1 or by the central government of the nation, and these two types of decision-making process are examined separately. The local government of region 2 is assumed to do nothing regarding SLR.

Two situations regarding the sequence of decision-making between households and the government are considered, corresponding to the government being the first mover or second mover, respectively. In the first case, the government determines seawall height first, and households make migration decisions after observing the government's decision. In the alternative scenario, households make migration decisions first, and the government determines seawall height after observing the migration decisions.

### 3.2.2 Initial Equilibrium

Suppose the two regions are symmetric in the initial equilibrium. Each region has $n$ households and total output $\overline{Y} = f(n)$. The local government of each region chooses local public good expenditure to maximize per capita utility in its region. Because the focus of this essay is on adaptation decisions, for simplicity, I assume that the local governments use direct taxation and do not consider migration response when making local public good expenditure decisions. Boadway (1982) proves that under direct taxation of residents, local governments' spending decisions will be socially optimal whether the governments behave myopically about migration or take into account migration responses to their spending decisions. Therefore, using direct taxation, migration response to provision of local public good is irrelevant. In addition, facing SLR shock, it is reasonable to assume that households primarily respond to potential damages.[30] The objective of the local government is[31]

$$\max_P \psi(n)u\Big[\frac{f(n)-P}{n}, P\Big]. \tag{3.1}$$

The first-order condition for (3.1) yields the Samuelson condition for the socially optimal allocation of private and public goods

$$\frac{nu_P}{u_z} = 1. \tag{3.2}$$

Clearly, the solution of problem (3.1) is contingent upon the population size $n$. The relationship between maximized per capita utility and population size is defined by the *maximum value function* $V(n)$:

$$V(n) = \max_P \psi(n)u\Big[\frac{f(n)-P}{n}, P\Big]. \tag{3.3}$$

$V(n)$ gives maximum per capita utility attained under different population sizes. The envelope theorem implies that $V'(n) = \partial[\psi(n)u(z,P)]/\partial n$ (evaluated at the optimum). Let $(z^*, P^*)$ be the optimal allocation of the private and public good. Therefore,

$$V'(n) = \psi'(n)u(z^*, P^*) + \psi(n)u_P^*[f'(n) - z^*]. \tag{3.4}$$

The first term is the marginal decrease of amenity caused by additional labor. Recall that $\psi'(n) < 0$, which means amenity decreases with population size. The second term is net marginal contribution to production of additional labor, which is equal to the marginal product of labor less labor's marginal claim on resource (per capita

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[30] The analysis can be rather complicated if the local governments consider migration responses to both the seawall decision and other local public good expenditure decisions, which can be captured by a four-stage sequential game, and different combinations of the action orders will result in different outcomes.

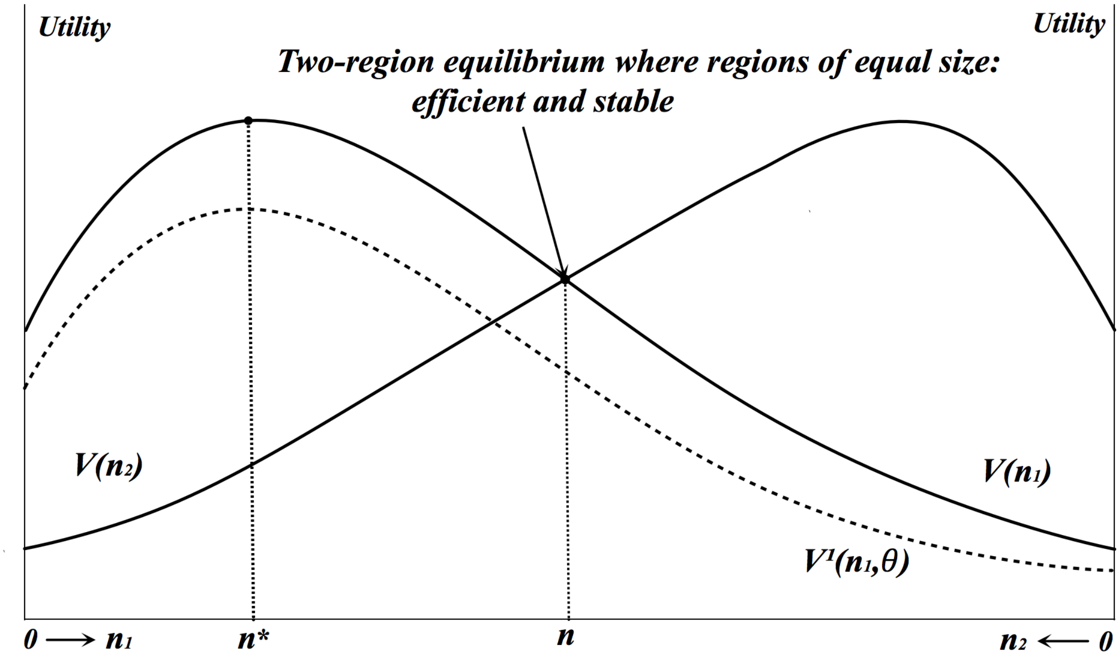
[31] Because the two regions are symmetric in all but SLR risk, subscript $i$ is dropped, and the problem of a local government is presented for a representative region.

private consumption). The optimal population size $n^*$ is determined by[32]

$$-\frac{\psi'(n^*)}{\psi(n^*)} = \frac{u_P^*[f'(n^*) - z]}{u(z^*, P^*)}. \tag{3.5}$$

The solid lines of Figure 3.2 depict the graph of $V(n)$ with two regions. $V(n)$ is single-peaked with $V''(n)$ being negative at first and eventually becoming positive. Stiglitz (1977) presents different cases for how per capita utility varies with population size, and shows that under-population causes instability of migration. Considering that optimal population is a rather special case, following Boadway (1982), I assume that both regions are over-populated initially, i.e. $n > n^*$. As shown in Figure 3.2, $n$ is a unique stable equilibrium.

Figure 3.2: Utility and Population Locus



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[32] The existence of a non-zero, finite optimal population $n^*$ requires that $f'(n^*) - z^* > 0$.

### 3.2.3 SLR shock

At T=0, SLR is anticipated to occur in period 1 in region 1 alone. Suppose without a seawall, flooding (and other associated hazards) caused by SLR will destroy a fraction ($\overline{\theta}$) of total output in region 1. In other words, $\overline{\theta} \in (0, 1)$, is the "baseline damage rate" that captures the damage rate caused by SLR when there is no seawall. $\overline{\theta}$ is common knowledge to households and the government (or a central planner). The government can protect region 1 by constructing a seawall. The function $\theta(g)$ captures how seawall height $g$ affects the damage rate, with $0 < \theta(g) < \overline{\theta}$, $\theta'(g) < 0$, and $\theta''(g) > 0$. Clearly, a higher seawall reduces the damage rate, but the marginal effect is diminishing so that the seawall cannot completely eliminate damages.[33] The next two sections examine how households and governments respond to this SLR shock, and how adaptation outcomes differ under different decision-making sequences and with different levels of government making adaptation decisions.

## 3.3 The Baseline and Social Optimum

Two extreme cases are examined in this section. One case is the baseline, in which the government does nothing about SLR (no seawall is built), and only households take adaptation actions–migrate freely to the risk-free region. The other one is the social optimum, in which the first-best solution is derived from the central planner's problem. The central planner is allowed to directly allocate households between the two regions. Households simply stay in the region they are assigned to and do not migrate. The central planner determines both seawall height and population allocation to achieve the social optimum.

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[33] A seawall can effectively prevent damages caused by flooding, however, the seawall cannot prevent damages caused by extreme weather conditions, such as storms.

### 3.3.1 The Baseline

Although the baseline can be seen as the "laissez-faire" outcome, it can also be viewed as the corner solution chosen by the government. The government might simply choose not to build a seawall if the cost of a seawall is higher than the benefit the seawall yields. The government is assumed to be aware of this corner solution, and compares it with the interior solutions derived in Section 3.4 to make the final choice.

Since SLR is anticipated to affect region 1 alone, absent migration, households perceive that per capita utility in region 2 in period 1 is equal to that in period 0. Let $V^2(n)$ be the maximum value function of region 2 in period 1 under SLR, therefore, $V^2(n) = V(n)$. However, absent migration, households perceive lower per capita utility in region 1 in period 1 under SLR than in period 0. Let $V^1(n, \overline{\theta})$ be the maximum value function of region 1 under SLR. Specifically,

$$V^1(n, \overline{\theta}) = \max_P \psi(n) u \Big[ \frac{f(n)(1 - \overline{\theta}) - P}{n}, P \Big]. \tag{3.6}$$

Now the maximum per capita utility is also contingent on the damage rate in addition to the population size. Notice that the first-order condition for (3.6) is identical to (3.2), which implies that the allocation between private and public good still follows the Samuelson rule. However, due to the damage to output, maximized per capita utility is lower than without SLR. Clearly, the higher the damage rate, the lower the per capita utility in region 1, because the partial derivative of $V^1(n, \overline{\theta})$ with respect to the baseline damage rate $\overline{\theta}$ is negative, or $V^1_{\overline{\theta}} = -\psi(n) u_P f(n) < 0$. The dashed line of Figure 3.2 represents the utility level in region 1 under SLR risk, which is lower than the original curve without SLR. Therefore, absent migration, households perceive lower per capita utility in region 1 than in region 2 for period 1, namely, $V^1(n, \overline{\theta}) < V^2(n)$. Hence, there is an incentive for households in region 1 to migrate to region 2.

Under the assumption that both regions are over-populated, per capita utility in region 2 falls with immigration, and per capita utility in region 1 increases with emigration. Eventually, population will be in equilibrium when

$$V^1(n_1, \overline{\theta}) = V^2(n_2), \tag{3.7}$$

where $n_1 < n$, is the number of households in region 1, and $n_2 = 2n - n_1 > n$, is the number of households in region 2 in period-1 equilibrium. To ensure that the new population equilibrium for period 1 is a unique and stable two-region equilibrium, I assume that both regions are still over-populated after migration. This assumption requires that the damage rate is not too high, so that the utility decrease in region 1 is moderate and region 1 will not lose all its population.[34] Comparing (3.6) with (3.3), it is clear that $V^1(n_1, \overline{\theta}) < V(n)$, because the expected output in period 1 is less than in period 0 due to the damage. Furthermore, from (3.7), we have $V^2(n_2) < V(n)$. In other words, per capita utility in region 2 in period 1 is lower than the initial level due to immigration, even though SLR does not cause damages to output in region 2.

### 3.3.2 Social Optimum

Suppose there is a central planner who chooses seawall height and allocates households between the two regions in order to maximize per capita utility in the nation for the two periods. Let $C(g)$ be the construction cost of a seawall, with $C(0) = C_0 > 0$, $C'(g) > 0$, $C'(0) = 0$ and $C''(g) > 0$. The central planner faces the budget constraint

$$2f(n) - 2nz - 2P - C(g) = 0. \tag{3.8}$$

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[34] Referring to Figure 3.2, if the damage rate is too high such that the decreasing portion of the dashed curve is completely below the utility curve of region 2, the equilibrium will not be stable and region 1 will lose all its population.

Equation (3.8) states that in period 0, the sum of total consumption of the private good in the regions ($2nz$), total consumption of the public good in the regions ($2P$), and the cost of seawall construction $C(g)$ is equal to total output in the nation, $2f(n)$. Rearranging (3.8) gives

$$2f(n)\Big[1-\frac{C(g)}{2f(n)}\Big]=2nz-2P.$$

Therefore, an output tax, $t=\frac{C(g)}{2f(n)}$, is imposed to finance the seawall. Let $V(n,t)$ be the maximum value function in period 0 when financing a seawall with an output tax $t$, then

$$V(n,t)=\max_{P}\psi(n)u\Big[\frac{f(n)(1-t)-P}{n},P\Big]. \tag{3.9}$$

Clearly, a higher tax rate results in a lower utility level, i.e., $V_t=-\psi(n)u_P f(n)<0$. Similar to the baseline, $V^1[n_1,\theta(g)]$ is the maximum value function of region 1 under SLR, but it now depends on seawall height:

$$V^1[n_1,\theta(g)]=\max_{P_1}\psi(n_1)u\Big\{\frac{f(n_1)[1-\theta(g)]-P_1}{n_1},P_1\Big\}. \tag{3.10}$$

Since there is no damage in region 2, the maximum value function of region 2 for period 1 is $V^2(n_2)$. The central planner's objective is

$$\max_{g,n_1}V\Big[n,\frac{C(g)}{2\overline{Y}}\Big]+\beta\Big\{\frac{n_1}{2n}V^1[n_1,\theta(g)]+\frac{n_2}{2n}V^2(n_2)\Big\}, \tag{3.11}$$

where $n_2=2n-n_1$, and $\beta$ is the discount factor. The first term is per capita utility in the nation in period 0. The second term is the (discounted) weighted per capita utility in the nation in period 1. The central planner chooses $g$ and $n_1$ to maximize the weighted sum of per capita utility in the nation in the two periods. The first-order conditions for (3.11) are

$$-\frac{V_t C'(g)}{2\overline{Y}} = \frac{n_1}{2n}\beta\theta'(g)V_\theta^1; \tag{3.12}$$

$$V^1[n_1,\theta(g)] + n_1 V_{n_1}^1 = V^2(n_2) + n_2 V_{n_2}^2. \tag{3.13}$$

Equation (3.12) determines seawall height. The LHS of (3.12) is the marginal social cost of seawall height in terms of forgone utility. The RHS of (3.12) is the marginal social benefit of seawall height, which is higher utility due to a lower damage rate. Notice that a seawall only benefits the households who live in region 1 in period 1 and does not affect per capita utility in region 2. Therefore, the marginal social benefit is equal to $\frac{n_1}{2n}$ multiplied by the (discounted) marginal per capita utility increase.

Equation (3.13) gives the condition for optimal population allocation. Allocating an addition household from region 2 to region 1 affects the utility levels in both regions. The LHS of (3.13) is the utility change in region 1, and the RHS of (3.13) is the utility change in region 2 due to the reallocation. The optimal allocation is achieved when the marginal utility changes in both regions are equal.

The following proposition gives the relationship of per capita utility between the two regions at the social optimum.

**Proposition 3.1** *In an over-populated nation, the first-best allocation of households between the two regions under SLR requires that per capita utility in the at-risk region is less than that in the risk-free region in period 1. That is,* $V^1[n_1,\theta(g)] < V^2(n_2)$.

Recall that migration is not allowed in the central planner's economy. Using a proof by contradiction, I demonstrate that the first-order condition (3.13) cannot hold if $V^1[n_1,\theta(g)] \geq V^2(n_2)$ . Rearranging equation (3.13) yields

$$V^1[n_1,\theta(g)] - V^2(n_2) = -n_1 V_{n_1}^1 - (-n_2 V_{n_2}^2). \tag{3.14}$$

Due to the damage $\theta(g)$ in region 1, it is clear that for $V^1[n_1, \theta(g)] \geq V^2(n_2)$ to hold, a necessary but not sufficient condition is $n_1 < n_2$. Given over-population and the concavity of the value function $V(\cdot)$, we have $-V^2_{n_2} > -V^1_{n_1} > 0$ when $n_1 < n_2$. Thus, the RHS of (3.14) is negative, whereas the LHS of (3.14) is positive. Therefore, $V^1[n_1, \theta(g)] \geq V^2(n_2)$ is incompatible with (3.13).

Proposition 3.1 states that the social optimum cannot be achieved if per capita utility in region 1 is equal to or greater than per capita utility in region 2. Suppose $(\tilde{n}_1, \tilde{n}_2)$ is the population allocation that equalizes per capita utility between the two regions for period 1. To achieve the first best, the central planner should allocate more households than $\tilde{n}_1$ to region 1 so that region 1 has lower per capita utility than region 2. Why should this outcome be preferable than equalization of utility between the two regions? Clearly, $\tilde{n}_1 < \tilde{n}_2$, and $-V^2_{\tilde{n}_2} > -V^1_{\tilde{n}_1} > 0$. Starting from the allocation $(\tilde{n}_1, \tilde{n}_2)$, when allocating an additional household from region 2 to region 1, the marginal per capital utility decrease in region 1 is less than the marginal per capital utility increase in region 2. Furthermore, the marginal total utility decrease in region 1 is $-V^1_{\tilde{n}_1}\tilde{n}_1$, and the marginal total utility increase in region 2 is $-V^2_{\tilde{n}_2}\tilde{n}_2$. Obviously, the marginal total utility increase in region 2 is greater than the marginal total utility decrease in region 1. Therefore, total utility for the nation increases in this reallocating process until the marginal total change of utility in both regions are equal, which will eventually occur as $n_2$ decreases and $n_1$ increases.

In other words, under the utility equalization allocation $(\tilde{n}_1, \tilde{n}_2)$, too many households are allocated to region 2 relative to the socially optimal level. Since region 2 has a larger population size, relocating some households from region 2 to region 1 raises utility for a majority of population, and thus raises total utility (or weighted per capita utility) in the nation. Therefore, the first-best population allocation requires more households to be allocated to region 1 for period 1 than the utility equalization allocation. This suggests that as long as the central planner does not have to equalize per capita utility between the two regions for some reason, in an over-populated economy, a large scale relocation of people from the at-risk region to the risk-free region in order to equalize utility is not socially preferred. The utility loss from over-congestion in the risk-free region might exceed that from damages in the at-risk region.

## 3.4 Household and Government Adaptation

After examining two extreme cases, in which only one of the agents (households or a central planner) takes adaptation actions, I now examine scenarios in which both agents are allowed to take adaptation actions. In addition, government adaptation decisions can be made at one of two levels (local government or central government). Unlike for the central-planner setup, neither the local government nor the central government can directly control household migration between the two regions in this section. Because the corner solution of no seawall has been examined in Section 3.3.1, this section focuses only on interior solutions in which the government chooses to build a seawall.

### 3.4.1 Local Government

Suppose the local government in region 1 determines seawall height. To finance the seawall, the local government imposes an output tax $t$ in region 1. Two cases are investigated depending on whether the government is the first mover.

#### The Government Moves First

In period 0, the local government in region 1 determines seawall height $g$ first, and households make migration decisions thereafter. I assume the government always commits to its decision. This sequential game can be solved using backward induction. In particular, after observing the announced $g$, households in region 1 decide where to live in period 1. Recall that $V^1[n_1, \theta(g)]$ is the maximum value function of region 1 under SLR defined by (3.10), and $V^2(n_2)$ is the maximum value function of region 2 in period 1. Because under the initial population $n$ in each region, $V^1[n, \theta(g)] < V^2(n)$, households in region 1 will migrate to region 2 until per capita utility is equal between the two regions:

$$V^1[n_1, \theta(g)] = V^2(n_2). \tag{3.15}$$

One can implicitly solve for $n_1$ as a function of $g$, $n_1(g)$, which gives the migration response function to seawall height. Total differentiation of (3.15) gives

$$V^1_\theta \theta'(g) + V^1_{n_1} \frac{\partial n_1}{\partial g} = -V^2_{n_2} \frac{\partial n_1}{\partial g}, \tag{3.16}$$

where $V^1_{n_1}$ is the derivative of (maximized) per capita utility with respect to population $n_1$ in region 1, $V^2_{n_2}$ is the derivative of per capita utility with respect to population $n_2$ in region 2, and $V^1_\theta$ is the derivative of per capita utility in region 1 with respect to the damage rate. Under the assumption of over population, $V^1_{n_1} < 0$, and $V^2_{n_2} < 0$. The LHS of (3.16) represents the effect of a higher seawall on utility in region 1. The first term is the positive effect due to a lower damage rate, and the second term is the negative effect due to less migration, because $\frac{\partial n_1}{\partial g} < 0$, which is demonstrated later in the essay. Intuitively, a higher seawall protects region 1 better, so that households have less incentive to leave. The RHS of (3.16) represents the effect of a higher seawall on utility in region 2. This effect is positive, because a higher seawall prevents migration to region 2, which prevents falling of per capita utility in region 2. Solving for $\frac{\partial n_1}{\partial g}$ from (3.16) gives

$$\frac{\partial n_1}{\partial g} = -\frac{\theta'(g) V^1_\theta}{D}, \tag{3.17}$$

where $D = V^1_{n_1} + V^2_{n_2} < 0$. Because $\theta'(g) < 0$, and $V^1_\theta < 0$, therefore, $\frac{\partial n_1}{\partial g} > 0$, which indicates that as seawall height increases, migration decreases, and the population remaining in region 1 increases.[35] Furthermore, one can prove that $\frac{\partial^2 n_1}{\partial g^2} < 0$, that is, the marginal effect of seawall height on migration is diminishing, so the seawall cannot completely prevent migration.[36]

The local government of region 1 incorporates the response function $n_1(g)$ when choosing seawall height $g$ to maximize the sum of per capita utility of periods 0 and 1 in region 1. Recall that $V(n,t)$ defined by (3.9) is the maximum value function in period 0 when an output tax $t$ is imposed to finance the seawall. The local government's objective is

$$\max_{g} V\left[n, \frac{C(g)}{\bar{Y}}\right] + \beta V^1[n_1(g), \theta(g)]. \tag{3.18}$$

Notice that the government substitutes the response function $n_1(g)$ defined by (3.15) into the value function of period 1. The first-order condition for (3.18) is

$$-\frac{V_t C'(g)}{\bar{Y}} - \beta V^1_{n_1}[n_1(g), \theta(g)]\frac{\partial n_1}{\partial g} = \beta\theta'(g)V^1_{\theta}[n_1(g), \theta(g)]. \tag{3.19}$$

The LHS of (3.19) represents the marginal social cost of seawall height, which is increasing with $g$.[37] The first term is the direct marginal social cost from seawall construction, in terms of the value of foregone marginal utility due to the tax. The second term is the indirect marginal social cost from less migration due to a higher seawall. When the region is over-populated, reducing population improves per capita utility. Therefore, as the seawall height increases, households have less incentive to move, which prevents an increase in per capita utility in region 1. The RHS of (3.19) represents the marginal social benefit of seawall height, which is a lower damage rate and thus higher per capita utility. Given $\theta''(g) > 0$, it is clear that the marginal

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[35] $V^1_{\theta} = -\psi(n_1)u_{P_1}f(n_1)$, and $V^1_{\theta\theta} = 0$.

[36] $\frac{\partial^2 n_1}{\partial g^2} = \frac{1}{D}\left[(-V^1_{n_1 n_1} + V_{n_2 n_2})(\frac{\partial n_1}{\partial g})^2 - V^1_{\theta}\theta''(g)\right]$, and $-V^1_{n_1 n_1} + V_{n_2 n_2} > 0$, $\theta''(g) > 0$.

[37] This requires $-\frac{V_t C''(g)}{\bar{Y}} - \beta V^1_{n_1 n_1}(\frac{\partial n_1}{\partial g})^2 > \beta V^1_{n_1}\frac{\partial^2 n_1}{\partial g^2}$. It is plausible if the construction cost increases faster than the migration effect as seawall height increases. The simulation results in the next section show this is true assuming appropriate parameter values.

social benefit is decreasing with seawall height. The government will choose $g$ such that the marginal social cost equals the marginal social benefit. Substituting the solution of $g$ into the migration response function $n_1(g)$, one obtains, in principle, the equilibrium population. I assume both the marginal social cost curve and the marginal social benefit curve are nicely behaved, i.e., they are monotonically increasing and decreasing with $g$, respectively, so that there is a unique solution.[38] Let $(g^{LG}, n_1^{LG})$ denote the solution for when the local government moves first.[39]

### Households Move First

Now suppose that households in region 1 make their migration decisions first, and the local government of region 1 chooses seawall height $g$ based on the observation of migration decisions. Recall that households do not actually migrate at the time when they make migration decisions. They are making a commitment to move to region 2 in period 1, and will move at the end of period 0. Therefore, all households in region 1 at the start of period 0 contribute to production in region 1 in period 0.

Backward induction requires examining the local government's problem first. The local government chooses $g$ to maximize the sum of per capita utility of both periods in region 1

$$\max_g V\left[n, \frac{C(g)}{\overline{Y}}\right] + \beta V^1[n_1, \theta(g)]. \tag{3.20}$$

In this case, migration decisions are made before the choice of seawall height $g$, so the actual seawall height $g$ chosen will not affect subsequent population size, because by assumption, there is no scope for adaptation in period 1. The first-order condition for (3.20) yields

$$-\frac{V_t C'(g)}{\overline{Y}} = \beta\theta'(g)V_\theta^1[n_1, \theta(g)]. \tag{3.21}$$

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[38] This assumption applies to all other cases discussed later in this section.

[39] The first superscript in $(g^{LG}, n_1^{LG})$ means it is the local government $(L)$ or central government $(C)$ that makes seawall decision, and the second superscript means the government moves first $(G)$ or households move first $(H)$.

The LHS of (3.21) is the marginal social cost of seawall height, and the RHS is the marginal social benefit. Equation (3.21) implicitly defines $g(n_1)$, which specifies how the local government's choice of seawall height responds to migration (remaining population in region 1). Households take this response function into account when making their migration decisions. The population will be in equilibrium when perceived per capita utility in period 1 is equal between the two regions.

$$V^1\{n_1, \theta[g(n_1)]\} = V^2(n_2). \tag{3.22}$$

Equivalently, one can solve for $g$ by jointly solving (3.21) and (3.15), which gives

$$-\frac{V_t C'(g)}{\overline{Y}} = \beta\theta'(g)V_\theta^1[n_1(g), \theta(g)]. \tag{3.23}$$

Substituting the solution of $g$ in (3.23) back into (3.15), the equilibrium population $n_1$ is determined. Let $(g^{LH}, n_1^{LH})$ denote the solution for when households move before the local government.

The following proposition summarizes how adaptation outcome differs when the decision-making sequence is different.

**Proposition 3.2** *When the local government makes the seawall decision, the local government being the first mover results in a lower seawall and more migration than that when it is the second-mover. That is,* $g^{LG} < g^{LH}$*, and* $n_1^{LG} < n_1^{LH}$*.*

Comparing (3.19) and (3.23), it is clear that the expressions for the marginal social benefit on the RHS are identical. However, there is an extra marginal social cost term on the LHS of (3.19), which is the migration effect. When the government moves first, the government knows that a higher seawall induces less migration to region 2, which reduces per capita utility in an over-populated region. When households move first, migration decisions have already been made, so a higher seawall protects region 1 better without inducing less emigration. Therefore, when the local government moves first, the marginal social cost of seawall height is higher, which yields a lower seawall height and more migration in equilibrium.

### 3.4.2 Central Government

When the central government makes the seawall decision, it is assumed that the seawall is financed by both regions. The budget constraint faced by the central government in period 0 is the same as in equation (3.8). The central government imposes the same output tax $t = \frac{C(g)}{2\bar{Y}}$ on each region. Therefore, the two regions have the same per capita utility of period 0, $V(n, t)$. Unlike the case for the local government of region 1, which is only concerned about per capita utility in region 1, the central government is concerned about per capita utility in the nation. As in the previous section, the government as the first mover is examined first, followed by an examination of the government being the second-mover.

#### The Government Moves First

After households in region 1 observe $g$, free migration ensures that the two regions achieve the same per capita utility level in equilibrium. The migration equilibrium is once again characterized by (3.15), which gives the same response function $n_1(g)$. The marginal effect of seawall height on migration is characterized by (3.17). The central government's objective is to maximize the sum of per capita utility over two periods in the nation. Notice that per capita utility in period 1 is the same between the two regions upon substituting $n_1(g)$ into the maximization problem.[40] Therefore, the central government chooses seawall height according to the following objective function

$$\max_{g} V\left[n, \frac{C(g)}{2\bar{Y}}\right] + \beta V^1[n_1(g), \theta(g)]. \tag{3.24}$$

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[40] The migration response function $n_1(g)$ implies that per capital utility is equalized between the two regions in period 1 due to free migration.

The first term is per capita utility in the nation in period 0, and the second term is (discounted) per capita utility in the nation in period 1. The first-order condition for (3.24) yields

$$-\frac{V_t C'(g)}{2\overline{Y}} - \beta V^1_{n_1}[n_1(g), \theta(g)]\frac{\partial n_1}{\partial g} = \beta\theta'(g)V^1_\theta[n_1(g), \theta(g)]. \tag{3.25}$$

Since per capita utility is equal between the two regions for both periods, the central government has the same objective as the local government of region 1, except that region 1 in the central government's problem bears only half of the cost of seawall construction. Therefore, the interpretation of (3.25) is similar to that of (3.19). The LHS of (3.25) represents the marginal social cost of seawall height. The first term is the direct marginal cost from construction of the seawall, and the second term is indirect marginal cost from less migration. The RHS of (3.25) represents the marginal social benefit of seawall height. Let $(g^{CG}, n_1^{CG})$ denote the solution for this case.

**Households Move First**

Now suppose that households in region 1 make migration decisions first, and the central government determines seawall height thereafter. Again, backward induction requires examining the government's problem first. Since by assumption, there is no scope for migration after the government's decision on seawall height is made, per capita utility in period 1 could be different between the two regions. However, the two regions have the same per capita utility in period 0. Thus, the objective of the central government is

$$\max_g V\left[n, \frac{C(g)}{2\overline{Y}}\right] + \beta\left\{\frac{n_1 V^1[n_1, \theta(g)] + n_2 V^2(n_2)}{2n}\right\}. \tag{3.26}$$

Notice that the second term is the (discounted) weighted per capita utility in the nation in period 1. The first-order condition for (3.26) yields

$$-\frac{V_t C'(g)}{2\overline{Y}} = \frac{n_1}{2n}\beta\theta'(g)V_\theta^1. \tag{3.27}$$

As before, the LHS of (3.27) is the marginal social cost of seawall height. The RHS of (3.27) is the marginal social benefit of seawall height, which is a "weighted" marginal increase in utility due to a lower damage rate. Because the central government cares about utilities of both regions, and a higher seawall only benefits households in region 1, the marginal social benefit is weighted by the fraction of population in region 1.[41] Equation (3.27) gives the response function for the central government's choice of seawall height to migration $g(n_1)$. Households take this response function into account when making their migration decisions. Equivalently, one can solve for $g$ by jointly solving (3.27) and (3.15), which yields

$$-\frac{V_t C'(g)}{2\overline{Y}} = \frac{n_1}{2n}\beta\theta'(g)V_\theta^1[n_1(g), \theta(g)]. \tag{3.28}$$

Substituting the solution of $g$ into $n_1(g)$ yields the equilibrium population $n_1$. Let $(g^{CH}, n_1^{CH})$ denote the solution for the case where households move before the central government.

The following proposition summarizes how adaptation outcomes differ under the two different decision-making sequences.

**Proposition 3.3** *When the central government makes the seawall decision, the central government being the first mover results in a higher seawall and less migration than that when it is the second mover. That is,* $g^{CG} > g^{CH}$*, and* $n_1^{CG} > n_1^{CH}$*.*

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[41] Notice that the expression in (3.27) coincides with that in (3.12), which is the first-order condition determining optimal seawall height in the central planner's problem. This is because both the central planner and the central government care about utility in the nation, so they face the same marginal social cost and benefit of seawall height when seawall height does not affect migration.

Refer to Appendix B.1 for a formal proof. Intuitively, because of the concavity of the value function, per capita utility falls faster as population size increases. When the central government moves first, a higher seawall can prevent migration towards (and hence falling of utility in) region 2. Recall that from Proposition 3.1, the social optimum requires per capita utility in region 2 to be higher than that in region 1. Although this cannot be achieved under free migration, the central government has an incentive to build a higher seawall when it moves first so as to reduce migration.

### 3.4.3 Local vs. Central Government

Finally, I compare adaptation behavior of the local government with that of the central government. The following proposition summarizes the results of this comparison.

**Proposition 3.4** *When the government moves first, the local government will build a lower seawall than the central government* ($g^{LG} < g^{CG}$)*; when households move first, the local government will build a higher seawall than the central government* ($g^{LH} > g^{CH}$)*.*

When the government moves before households, recall that the local government's choice of seawall height $g$ is determined by (3.19), and the central government's choice is determined by (3.25). It is clear that the RHS of those two equations are identical, which means the expressions for the marginal social benefit are the same. However, given any $g$, the marginal social cost is higher from the perspective of the local government. Because region 1 bears the entire cost of the seawall, given any seawall height, the direct marginal social cost for the local government of region 1 is higher. Therefore, the local government of region 1 will build a lower seawall than the central government if the government moves first.

When households make their migration decisions first, seawall heights under the local government and central government are determined by (3.23) and (3.28), respectively. Dividing both sides of (3.28) by 2 yields

$$-\frac{V_t C'(g)}{\overline{Y}} = \frac{n_1}{n} \beta \theta'(g) V_\theta^1 [n_1(g), \theta(g)]. \tag{3.29}$$

Obviously, the LHS of (3.23) and (3.29) are identical, which means the expressions of the marginal social cost are the same. However, the marginal social benefit is higher for the local government. This is because when the seawall decision is made after migration decisions, all households in region 1, but none of the households in region 2, benefit from the seawall. Since the local government of region 1 only cares about households in region 1, from its perspective, all households benefit from the seawall. The central government, in contrast, cares about all households in both regions. From the central government's perspective, only a fraction ($\frac{n_1}{n}$) of households benefit from the seawall. Therefore, the marginal social benefit of seawall height is lower for the central government.

One shortcoming of the analysis so far is the inability to draw any conclusions analytically about differences in the utility levels achieved for different cases. Therefore, the next section provides a numerical analysis to compare social welfare across cases.

## 3.5 Welfare Comparisons

In this section, welfare comparisons under the different scenarios analyzed in the previous sections are illustrated via a simulation.

### 3.5.1 Functional Forms and Parameters

Cobb-Douglas production is assumed,

$$f(n) = A n^\alpha L^{1-\alpha}. \tag{3.30}$$

$A$ is total factor productivity, and $\alpha$ is the elasticity of output with respect to labor. $L$ is the fixed land available for production in each region. Next, recall that per capita utility is defined as $U = \psi(n)u(z, P)$, where $\psi(n)$ is a disamenity function, and $u(z, P)$ is a strictly quasi-concave utility function. Following Henderson (1982), $\psi(n)$ is assumed to take the form

$$\psi(n) = \Omega e^{-n\varepsilon}, \tag{3.31}$$

where $\Omega$ is the amenity index, and $\varepsilon$ is the disamenity parameter which determines the level and the decreasing rate of amenity with population size. The utility function also takes the Cobb-Douglas form

$$u(z, P) = z^{\gamma} P^{1-\gamma}, \tag{3.32}$$

where $\gamma$ is the share of private good consumption, and $1 - \gamma$ is the share of local public good consumption.

Recall that the function $\theta(g)$ defines how seawall height $g$ affects the damage rate. $\theta(g)$ has the properties of $0 < \theta(g) < \overline{\theta}, \theta'(g) < 0$, and $\theta''(g) > 0$. I assume the following functional form that satisfies these properties,

$$\theta(g) = \frac{\overline{\theta}}{0.5g + 1}. \tag{3.33}$$

The baseline damage rate is $\overline{\theta}$, which is the damage rate when there is no seawall. Finally, the cost of seawall construction is assumed to be

$$C(g) = C_0 + cg^3 = 2\delta\overline{Y} + cg^3, \tag{3.34}$$

where $\delta \in (0, 1)$, and $C_0$ is the fixed cost, which is a fraction $\delta$ of total output in the nation.

Using the functional forms specified above, the maximum value function $V(n)$ defined in (3.3) is

$$V(n) = \Omega e^{-n\varepsilon}(1-\gamma)^{1-\gamma}\gamma^{\gamma}\frac{f(n)}{n^{\gamma}} = \Lambda e^{-n\varepsilon}n^{\alpha-\gamma}, \tag{3.35}$$

where $\Lambda \equiv \Omega(1-\gamma)^{1-\gamma}\gamma^{\gamma}AL^{1-\alpha}$. Taking the derivative with respect to $n$ yields

$$V'(n) = -\Lambda\varepsilon e^{-n\varepsilon}n^{\alpha-\gamma} + \Lambda(\alpha-\gamma)e^{-n\varepsilon}n^{\alpha-\gamma-1}. \tag{3.36}$$

Therefore, the optimal population size is

$$n^* = \frac{\alpha-\gamma}{\varepsilon}. \tag{3.37}$$

Clearly, the existence of a positive optimal population size requires $\alpha > \gamma$. Also, as the disamenity parameter $\varepsilon$ increases, the optimal population size decreases. Because given any population size, a larger $\varepsilon$ results in lower utility from amenity, the population size must be smaller to achieve a given utility level.

Table 3.1 summarizes the values of the parameters used in the simulation. For production, $A = 100$, and $\alpha = 0.75$, which is the empirically estimated exponent of labor (Cobb and Douglas, 1928; Felipe and Adams, 2005). For utility, $\Omega = 100$, and $\gamma = 0.7$, which guarantees $n^* > 0$. The initial population in each region is assumed to be 3,000 ($n = 3000$), and the disamenity parameter $\varepsilon = 0.0005$. According to (3.37), the optimal population size $n^*$ is equal to 1000, and both regions are over-populated. Because adaptation costs relative to GDP is estimated to range from 0.05% to 0.5% (Stern et al., 2006), I set $\delta = 0.1\%$. I use a discount rate of 3%; the corresponding discount factor is $\beta = 0.97$. Finally, the baseline damage rate ($\overline{\theta}$) varies from 1% to 10% with an interval of 1% to obtain corresponding numerical solutions. This range of the baseline damage rate guarantees that the migration equilibrium under SLR is unique and stable for all cases.

Table 3.1: Parameter Values and Descriptions

| Parameter | Value | Description |
|---|---|---|
| $A$ | 100 | Total factor productivity |
| $\alpha$ | 0.75 | The elasticity of output with respect to labor |
| $\Omega$ | 100 | Amenity index |
| $\varepsilon$ | 0.00005 | Disamenity coefficient |
| $\gamma$ | 0.7 | The share of private good expenditure |
| $\delta$ | 0.001 | Parameter of fixed cost of seawall construction |
| $\beta$ | 0.97 | Discount factor |
| $n$ | 3000 | Initial population in each region |
| $c$ | 10 | Coefficient of variable cost of seawall construction |
| $\overline{\theta}$ | 0.01-0.1 | Baseline damage rate |

### 3.5.2 Results

Table 3.2 shows the simulation results when the baseline damage rate, $\overline{\theta}$, is equal to 0.1. Panel A shows the equilibrium results for seawall height and migration rate. Clearly, columns (3) to (6) confirm the results presented in Propositions 3.2 to 3.4. When the local government makes adaptation decisions, households moving first yields a higher seawall (5.3 vs. 4.43) and a lower migration rate (13.9% vs.15.9%). When the central government makes adaptation decisions, the central government moving first yields a higher seawall (5.4 vs. 5.06) and a lower migration rate (13.7% vs. 14.4%). The first-best solution yields a seawall height of 5.2, which is in between the values in columns (3) to (6). However, since households do not have free mobility in the central planner's problem, the first-best solution has the most population remaining in region 1 (2842), which is equivalent to a migration rate of

5.3%. Finally, because there is no seawall in the baseline, the baseline has the highest migration rate (56.4%).

Panel B of Table 3.2 shows the per capita utility difference relative to the baseline for each case in columns (2) to (6). Obviously, the sum of per capita utility of the two periods for region 1, region 2, and the nation in all cases is higher than that in the baseline. In other words, given the parameter values shown in Table 3.1, the interior solutions for all cases are preferable to the corner solution. Therefore, despite of the type of government and the sequence of decision-making, constructing a seawall is a Pareto improvement that improves welfare for both regions. Column (2) also confirms the result presented in Proposition 3.1. In the social optimum, per capita utility in region 2 is higher than that in region 1 for period 1.

Panel C of Table 3.2 shows the per capita utility difference relative to the first best for each case in columns (3) to (6). Clearly, the social welfare (weighted per capita utility in the nation) for all four cases is lower than in the first best. Because of free migration, per capita utility is equalized between the two regions in period 1 for all four cases, whereas according to Proposition 3.1, the social optimum requires that region 1 has lower per capita utility than region 2. Therefore, the social optimum cannot be achieved as long as free migration is allowed. However, we can predict that the case with an outcome that has more households remaining in region 1 (i.e., less migration) will be closer to the social optimum.

Furthermore, Panel C shows that when the central government moves before households, the difference relative to the first best is lowest (-34.18). In other words, the central government being the first mover is socially most preferred given free migration. This result is consistent with the concept of (second-best) social optimum largely used in the local public goods literature. In that literature, the government or social planner making decisions before households is implicitly assumed. The social optimum is characterized by the social planner maximizing the utility of a repre-

Table 3.2: Simulation Results

| $\overline{\theta} = 0.1$ | Baseline | First Best | Local Government |  | Central Government |  |
|---|---|---|---|---|---|---|
|  |  |  | Govt. First | HH First | Govt. First | HH First |
|  | (1) | (2) | (3) | (4) | (5) | (6) |
| Panel A. Seawall Height and Migration |  |  |  |  |  |  |
| Seawall Height | 0 | 5.2 | 4.43 | 5.3 | 5.4 | 5.06 |
| Population (Period 1) |  |  |  |  |  |  |
| -Region 1 | 1307 | 2842 | 2524 | 2582 | 2588 | 2567 |
| -Region 2 | 4693 | 3158 | 3476 | 3418 | 3412 | 3433 |
| Migration Rate | 56.40% | (5.3%)* | 15.90% | 13.90% | 13.70% | 14.40% |
| Panel B. Per Capita Utility Difference (Relative to the Baseline) |  |  |  |  |  |  |
| Region 1 |  | 1272.45 | 1447.83 | 1418.51 | 1585.82 | 1582.63 |
| -Period 0 |  | -160.28 | -227.75 | -334.08 | -174.83 | -150.97 |
| -Period 1 |  | 1432.73 | 1675.58 | 1752.59 | 1760.65 | 1733.6 |
| Region 2 |  | 1932.68 | 1675.58 | 1752.59 | 1585.82 | 1582.63 |
| -Period 0 |  | -160.28 | 0 | 0 | -174.83 | -150.97 |
| -Period 1 |  | 2092.96 | 1675.58 | 1752.59 | 1760.65 | 1733.6 |
| Nation |  | 1620 | 1561.7 | 1585.55 | 1585.82 | 1582.63 |
| Panel C. Per Capita Utility Difference (Relative to the First Best) |  |  |  |  |  |  |
| Region 1 |  |  | 175.37 | 146.05 | 313.37 | 310.18 |
| -Period 0 |  |  | -67.47 | -173.8 | -14.55 | 9.31 |
| -Period 1 |  |  | 242.84 | 319.86 | 327.92 | 300.87 |
| Region 2 |  |  | -257.1 | -180.09 | -346.86 | -350.05 |
| -Period 0 |  |  | 160.28 | 160.28 | -14.55 | 9.31 |
| -Period 1 |  |  | -417.38 | -340.37 | -332.31 | -359.36 |
| Nation |  |  | -58.3 | -34.45 | -34.18 | -37.37 |

*Migration is not allowed in the First Best, but the allocation is equivalent to a migration rate of 5.3%.

sentative household in region 1, subject to free migration condition, which is utility equalization between the two regions.[42] By contrast, the case in which the local

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[42] This is the standard approach in the literature. However, Myers (1990) argues that this procedure imposes private decision-making on the optimality problem, and he instead imposes the constraint that holding the utility of a representative individual from the other region at a predetermined level.

government moves first yields the lowest social welfare. This is not surprising. The central government favors less migration, because less migration results in less congestion in region 2 and yields overall higher social welfare in the nation. However, the local government of region 1 favors more migration, because emigration raises per capita utility in region 1. Therefore, when the central government makes the decision and moves first, it has the strongest incentive to build a seawall resulting in the lowest migration rate, an outcome closest to the first-best outcome. When the local government makes the decision and moves first, the migration rate is highest and the outcome is socially least preferred.

Next, the case in which households move before the local government yields a slightly lower social welfare than the case in which the central government moves before households. When the local government makes the seawall decision, households moving first provides an incentive for the local government to build a higher seawall. Because migration decisions have already been made, building a higher seawall reduces more damages in region 1 without reducing emigration. Therefore, we can see that the local government in this case chooses a seawall height quite close to that chosen by the central government when it moves first. Finally, the case in which households move before the central government yields a lower social welfare than the case in which households move before the local government. As shown in Proposition 3.4, since the local government of region 1 only cares about households in region 1 while the central government cares about all households in both regions, the marginal social benefit of seawall height is lower for the central government. Therefore, there are fewer households remaining in region 1 under the central government, which results in a lower social welfare.

Notice that the welfare of region 1 in all four cases is higher than that in the first best, whereas the welfare of region 2 in all four cases is lower than that in the first best. This is because free migration is not allowed in the first best. As shown in

Panel A, the first best has the largest number of households in region 1. Although allocating relatively more households to region 1 can improve social welfare in the nation, it is not sustainable under free migration. Therefore, under free migration, the case in which the central government makes the adaptation decision and moves first yields the highest social welfare.

Figure 3.3 shows the results for seawall height for the different cases as $\overline{\theta}$ (the baseline damage rate) varies from 0.01 to 0.1. The pattern is consistent with that in Table 3.2. We can see that the gaps among cases shrink as the baseline damage rate decreases. Figure 3.4 extends the results in Panel C in Table 3.2 and shows utility differences relative to the first best as $\overline{\theta}$ varies from 0.01 to 0.1. The pattern is consistent, but the gaps shrink as the damage rate decreases. Let $V^{CG}, V^{LH}, V^{CH}$, and $V^{LG}$ be the social welfare for the cases in columns (3) to (6) in Table 3.2 respectively. The comparison results regarding social welfare are summarized as below.

**Results:** Under free migration, we have $V^{CG} > V^{LH} > V^{CH} > V^{LG}$.

Figure 3.4 indicates that for all $\overline{\theta} \in [0.01, 0.1]$, having the central government move first yields the highest social welfare. However, the social welfare in the case where households move before the local government is just slightly lower. The case where the local government moves first yields the lowest social welfare; it is significantly lower than the other three cases.

## 3.6 Conclusions

This essay starts with a basic model from the theory of local public goods, one in which the local government maximizes per capita utility and allocates private and public consumption according to the Samuelson rule. When SLR is anticipated in the coastal region, the government (either the local government of the coastal region or the central government of the nation) adapts to this risk by building a seawall

Figure 3.3: Seawall Height under Different Cases

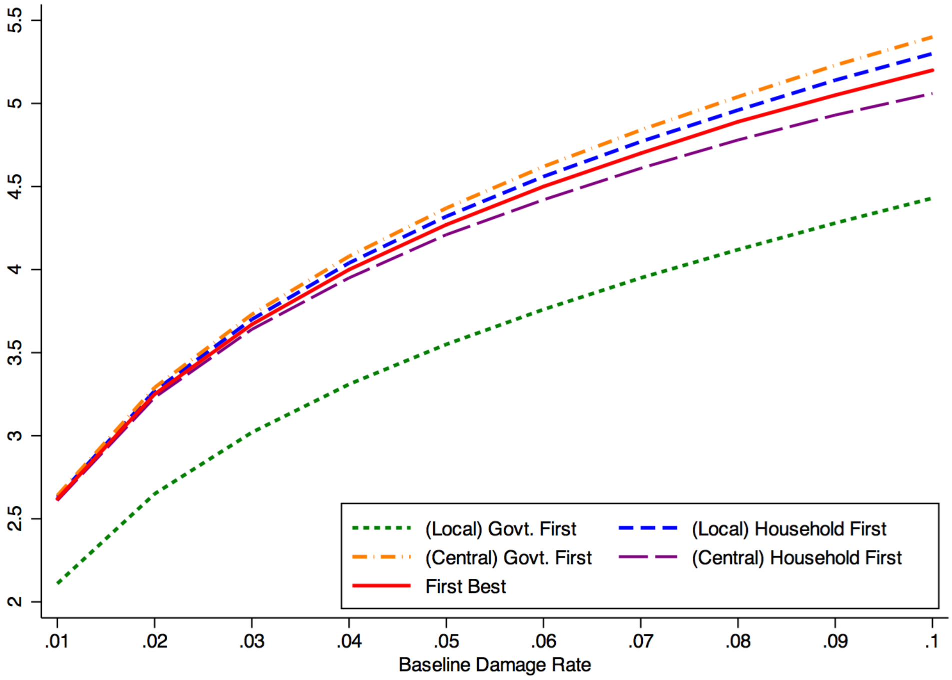
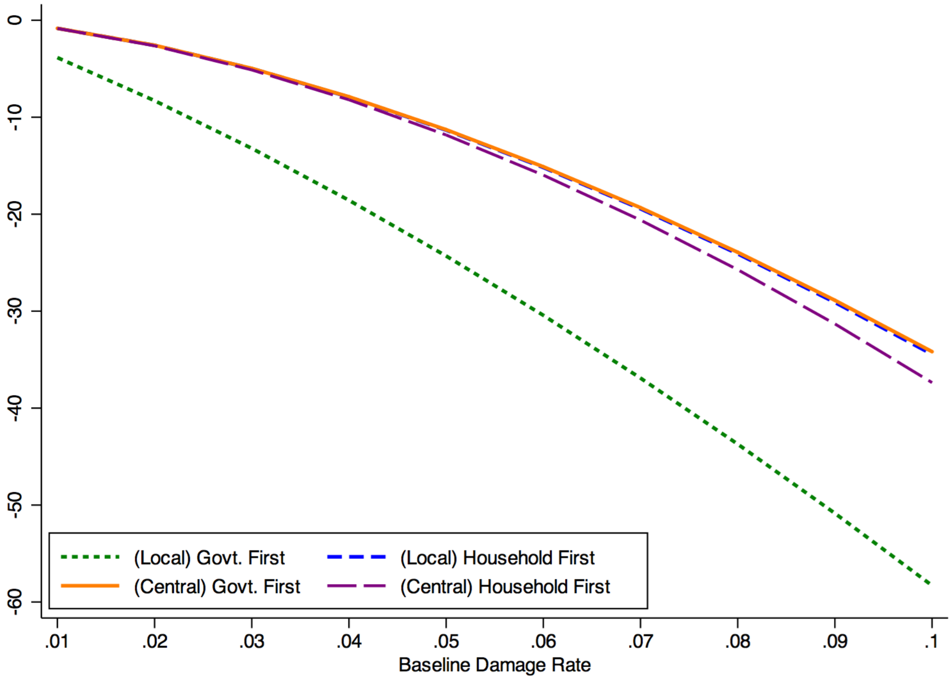


Figure 3.4: Utility Difference relative to the First Best



to reduce damages to output, while households adapt to this risk by migrating to the risk-free, inland region. Viewing the choices of the government and households as a sequential game, this essay examines how the decision-making sequence affects adaptation outcomes.

The analysis reveals that when a local government makes the seawall decision, the local government being the first mover yields a lower seawall and more migration than it being the second-mover. Because emigration is beneficial to an over-populated region, and a higher seawall reduces this benefit, having the local government move first reduces its incentive to raise seawall height. When the central government makes the seawall decision, the central government being the first mover yields a higher seawall and less migration than it being the second mover. Due to the concavity of the maximum value function of population, utility drops faster as population increases in the inland region. Since the central government considers the welfare of the nation, less migration from the coastal region to the inland region results in less social cost for the nation.

Furthermore, comparing behavior of the local government with that of the central government, the local government will build a lower seawall than the central government when the government is assumed to be the first mover. Because the local government finances the seawall locally, only households in the coastal region bear the burden of building the seawall. However, when households move before the government, the local government will choose a higher seawall than the central government. Since the central government cares about welfare in the nation (both regions), from its perspective, only a fraction of households in the nation (households in the coastal region) benefit from the seawall. In contrast, the local government of the coastal region only cares about welfare in its own region. From the local government's perspective, all households in its region benefit from the seawall. Therefore, the marginal social benefit from the seawall is higher for the local government, and the local government will build a higher seawall.

The simulation results show that, although the first-best optimum cannot be obtained by any of the cases examined due to free migration, having the central government making the seawall decision and being the first mover is socially preferable, because this case yields the lowest migration rate, which is closest to the first-best outcome. If the local (central) government determines seawall height, households moving first (second) generates higher social welfare. Because households moving first gives the local government an incentive to build a higher seawall than when they move second, there are more households remaining in region 1. In contrast, households moving first reduces the central government's incentive to raise seawall height, because seawall height can no longer prevent migration, and there are fewer households remaining in region 1.

Finally, one should keep in mind that the results obtained in this essay are based on the assumption of over population in each region, namely, per capita utility decreases with population size. Recall that in the extension of the first essay, when there is a congestion cost in production, the two local governments choose lower seawall height than the central government. Although the model setup is different in this essay, we have a consistent result–the local government of the coastal region chooses lower seawall height than the central government given the government being the first mover. However, this essay shows that if households move first, the local government will build a higher seawall than the central government, which highlights the importance of the decision-making sequence.

# Chapter 4: Travel Time Use over Five Decades[43]

## 4.1 Introduction

Travel time, which includes time spent on travel related to work, travel for the purpose of non-market work, and travel for the purpose of leisure activities, makes up a sizable fraction of discretionary time use.[44] In this essay, we use five decades of time-use surveys to examine trends in travel time use (includes all modes of travel) within the United States. We find that there have been dramatic changes in travel time over the past five decades. Total travel time (hours per week) increased by nearly 19 percent from 1965 to 1993 for an average individual between 19 and 65 years old, and by roughly 20 percent from 1975 to 1993 if we expand the sample to those 18 and up. In 1975, average travel time for an adult was 8.43 hours per week, and grew to 10.1 hours per week in 1993. Average travel time peaked some time between 1993 and 2003, possibly about the turn of the century. Due to the lack of annual data, we cannot exactly pin down the peak year. By 2003, average travel time per adult has already declined to 9.03 hours per week, a decline of nearly 11 percent since 1993. The decline has then continued throughout the following decade. In 2013 average travel time per adult has become 8.29 hours per week, registering a decline of 18 percent compared to that in 1993. Regardless of dramatic changes in all aspects of the U.S. economy since 1965, people in 2013 spent similar amount of travel time as those five decades ago.

The dramatic change in travel time is not an isolated phenomenon. Total vehicle miles of travel (VMT) within the U.S. began to plateau in 2004 and dropped in 2007 for the first time since 1980. Similarly, the growth rate in VMT per capita began to

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[43] This is a joint work with Professor Chao Wei.

[44] Non-market work includes home production, obtaining goods and services, child care and other care. Here home production includes any time spent on meal preparation, housework, and vehicle maintenance. Section 4.2.2 presents the measures of time use activities in detail.

plateau around 2000, and the per capita level of VMT started to slide after 2005.[45] In addition, distance driven per light-duty vehicle, and the number of light-duty vehicles per capita also peaked shortly after the turn of the century(Sivak, 2013). Since vehicle travel remains the primary travel mode of the country, the peak and subsequent decline in distance driven and vehicle ownership corroborate the dramatic turn in the total travel time around the same time. Considering that total travel time is also closely related to travel patterns and gasoline use in this country, the importance of explaining forces behind variations in travel time becomes self-evident.

The intriguing questions are: What are the forces behind the dramatic variations in total travel time over the five decades? To what extent do demographic shifts, including the aging of baby boomers, the peak of female labor-force participation, changes in education composition, and the fraction of population with children, contribute to the evolving patterns of travel time use? What are the causes behind the recent decline in total travel time, especially after 2003? Can the decline in travel time be attributed to an increase in efficiency as a result of telecommuting and e-commerce, or is it caused by less time allocated to activities complementary with travel? Will the forces behind the decline over the past decade carry into the future and cause continuing decline in total travel time?

To address these questions, we link five major time use surveys to characterize patterns of travel time use. These time-use surveys are: 1965-1966 America's Use of Time; 1975-1976 Time Use in Economics and Social Accounts; 1985 Americans' Use of Time; 1992-1994 National Human Activity Pattern Survey; and the 2003-2013 Annual American Time Use Survey (ATUS). We seek to explain travel time variations by taking a close look at two driving forces. The first driving force is changes in demographic composition in terms of age, gender, work status, education and whether there is a child present in the household. We decompose unconditional

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[45] Metropolitan Policy Program at Brookings,"The Road ... Less Traveled".

mean changes in travel time to gauge the contribution by shifts in each demographic attribute. The second driving force is changes in travel time allocation that are common across demographic groups. We examine how travel time co-varies with other time use categories. The common components represent changes not explained by shifts in demographic composition.

We have the following main findings: First, demographic shifts explain roughly 45 percent of the increase in total travel time from 1975 to 1993. Increases in educational attainment alone contribute to 28 percent of the increases, followed by nearly 18 percent contributed by changes in age, work and gender composition. However, demographic shifts play a much smaller role in the evolution of total travel time afterwards. Between 2003 and 2013, the negative effect on total travel time due to aging of baby boomers and decreasing labor force participation was mostly offset by the positive effect due to increases in education attainment. As a result, changes in total travel time are not explained by demographic shifts. Second, variations in total travel time from 2003 to 2013 are dominated by time effects that are common to all demographic groups. In particular, the shift of time allocation from more travel-intensive non-market work to less travel-intensive leisure accounts for roughly 50 percent of the decline in total travel time. There are no strong evidence for economizing on travel during the recent decade. Third, travel time is complementary with time spent on obtaining goods and services, civil activities, and leisure outside, including exercises and sports, and social activities. Time spent on travel is substitutionary with time spent on home entertainment, on computer and TV, sleeping, and home production. The substitutionary and complementary patterns of travel time use with other time use categories indicate that there has also been a shift of time allocation from leisure outside to leisure at home, in addition to the shift of time from non-market work to leisure.

Our work contributes to the existing literature on measuring changes in time allocation. Robinson and Godbey (1999) uses the same time-use surveys we use from 1965, 1975, and 1985, as well as some additional information from the early 1990s, to document time use in all categories. Aguiar and Hurst (2007) document trends in leisure from 1965 to 2003 by using time-use surveys in 1965, 1975, 1985, 1993 and 2003. Similar to Ramey and Francis (2009), they find a dramatic increase in leisure time during the sample period. We further extend Aguiar and Hurst (2007) sample to include annual time-use surveys from 2003 to 2013 conducted by the Bureau of Labor Statistics. The availability of annual data and consistency of time-use definitions for surveys after 2003 provide more detailed information on time uses compared to previous surveys. While Aguiar and Hurst (2007) focus on leisure, which makes up more than half of the time use, we focus on total travel time. Although travel time makes up a small fraction of total time use, percentage changes in total travel time have been dramatic. Our work also differs from Aguiar and Hurst (2007) in the choice of sample population. Our sample includes population aged 18 and up, while Aguiar and Hurst (2007) only include those between 21 and 65.

The U.S. Department of Transportation conducts the National Household Travel Survey (NHTS) periodically to gather data such as mode of transportation, duration, distance and purpose, and then links the travel-related information to demographic and economic data for analysis. In the NHTS, respondents only need to report the trips they took on a single day, but not all the activities within 24 hours as done in the time-use surveys we work with. Robinson and Godbey (1999) find that time-use surveys seem to show more travel and more trips than reported in the 1992 National Transportation Survey. However, they also find that the Department of Transportation data show much the same distribution across trip purposes and correlations of travel time as time-use surveys, despite the overall lower numbers. One of the important advantages of the five time-use surveys we use is that we can not only relate travel time with the corresponding activity based on the purpose of the travel, but also examine travel time as part of optimal time allocation among all time uses. Since 2003, the linking of time-use surveys with the Current Population Survey (CPS) yields a large sample with rich demographic and economic data on respondents, making it a valuable data source for optimal time allocation. The American time-use surveys have become annual after 2003, while the National House Travel Surveys are only conducted periodically in 1969, 1977, 1983, 1990, 1995, 2001 and 2009. When applicable, we use information from the NHTS to corroborate our findings on travel trends from time-use surveys.

## 4.2 Time-Use Surveys and Data Construction

We link five major time-use surveys to characterize travel time patterns. In addition to surveys used in Aguiar and Hurst (2007) (hereafter A&H), we include the ATUS from 2003 to 2013. We also examine different sample population, construct new measures of travel time, and form demographic cells differently from A&H due to our focus on travel time use. Below we describe the three differences in detail. Table 4.1 reports our sample sizes and the number of time-use categories.

### 4.2.1 Two Samples

The primary sample of A&H consists of respondents aged 21 through 65 who are neither students nor retirees. Since we focus on travel time allocation, it is appropriate to include all possible drivers, both younger than 20 and older than 65 in the sample. However, time-use surveys differ in terms of the minimum and maximum ages. We form two different samples based on a tradeoff between the size of our sample population and the length of sample periods. Our first sample consists of respondents aged 18 and up from 1975 to 2013, where 18 is the minimum age allowed by all surveys from 1975 on. Our second sample consists of respondents aged 19 through 65 from 1965 to 2013, to accommodate the narrow age limit in the 1965-1966 America's

Use of Time. We exclude respondents whose answers on age, gender, working status, education, and child status are missing, or whose time use record is incomplete (i.e. all time-use components in the diary do not add up to 1440 minutes per week).

As shown in Table 4.1, during the period from 1975 to 2013 when two samples can be formed for the same year, the second sample can be as much as 20 percent smaller than the first sample. The first sample is the primary focus of our investigation. The main results obtained by using the second sample are presented in C.2.

### 4.2.2 Measures of Non-travel Activity and Corresponding Travel Time

We characterize three major uses of non-travel time and their corresponding travel time: (non-travel) market work and work travel; (non-travel) non-market work and non-market work travel; (non-travel) leisure and leisure travel. From now on, we omit the "(non-travel)" qualification unless confusion might arise. Our time use conventions are broadly similar to A&H except for two differences: First, A&H's measures of market work, non-market work and leisure include their corresponding travel time, whereas here those three terms refer to non-travel component of the three major time uses; Second, child care either stands alone or counts as part of broad measure of leisure in A&H, while we count child care as non-market work. There has been debate on whether child care should be counted as non-market work or leisure. Ramey and Francis (2009) count a subset of child care as leisure. However, since we do not have disaggregated travel time corresponding to each subset of child care, we choose to treat all the time spent on child care as non-market work.

Table 4.1 shows that time-use surveys from 2003 to 2013 have the most comprehensive measures of both non-travel and travel time.

#### Measures of Non-Travel Time

Our measure of market work includes non-travel portion of work for pay (all time

Table 4.1: Description of Time Use Surveys and Analysis Samples

| Dataset | Survey | Total Sample Size | Analysis Sample 1 Size | Analysis Sample 2 Size | Number of Time Use & Travel Categories |
|---|---|---|---|---|---|
| 1965 | Americans' Use of Time | 2,001 | | 1,934 | [95], [9] |
| 1975 | Time Use in Economic and Social Accounts | 2,406 | 2,217 | 1,870 | [87], [9] |
| 1985 | Americans' Use of Time | 4,939 | 4,240 | 3,629 | [88], [9] |
| 1993 | National Human Activity Pattern Survey | 9,383 | 7,258 | 6,018 | [91], [10] |
| 2003 | American Time Use Survey | 20,720 | 19,759 | 16,255 | [435], [58] |
| 2004 | | 13,973 | 13,318 | 10,889 | [449], [68] |
| 2005 | | 13,038 | 12,418 | 10,255 | [456], [76] |
| 2006 | | 12,943 | 12,200 | 9,970 | [456], [76] |
| 2007 | | 12,248 | 11,606 | 9,477 | [459], [76] |
| 2008 | | 12,723 | 12,108 | 9,876 | [459], [76] |
| 2009 | | 13,133 | 12,568 | 10,220 | [459], [76] |
| 2010 | | 13,260 | 12,679 | 10,277 | [459], [76] |
| 2011 | | 12,479 | 11,978 | 9,623 | [459], [76] |
| 2012 | | 12,443 | 11,975 | 9,557 | [459], [76] |
| 2013 | | 11,385 | 10,952 | 8,626 | [459], [76] |

Analysis Sample 1: uses surveys 1975-2013, including age 18 and above who report age, working and retirement status have children or not, and have complete time use record.

Analysis Sample 2: uses surveys 1965-2013, including age 19 (included) to age 65 (included) who report age, working and retirement status, have children or not, and have complete time use record.

For surveys prior to 2003, the number of time use and travel categories are counted by variables constructed in the dataset. For 2003-2013 ATUS, the number of time use and travel categories are counted by the 6-digit activity codes.

spent on working in the market sector on main jobs, second jobs, overtime, and working at home) plus time spent on ancillary work activities, such as time spent at work on breaks or eating a meal, and time spent on searching for a job. The measure is the same as A&H's measure of market work excluding commuting to/from work and other work-related travel.

Our measure of non-market work includes four categories of time uses: home production, obtaining goods and services, child care and other care. Here home production includes any time spent on meal preparation, housework, and vehicle maintenance.[46] Obtaining goods and services includes time spent on non-travel portion of acquiring any goods and services (excluding medical care, education and restaurant meals). Child care includes time spent on non-travel portion of primary, educational and recreational child care as defined in A&H. Other care includes time spent on helping and caring for household and non-household adults.

We have both narrow and broad measures of leisure. We define a narrow measure of leisure as time spent on sports, exercise, recreation, socializing and communicating, hosting and attending social events, relaxing and leisure, arts and entertainment, and telephone calls. Our broad measure of leisure includes time spent on eating and drinking, sleeping, personal care, own medical care, religious, spiritual, volunteering, gardening and pet care, and other leisure activities.

In addition to the narrow and broad measures of leisure, we also categorize leisure into three categories by the most likely location of enjoying the leisure time. We define home leisure as leisure time most likely spent at home, including time spent on watching TV, using computer, sleeping and other home-based leisure.[47] We define outside leisure as time spent on some typical outside activities, such as exercise and

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[46] Different from A&H, we include time spent on gardening and pet care in leisure, instead of as both home production and leisure. Our main results do not change if we categorize it otherwise.

[47] Other home-based leisure includes hobbies, listening to radio, listening to/playing music (not radio), reading, relaxing and thinking, and tobacco and drug use.

sports, socializing, and entertainment and arts. We put all the rest leisure time, including gardening and pet, personal care and other self care into the third category.

### Measures of Travel Time

Our measure of travel time includes all modes of travel. The period from 2003 to 2013 has the most comprehensive disaggregation of travel time. In the Appendix C.1, Table C.1 summarizes travel time use classification and definitions. Table C.2 summarizes coding rules of traveling in ATUS.[48] Table C.3 summarizes coding rules of traveling in 1975-1976 Time Use in Economic and Social Accounts. We define work travel as travel related to work, including commuting to and from work. The non-market work travel is defined as travel for the purpose of obtaining goods and services (obtaining travel), for household activities (home production), for child care and other care. The obtaining travel is a major component of non-market work travel. The leisure travel includes travel related to sports, recreational, social and communicating, and personal care activities. Taken together, work travel, non-market work travel, and leisure travel make up roughly 95 percent of total travel time in our sample period. We also define a narrow measure of leisure travel as the travel time related to the narrow measure of leisure.

We consider total travel time comparable across all the time use surveys, but take a conservative approach toward disaggregated travel time. There are far fewer categories of disaggregated travel time prior to 2003. As a result, we restrict our attention to a selected few disaggregated measures when we examine the long horizon from 1975 to 2013.

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[48] The coding rules for 2003-2013 ATUS are generally the same. Refer to Differences between the 2003 to 2013 lexicons to see minor changes across these surveys.

## 4.3 Total Travel Time Over Five Decades

This section describes the evolution of total travel time for the full sample and by demographic groups from 1975 to 2013. Figure 4.1 and Table 4.2 display the total travel time for our first (1975-2013) and second (1965-2013) samples. The primary difference between the first sample and the second sample is that the former includes population older than 65, who may travel less than younger population. As shown in Figure 4.1, the path of total travel time for the first sample stays below that for the second sample, but shares similar patterns of variations over time. For the second sample, total travel time in 1965 is slightly below that in 1975. Given the similar patterns of variations, from now on we focus on the first sample when describing variations of total travel time for the full sample and by demographic groups.[49]

The average increase in travel time from 1975 to 1993 has been 1.67 hours per week or 20 percent for the entire period. From 1993 to 2003, total travel time declined by 1.07 hours per week followed by a further decline of 0.74 hours per week from 2003 to 2013. The differences in mean hours of travel across the three periods (1975-1993, 1993-2003, 2003-2013) are statistically significant. In the past two decades total travel time has declined by 18 percent. The decline puts total travel time in 2013 at an amount statistically indifferent from that in 1975, despite markedly different demographic compositions and transportation environment at those two points.

In Table 4.2 we report results from pooled regressions with all available observations over the five decades. We give equal weight to each year. Columns 2 and 4 report estimation results of regressing total travel time on demographic dummies using the weighted OLS method on two samples. Regression results show that estimated coefficients are statistically significant for demographic dummies based on age, gender, work status, education, and having children or not.[50] Even after controlling

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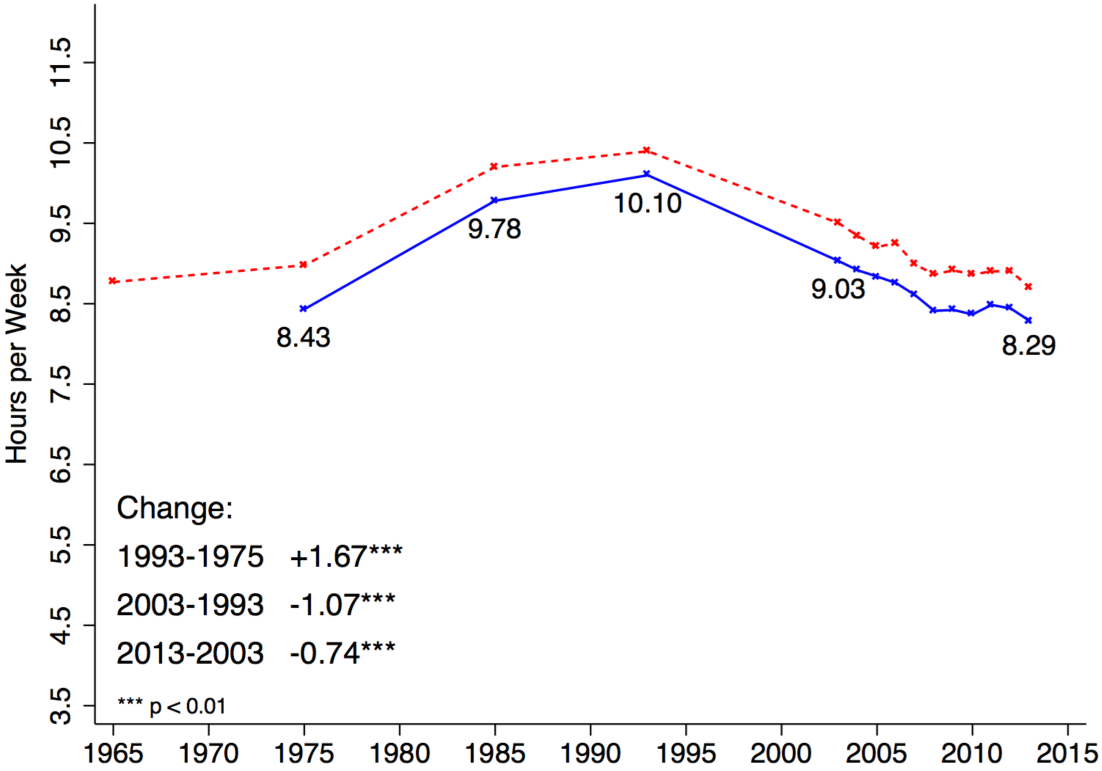
[49] We examine the second sample over the period 1965-2013 in Appendix C.2.

[50] We also run regressions including married status and race dummies. The estimated coefficients of those are insignificant.

Figure 4.1: Total Travel Time Use
(1975-2013 Sample vs. 1965-2013 Sample)



demographic characteristics, total travel time still demonstrates the same trend: first increasing, reaching the peak in the mid-80s or mid-90s, and embarking on a declining trend afterwards.

The pooled regression helps us to identify demographic attributes that may affect total travel time. The results show that those who are younger, male, working or more educated spend more time on travel than others. By pooling observations across all years together, the regression also imposes a restriction that coefficients for demographic attributes are the same for each year. However, the impact of each demographic attribute on total travel time may vary over years, which may be reflected in changes in within-cell means of total travel time. Here within-cell means within a group of people sharing the same demographic characteristics. We next examine evolutions of total travel time by demographic groups.

Table 4.2: Average Total Travel Time Use (Hours per Week)

(Pooled Regression Results)

| | 1975-2013 Sample | | | | 1965-2013 Sample | | | |
|---|---|---|---|---|---|---|---|---|
| | Weighted OLS | | Demographics | | Weighted OLS | | Demographics | |
| | (1) | | (2) | | (3) | | (4) | |
| Survey_1965 | | | | | 8.77*** | (0.10) | 7.05*** | (0.23) |
| Survey_1975 | 8.43*** | (0.09) | 7.78*** | (0.16) | 8.98*** | (0.10) | 7.36*** | (0.22) |
| Survey_1985 | 9.78*** | (0.09) | 8.67*** | (0.16) | 10.20*** | (0.10) | 8.27*** | (0.23) |
| Survey_1993 | 10.10*** | (0.09) | 8.64*** | (0.16) | 10.40*** | (0.10) | 8.16*** | (0.23) |
| Survey_2003 | 9.03*** | (0.09) | 7.73*** | (0.16) | 9.50*** | (0.10) | 7.27*** | (0.23) |
| Survey_2004 | 8.92*** | (0.09) | 7.61*** | (0.16) | 9.34*** | (0.10) | 7.12*** | (0.23) |
| Survey_2005 | 8.84*** | (0.09) | 7.51*** | (0.16) | 9.21*** | (0.10) | 6.95*** | (0.23) |
| Survey_2006 | 8.76*** | (0.09) | 7.44*** | (0.17) | 9.25*** | (0.10) | 7.01*** | (0.23) |
| Survey_2007 | 8.61*** | (0.09) | 7.25*** | (0.17) | 8.99*** | (0.10) | 6.72*** | (0.23) |
| Survey_2008 | 8.41*** | (0.09) | 7.07*** | (0.17) | 8.86*** | (0.10) | 6.59*** | (0.23) |
| Survey_2009 | 8.42*** | (0.09) | 7.12*** | (0.17) | 8.92*** | (0.10) | 6.69*** | (0.23) |
| Survey_2010 | 8.37*** | (0.09) | 7.08*** | (0.16) | 8.86*** | (0.10) | 6.65*** | (0.23) |
| Survey_2011 | 8.49*** | (0.09) | 7.19*** | (0.16) | 8.90*** | (0.10) | 6.68*** | (0.23) |
| Survey_2012 | 8.44*** | (0.09) | 7.16*** | (0.17) | 8.90*** | (0.10) | 6.70*** | (0.23) |
| Survey_2013 | 8.29*** | (0.09) | 7.00*** | (0.17) | 8.70*** | (0.10) | 6.47*** | (0.23) |
| Age:20-49 | | | -1.06*** | (0.14) | | | -0.52*** | (0.20) |
| Age:50-65 | | | -1.57*** | (0.14) | | | -0.97*** | (0.20) |
| Age: 65+ | | | -2.64*** | (0.15) | | | | |
| Male | | | 0.53*** | (0.05) | | | 0.57*** | (0.05) |
| Working | | | 1.68*** | (0.06) | | | 1.71*** | (0.06) |
| Grade:12 | | | 0.67*** | (0.07) | | | 0.51*** | (0.08) |
| Grade:13-15 | | | 1.50*** | (0.08) | | | 1.40*** | (0.09) |
| Grade:16+ | | | 2.21*** | (0.08) | | | 2.03*** | (0.09) |
| Have Child | | | 0.34*** | (0.05) | | | 0.34*** | (0.05) |
| Difference: | | | | | | | | |
| 1993-1965 | | | | | 1.63*** | | | |
| 1993-1975 | 1.67*** | | | | 1.42*** | | | |
| 2003-1993 | -1.07*** | | | | -0.90*** | | | |
| 2013-2003 | -0.74*** | | | | -0.80*** | | | |

Notes: Standard errors in parentheses. $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$.

### 4.3.1 Travel Time Use by Demographic Groups

We divide our sample population by demographic groups for better understanding of travel patterns within our sample population. Based on regression results in Table 4.2, we divide the sample into demographic cells defined by four age groups (18-19, 20-49, 50-64, 65 and up), four education categories (less than high school, high school, some college, and college degree or more), two gender categories, two working status categories, and whether or not there is a child present in the household. We only have the first three education cells for those younger than 20.[51] This division yields 120 cells.[52]

Figure 4.2 displays evolution of total travel time by demographic groups defined respectively by age, work and gender, education and whether or not there is a child in the household. In the following subsections we analyze each panel of Figure 4.2 in detail. Table 4.3 records the data on total travel time used to plot the figure.

#### Travel Time Use by Age Groups

In Panel A of Figure 4.2, we divide the sample by four age-related groups (18-19, 20-49, 50-64, and 65 and above). We pool population between 20 and 49 together as they share more common characteristics of travel than the younger and older population.[53] We separately group those younger than 20 as the time use of this group is strongly affected by education needs.

There are three salient patterns of total travel time by age groups. First, the younger population on average spend more time on travel than the older. Second, the total travel time of all age groups have experienced an increase in travel time since 1975, reached a peak before 2003, and continued to decline for more than a

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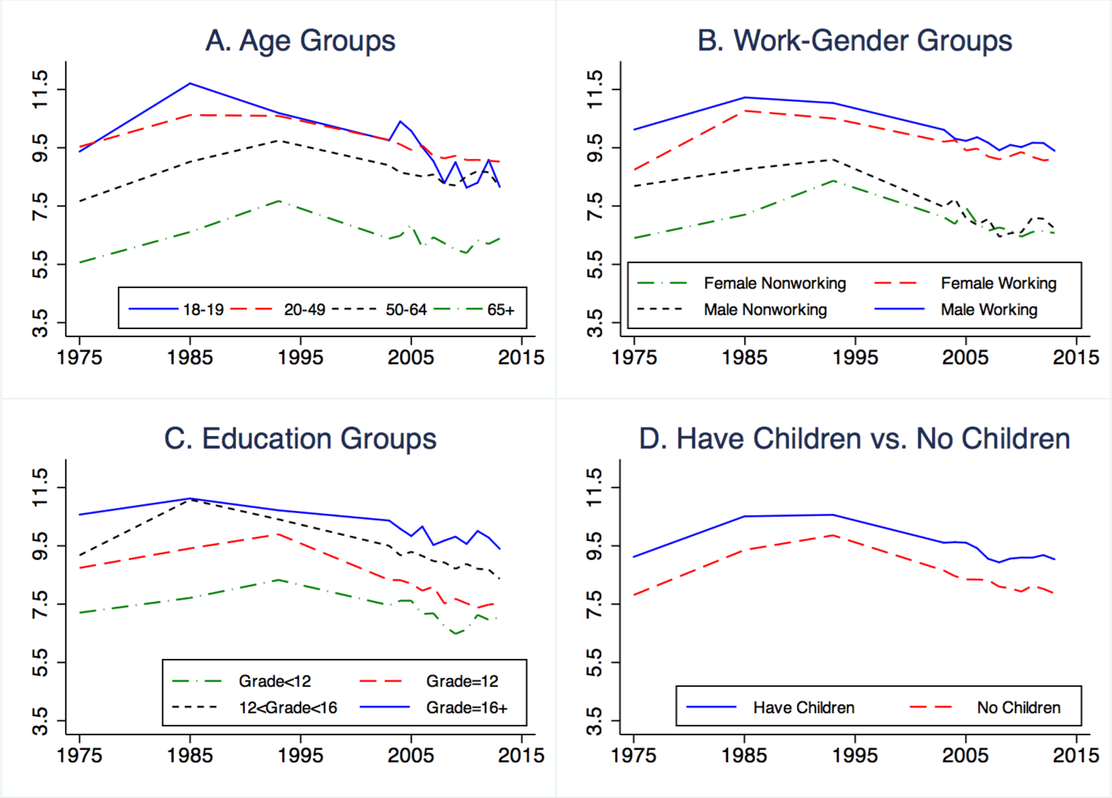
[51] There are only 3 observations whose age are less than 20 while having college (or higher) degrees.

[52] For each age group + education group, there will be eight work-gender and have child or not combinations, so if we drop age under 20 while grade higher than 15, total cells will be 128-8.

[53] For robustness check we have grouped the sample by six groups with those between 20 and 49 divided into 20-29, 30-39 and 40-49. The main decomposition results are similar.

Figure 4.2: Total Travel Time Use by Demographic Groups



decade. Third, the difference in total travel time between the younger population (20-49) and those in the 50-64 age group has been narrowing since 1975, and becomes the narrowest in 2012, before widening again in 2013. The total travel time of younger population (20-49) has declined since 1993, while the travel time of those in the 50-64 age group has increased in the latter half of the recent decade, and in 2012 has almost reached the same level of travel as those in the 20-49 age group.

### Travel Time Use by Work-Gender Groups

We divide the sample population into four groups based on gender and employment. Panel B of Figure 4.2 describes travel patterns by work and gender groups from 1975 to 2013. There are three notable features. First, workers spend consistently more time on travel than non-workers, with a gap close to 3 hours per week between male workers and nonworkers around years 2008-2010. Second, although males in general travel more than females, the gap has been consistently narrowing among both workers and nonworkers. In most of the recent decade female nonworkers travel slightly more than male nonworkers. Third, the total travel time within each work and gender group increased from 1975 and turned downward after reaching the peak some time between mid-eighties and mid-nineties. The turning point for workers came before that for nonworkers.

### Travel Time Use by Education Groups

We divide the sample population by four education categories (less than high school, high school, some college, and college degree or higher). Panel C of Figure 4.2 describes travel patterns by education groups from 1975 to 2013. The panel shows that more educated groups spend more time on travel than less educated. The difference in total travel time between the most and the least educated can be as large as 3.4 hours per week. It also demonstrates the similar time trend as that for the entire sample: a peak and then a decline in total travel time for each education group.

### Travel Time Use by Having Children or Not

Finally, we divide the sample population by whether or not there is a child present in the household. Panel D of Figure 4.2 shows that the sample population with children in the household travel more than those without children. The difference is around one hour or so per week. Total travel time for both groups again follow the similar time trend as travel time for the entire sample population: an increase from 1975 to 1980s and 1990s, and then a graduate decline toward 2013.

Panels A to D of Figure 4.2 show that people who are younger, working, more educated, and have children travel more than their respective counterparts, consistent with estimated coefficients in Table 4.2. Such patterns indicate that shifts in demographic composition may contribute to the evolution of total travel time, even when there are no changes in travel time within each demographic group.

Table 4.3: Average Total Travel Time Use (Hours per Week) by Demographic Groups

| | 1975 | 1985 | 1993 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Panel A: By Age Groups | | | | | | | | | | | | | | |
| 18-19 | 9.37 | 11.71 | 10.69 | 9.75 | 10.40 | 10.07 | 9.52 | 9.04 | 8.28 | 9.01 | 8.13 | 8.30 | 9.09 | 8.16 |
| 20-49 | 9.53 | 10.62 | 10.59 | 9.77 | 9.62 | 9.42 | 9.58 | 9.22 | 9.14 | 9.23 | 9.08 | 9.09 | 9.05 | 9.03 |
| 50-64 | 7.67 | 9.02 | 9.75 | 8.90 | 8.65 | 8.58 | 8.52 | 8.58 | 8.26 | 8.21 | 8.52 | 8.70 | 8.66 | 8.14 |
| 65+ | 5.56 | 6.61 | 7.67 | 6.38 | 6.48 | 6.86 | 6.08 | 6.43 | 6.22 | 6.01 | 5.89 | 6.33 | 6.20 | 6.39 |
| Panel B: By Work-Gender Groups | | | | | | | | | | | | | | |
| Female Nonworker | 6.40 | 7.20 | 8.37 | 7.12 | 6.89 | 7.45 | 6.90 | 6.65 | 6.76 | 6.66 | 6.45 | 6.61 | 6.65 | 6.57 |
| Female Worker | 8.75 | 10.77 | 10.51 | 9.71 | 9.76 | 9.41 | 9.47 | 9.20 | 9.10 | 9.21 | 9.35 | 9.19 | 9.07 | 9.11 |
| Male Nonworker | 8.19 | 8.76 | 9.09 | 7.47 | 7.75 | 7.08 | 6.85 | 7.06 | 6.45 | 6.57 | 6.60 | 7.10 | 7.06 | 6.73 |
| Male Worker | 10.12 | 11.23 | 11.03 | 10.11 | 9.81 | 9.74 | 9.86 | 9.67 | 9.41 | 9.60 | 9.52 | 9.67 | 9.66 | 9.40 |
| Panel C: By Education Levels | | | | | | | | | | | | | | |
| Grade<12 | 7.21 | 7.71 | 8.33 | 7.46 | 7.62 | 7.62 | 7.16 | 7.19 | 6.74 | 6.48 | 6.63 | 7.13 | 6.96 | 7.05 |
| Grade=12 | 8.74 | 9.41 | 9.90 | 8.33 | 8.32 | 8.20 | 7.96 | 8.10 | 7.52 | 7.68 | 7.53 | 7.38 | 7.48 | 7.53 |
| Grade:13-15 | 9.18 | 11.08 | 10.41 | 9.50 | 9.17 | 9.29 | 9.15 | 8.98 | 8.93 | 8.71 | 8.88 | 8.71 | 8.68 | 8.37 |
| Grade=16+ | 10.57 | 11.13 | 10.72 | 10.37 | 10.09 | 9.84 | 10.16 | 9.53 | 9.68 | 9.81 | 9.56 | 10.01 | 9.78 | 9.40 |
| Panel D: By Have Child or Not | | | | | | | | | | | | | | |
| No Child | 7.81 | 9.36 | 9.86 | 8.65 | 8.46 | 8.35 | 8.34 | 8.33 | 8.10 | 8.05 | 7.93 | 8.13 | 8.02 | 7.87 |
| Have Child(ren) | 9.12 | 10.51 | 10.56 | 9.61 | 9.63 | 9.61 | 9.42 | 9.06 | 8.93 | 9.06 | 9.10 | 9.09 | 9.18 | 9.04 |

Note: The calculations of total travel time by demographic groups are based on Analysis Sample 1 (1975-2013).

### 4.3.2 Patterns of Demographic Shifts

Table 4.4 shows the evolving weights of aforementioned demographic groups. Over the period from 1975 to 2013, on average the 20-49 age group makes up 57 percent of our total sample. The 50-64 group and those older than 65 account for around 23 percent and 16 percent respectively. Those between 18 and 19 account for 3 percent of the sample. Over the past decades relative proportions of each age group have registered substantial variations as baby boomers go through each stage of their life cycle. The fraction of population between 20 and 49 increased by 8.5 percent from 1975 to 1993, but declined by 14.5 percent from 1993 to 2013. By contrast, the proportion of those between 50 and 64 declined by 2.6 percent from 1975 to 1993, but increased by 7.8 percent from 1993 to 2013. The fraction of population above 65 have steadily increased since 1993.

Figure 4.3 shows the evolving weights of each age-work-gender group from 1975 to 2013.[54] The first to fourth columns are respectively for the 18-19, 20-49, 50-64, at and older than 65-year-old age groups. Those between 20 and 49 year old constitute the dominant group. It is worth noting that changes in relative weights of male and female workers in this age group coincide with those in total travel time. The relative weight of female workers between 20 and 49 increased from 15 percent to 25 percent of total population from 1975 to 1993, and then declined steadily to roughly 18 percent of total population in 2013. The relative weight of male workers in this age group experienced a small increase from 1975 to 1993, and then a decline of similar magnitude as that of female workers afterwards. The largest decline of the relative weights of working population in this age group occurred from 1993 to 2003, during which period the proportion of male workers declined by 3 percent, while that of female workers declined by 4 percent. Around year 2008 the percentage weights of

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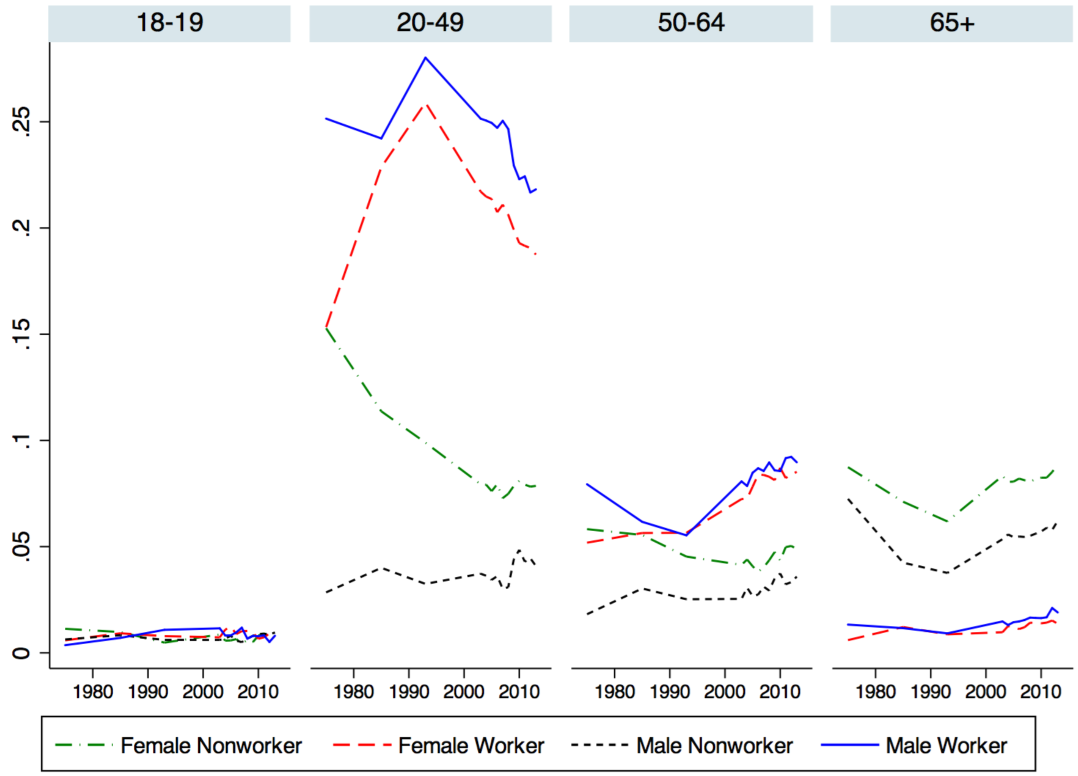
[54] There is an issue of over-sampling of gender in 1993 survey. We may need other information on relative weights for robustness check.

Table 4.4: Evolving Weights (in Percentage) of Demographic Groups

| | 1975 | 1985 | 1993 | 2003 | 2013 | Average 1975-2013 | Difference 1993-1975 | Difference 2003-1993 | Difference 2013-2003 |
|---|---|---|---|---|---|---|---|---|---|
| Panel A: By Age Groups | | | | | | | | | |
| 18-19 | 2.7 | 3.4 | 3.0 | 3.4 | 3.2 | 3.1 | 0.2 | 0.4 | -0.2 |
| 20-49 | 58.6 | 62.4 | 67.1 | 58.5 | 52.5 | 57.2 | 8.5 | -8.5 | -6.0 |
| 50-64 | 20.8 | 20.4 | 18.2 | 22.0 | 26.0 | 23.4 | -2.5 | 3.8 | 4.0 |
| 65+ | 17.9 | 13.7 | 11.7 | 16.1 | 18.4 | 16.3 | -6.2 | 4.4 | 2.2 |
| Panel B: By Work-Gender Groups | | | | | | | | | |
| Female Nonworker | 31.0 | 25.0 | 21.1 | 21.3 | 22.3 | 22.1 | -9.9 | 0.2 | 1.0 |
| Female Worker | 21.7 | 30.6 | 33.2 | 30.7 | 29.4 | 30.2 | 11.5 | -2.6 | -1.3 |
| Male Nonworker | 12.5 | 12.1 | 10.1 | 12.2 | 14.8 | 13.00 | -2.4 | 2.1 | 2.6 |
| Male Worker | 34.8 | 32.2 | 35.5 | 35.8 | 33.5 | 34.7 | 0.8 | 0.3 | -2.4 |
| Panel C: By Education Levels | | | | | | | | | |
| Grade<12 | 38.9 | 17.5 | 10.3 | 15.4 | 11.8 | 15.3 | -28.7 | 5.1 | -3.6 |
| Grade=12 | 35.6 | 43.2 | 36.1 | 32.5 | 30.3 | 33.1 | 0.5 | -3.6 | -2.2 |
| Grade:13-15 | 12.9 | 17.4 | 25.0 | 26.5 | 26.1 | 24.8 | 12.1 | 1.5 | -0.4 |
| Grade=16+ | 12.6 | 21.9 | 28.7 | 25.6 | 31.8 | 26.8 | 16.1 | -3.0 | 6.2 |
| Panel D: By Have Child or Not | | | | | | | | | |
| No Child | 52.8 | 63.2 | 66.0 | 60.6 | 64.2 | 61.9 | 13.2 | -5.4 | 3.5 |
| Have Child(ren) | 47.2 | 36.8 | 34.0 | 39.4 | 35.8 | 38.1 | -13.2 | 5.4 | -3.5 |

working population, both male and female within the 20-49 age group, started a sharp decline. The weight of this age group in our sample declined by 3.3 percent from 2008 to 2013, but the working population of both genders declined by 4.7 percent.

Figure 4.3: Evolving Weights of Age-Work-Gender Groups



Comparably, the percentage weights of working and nonworking population evolve relatively smoothly among the 50-65 age group. The period from 1975 to 1993 is characterized by declines in both total weights, and the relative proportion of male workers of this age group. The total weights and the relative proportion of workers of this age group have increased steadily ever since, with the relative weight of female workers increased by 2.9 percent and that of male by 3.5 percent from 1993 to 2013. In contrast to sharp declines in relative weights of working population among the 20-49 age group around year 2008, there is no obvious downturn in relative working population among the 50-65 age group around that time.

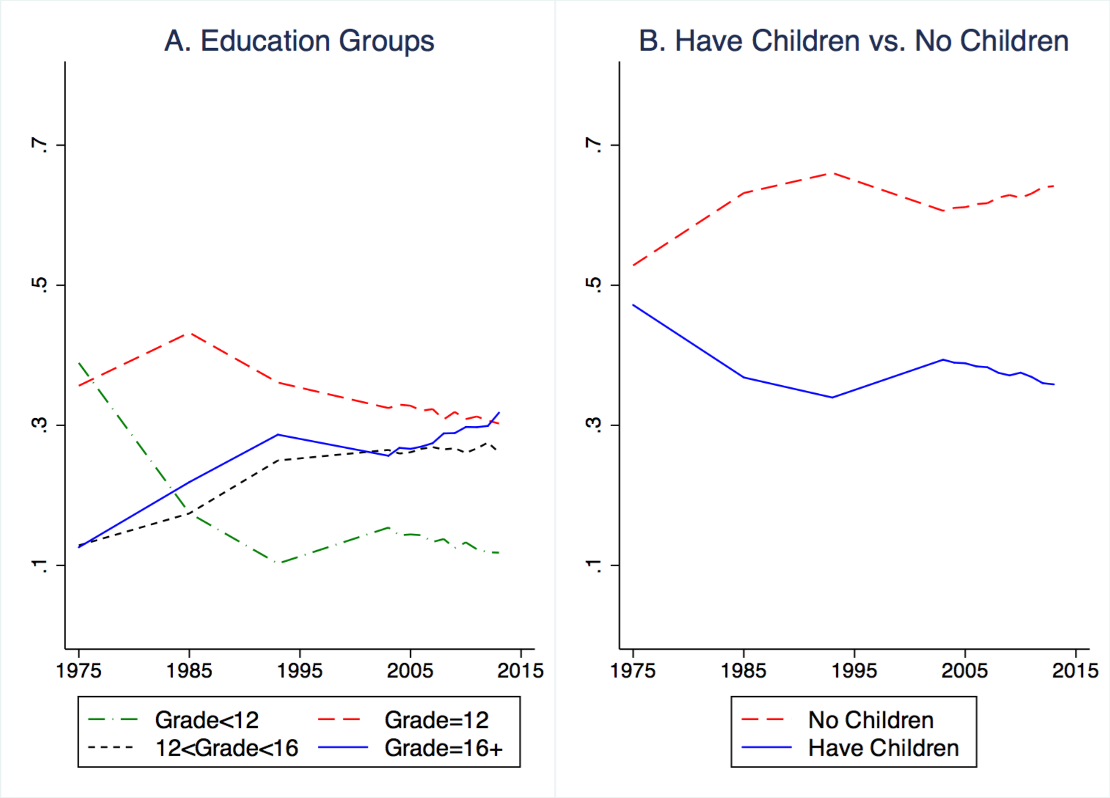
These observations suggest that the shift from working to nonworking population among the 20-49 age group may help to explain patterns of total travel time over time. The increase in relative weights of the working population among the 50-64 age group may help cushion the decline in total travel time of this age group after 1993. The increase in both relative weights of the age group above 65 and the fraction of nonworking population within this group helps to explain the decline in total travel time. However, given the dominant proportion of the 20-49 age group, the shift from work to non-work status of this younger group may have larger impact on the decline in travel time, as compared to such shifts among the age group above 65.

Panel A of Figure 4.4 shows evolving weights of education groups from 1975 to 2013 in the sample population. The proportion of people in the third group (with some college) and the fourth group (college degree or more) have steadily increased over time, each rising from about 13 percent in 1975 to around 30 percent in 2013. The portion with less than high school degree declined from around 39 percent in 1975 to around 10 percent in 1993, and has stayed at that level afterwards. The portion with high school education increased from 1975 to 1985, and declined ever since. However, this group has stayed above 30 percent for the entire sample period, and only recently was surpassed by the group with college degree or more in terms of weights. In 2013, the three groups with highest levels of education each make up about 30 percent of sample population, with those less than high school accounting for the remaining 12 percent.

Panel B of Figure 4.4 shows that the fraction of sample population with children in the household declined from around 47 percent to 34 percent from 1975 to 1993. The weight for this group increased slightly from 1993 to 2003, resumed the decline after 2003 and settled at around 36 percent in 2013.

In summary, major demographic shifts from 1975 to 1993 are: (i) Baby boomers reached prime driving age; (ii) An increasing number of women shifted into working

Figure 4.4: Evolving Weights of Education and With Children Groups



status; (iii) The fraction of population with high school degree and above increased, while the fraction without high school degree declined dramatically; and (iv) the fraction of people with children in the household declined. Based upon travel time patterns by demographic groups, the first three demographic shifts may contribute positively to the increase in travel time during the sample period, while the last shift may contribute negatively.

From 1993 to 2003, the first two demographic shifts reversed themselves. Baby boomers got older from the prime driving age, and labor participation rates of both males and females declined. The reversals may contribute to the decline in total travel time during the sample period. In the meantime, advances in education attainments slowed down, coupled with a decline in the population with college degree or more, and an increase in the fraction of population with less than high school degree. The fraction of sample population with children slightly increased.

The period from 2003 to 2013 witnessed the following demographic changes: (i) Baby boomers started retiring, raising the fraction of population aged 50 and above. (ii) There had been continuing decline in the fraction of working population, especially those in the 20-49 age group. The fraction of working population in the 50-64 age group increased instead. (iii) The fraction of sample population with college or more increased steadily during this period.

## 4.4 Quantifying the Role of Demographic Shifts

In order to understand the change in total travel time use over the past five decades, we seek to distinguish the portion that can be explained by changing demographics and the portion that cannot be explained by demographic shifts, but may be explained by changes in aggregate forces that impact all demographic groups, or by changes in relevances of demographic attributes to travel patterns. The analysis above by each demographic attribute shows that both portions may have played a role in the evolution of total travel time. In this section, we conduct a Blinder-Oaxaca style decomposition of changes in the unconditional mean of total travel time to quantify the contribution of demographic shifts and other forces.

### 4.4.1 Blinder-Oaxaca Decomposition

Formally, total travel time for any given period $t$ can be expressed as the dependent variable of a linear model

$$Y_t = X_t'\beta_t + \varepsilon_t, \tag{4.1}$$

where $Y_t$ represents a vector of total travel time, with its length equal to the number of observations for that year, and $X_t$ represent a matrix of dummy variables that characterize demographic features of all observations. Based upon our analysis of travel time by demographic groups above, we construct nine dummy variables: three dummy variables for age groups, depending upon whether the observed individual is in the 20-49, 50-64 or above 65 year old age group; one dummy variable for gender; one dummy variable for working status; three dummy variables for education groups, depending upon whether the observed individual has high school, some college, or college and above degrees; and one dummy variable for having children in the household. This linear regression allows us to capture the correlation among demographic variables, which are not possible if we examine total travel time along only one dimension.

Let $\widehat{\beta}_{t_0}$ and $\widehat{\beta}_{t_1}$ be the least-square estimates for $\beta$ in periods $t_0$ and $t_1$, obtained separately from the two year-specific samples. Furthermore, use the year-specific sample means $\overline{X}_{t_0}$ and $\overline{X}_{t_1}$ as estimates for unconditional expectation of $X_{t_0}$ and $X_{t1}$. Here $\overline{X}_t$ is a 10-by-1 vector of sample means of the nine dummy variables and the constant at the end. The $j-th$ element of $\overline{X}_t$ is effectively the fraction of sample population with the $j-th$ dummy variable equal to 1. Thus $\overline{X}_{t_1} - \overline{X}_{t_0}$ represent changes in demographic weights, and $\widehat{\beta}_{t_1} - \widehat{\beta}_{t_0}$ represent changes in the relevance of those demographics to total travel time. Based upon these estimates, we can decompose the change in the sample mean of total travel time between year $t_0$ and year $t_1$ as follows:

$$\overline{Y}_{t_1} - \overline{Y}_{t_0} = \left(\overline{X}_{t_1} - \overline{X}_{t_0}\right)' \widehat{\beta}_{t_0} + \overline{X}'_{t_1}\left(\widehat{\beta}_{t_1} - \widehat{\beta}_{t_0}\right). \qquad (4.2)$$

The term $\left(\overline{X}_{t_1} - \overline{X}_{t_0}\right)' \widehat{\beta}_{t_0}$ represents the contribution to the total change in travel time due to evolving demographic weights, given a fixed set of coefficient estimates, while $\overline{X}'_{t_1}\left(\widehat{\beta}_{t_1} - \widehat{\beta}_{t_0}\right)$ represents the contribution due to changes in the relevance of demographics to travel time use, given fixed demographic weights. In the Blinder-Oaxaca literature, the first and second terms are sometimes called the "explained" and "unexplained"portions respectively. Here "unexplained" means unexplained by demographic shifts, but possibly explainable by other forces, including time effects that are reflected in the difference in estimates of the constant term. An alternative would be to use the following decomposition:

$$\overline{Y}_{t_1} - \overline{Y}_{t_0} = \left(\overline{X}_{t_1} - \overline{X}_{t_0}\right)' \widehat{\beta}_{t_1} + \overline{X}'_{t_0} \left(\widehat{\beta}_{t_1} - \widehat{\beta}_{t_0}\right), \tag{4.3}$$

where the coefficient estimates from year $t_1$ sample are used to weigh demographic shifts.

As decomposition results may be sensitive to using the starting or the end year of coefficient estimates to weigh demographic shifts, we also use pooled sample for more representative coefficient estimates, which is to pool year $t_0$ and $t_1$ observations to obtain coefficient estimates (the "pooled-two" method). Appendix C.3 describes the details of the pooled sample estimation.

We also conduct an alternative Blinder-Oaxaca decomposition by forming 120 cells based upon demographic dummies as described in Section 4.2.2. The change in the unconditional mean between year $t_0$ and year $t_1$ can be decomposed as:

$$\begin{aligned} \overline{Y}_{t_1} - \overline{Y}_{t_0} &= w'_{t_1} y_{t_1} - w'_{t_0} y_{t_0} \\ &= \left(w'_{t_1} - w'_{t_0}\right) y_{t_1} + w'_{t_0} \left(y_{t_1} - y_{t_0}\right), \end{aligned} \tag{4.4}$$

where $\overline{Y}_t$ represents the unconditional mean of travel time in year $t$, $w_t$ represents the vector of demographic weights for each demographic cell at period $t$, and $y_t$ represents the vector of cell means in year $t$. Here variations in demographic components are weighed by $y_{t_1}$, the vector of cell means in $t_1$, while changes in travel patterns are weighted by $w'_{t_0}$, demographic weights in the base year. This method of decomposition shows that the portion unexplained by demographic shifts (the second term) represents changes in cell means within each demographic group. The decomposition results with regard to the division of explained and unexplained portions are similar to those obtained using the linear regression method, but the latter has the added benefits of allowing a detailed decomposition of each demographic component.

### 4.4.2 The Role of Demographic Shifts

Table 4.5 shows the decomposition of unconditional changes in total travel time for the three subperiods: 1975-1993, 1993-2003 and 2003-2013. We divide the sample period into three subperiods as these periods feature drastically different trends in both travel time and demographics. Panels A, B, and C report the decomposition results for the three subperiods. In all panels, the first column reports decomposition results using the "pooled-two" method, while the second and third columns report results using equations (4.2) and (4.3). Since the results are broadly similar using different coefficient estimates, we focus on the pooled-two decomposition results. The fourth column gives the ratio of explained or unexplained part relative to total difference.

The first part of Panel A shows the overall decomposition results. The first and second rows show the average total travel time in years 1993 and 1975, with the difference being 1.67 hours per week as shown in the third row. The fourth row reports the portion of difference explained by demographic shifts and the fifth row captures the rest. The numbers in fourth and fifth rows add up to the total difference reported in the third row. The decomposition shows that 45 percent of the difference in total travel time from 1975 to 1993 can be explained by demographic shifts.

The second part of Panel A details the individual contribution of each demographic attribute. The four rows in the second part add up to the total "explained" portion in row four of part one. Out of the 45 percent explainable by demographic shifts, advances in education attainment alone contribute to roughly 28 percent of the increase in total travel time for this subperiod. 10.5 percent are explained by changes in age composition. Shifts across work-gender groups, including the increase in female labor force contribution contribute to 7.1 percent of the increase in total travel, while the rest is explained by declines in the proportion of sample population with children in that sample period, which moves total travel time in opposite direction. In all, demographic shifts in age, work-gender, and education contribute positively to the increase in total travel time for this sample period. It is interesting to note that once education is controlled for, shifts in age composition play lesser roles. The third part of Panel A reports the individual contribution of changes in each coefficient estimate to evolution of total travel time.

Panel B shows that total travel time declined by 1.07 hours per week from 1993 to 2003. However, demographic shifts can only explain around 16 percent of the decline. Shifts in age, work-gender and education composition all contribute to the decline in the total travel time, with shifts in the composition of age and education groups respectively accounting for 8.9 and 6.3 percent of the decline. Shifts across work-gender groups contribute to around 1.8 percent of the decline, while increases in the fraction of people with children during this period push the total travel time in the opposite direction, albeit by a small amount.

Panel C shows that total travel time declined by 0.74 hours per week from 2003 to 2013. Contrary to previous periods, contribution from demographic shifts is statistically insignificant, while the decline not explained by demographic shifts amounts to 0.73 hours per week. Detailed decomposition of the explained part shows countering forces of demographic shifts. Changing compositions across age, work-gender groups and population with and without children reduce total travel time by 0.12 hours per week. However, increases in the fraction of people with higher education add an extra 0.11 hour-per-week travel time, completely offsetting the combined impact of those three demographic shifts. The significance of unexplained part of the total change in the travel time indicate that there may be aggregate forces at work from 2003 to 2013 that impact all demographic groups. [55]

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[55] Table C.4 in Appendix C.2 shows the decomposition results from 1965 to 2013.

Table 4.5: Blinder-Oaxaca Decomposition of Total Travel Time

Panel A: 1975 -1993

| | (1)<br>Pooled-two | (2)<br>Ref_1993 | (3)<br>Ref_2003 | (4)<br>Ratio |
|---|---|---|---|---|
| **Overall** | | | | |
| Survey_1993 | $10.10^{***}$ | $10.10^{***}$ | $10.10^{***}$ | |
| | (0.10) | (0.15) | (0.15) | |
| Survey_1975 | $8.43^{***}$ | $8.43^{***}$ | $8.43^{***}$ | |
| | (0.42) | (0.20) | (0.20) | |
| Difference | $1.67^{***}$ | $1.67^{***}$ | $1.67^{***}$ | |
| | (0.43) | (0.25) | (0.25) | |
| Explained | $0.75^{***}$ | $0.90^{***}$ | $0.65^{***}$ | 45.2% |
| | (0.12) | (0.17) | (0.14) | |
| Unexplained | $0.91^{**}$ | $0.76^{***}$ | $1.02^{***}$ | 54.8% |
| | (0.43) | (0.28) | (0.28) | |
| **Explained** | | | | |
| Age | $0.18^{***}$ | $0.25^{***}$ | $0.11^{***}$ | 10.5% |
| | (0.04) | (0.06) | (0.04) | |
| Work-Gender | $0.12^{***}$ | 0.08 | $0.15^{***}$ | 7.1% |
| | (0.04) | (0.07) | (0.05) | |
| Education | $0.47^{***}$ | $0.53^{***}$ | $0.41^{***}$ | 27.9% |
| | (0.10) | (0.14) | (0.13) | |
| Child | -0.01 | 0.05 | -0.03 | -0.3% |
| | (0.04) | (0.06) | (0.05) | |
| **Unexplained** | | | | |
| Age | -0.20 | -0.28 | -0.14 | |
| | (0.63) | (0.37) | (0.34) | |
| Work-Gender | -0.32 | -0.28 | -0.36 | |
| | (0.61) | (0.41) | (0.35) | |
| Education | 0.06 | -0.00 | 0.11 | |
| | (0.17) | (0.09) | (0.13) | |
| Child | 0.26 | 0.21 | 0.29 | |
| | (0.47) | (0.21) | (0.29) | |
| Constant | 1.12 | $1.12^{**}$ | $1.12^{**}$ | |
| | (0.96) | (0.55) | (0.55) | |

Notes: $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$. Robust Standard Errors in Parentheses. The ratio of explained or unexplained part relative to total difference in column (4) is calculated based on the pooled-two method.

Table 4.5 Continued: Blinder-Oaxaca Decomposition of Total Travel Time

Panel B: 1993 -2003

| | (1) Pooled-two | (2) Ref_1993 | (3) Ref_2003 | (4) Ratio |
|---|---|---|---|---|
| **Overall** | | | | |
| Survey_2003 | $9.03^{***}$ | $9.03^{***}$ | $9.03^{***}$ | |
| | (0.06) | (0.09) | (0.09) | |
| Survey_1993 | $10.10^{***}$ | $10.10^{***}$ | $10.10^{***}$ | |
| | (0.28) | (0.15) | (0.15) | |
| Difference | $-1.07^{***}$ | $-1.07^{***}$ | $-1.07^{***}$ | |
| | (0.29) | (0.17) | (0.17) | |
| Explained | $-0.18^{***}$ | $-0.15^{***}$ | $-0.21^{***}$ | 16.0% |
| | (0.03) | (0.05) | (0.04) | |
| Unexplained | $-0.89^{***}$ | $-0.91^{***}$ | $-0.86^{***}$ | 84.0% |
| | (0.29) | (0.18) | (0.18) | |
| **Explained** | | | | |
| Age | $-0.10^{***}$ | $-0.09^{***}$ | $-0.11^{***}$ | 8.9% |
| | (0.02) | (0.03) | (0.02) | |
| Work-Gender | -0.02 | -0.02 | $-0.03^{*}$ | 1.8% |
| | (0.01) | (0.02) | (0.01) | |
| Education | $-0.06^{***}$ | $-0.06^{**}$ | $-0.07^{***}$ | 6.3% |
| | (0.02) | (0.02) | (0.02) | |
| Child | 0.01 | 0.01 | 0.00 | -1.0% |
| | (0.01) | (0.02) | (0.01) | |
| **Unexplained** | | | | |
| Age | -0.13 | -0.14 | -0.12 | |
| | (0.37) | (0.22) | (0.24) | |
| Work-Gender | 0.08 | 0.07 | 0.08 | |
| | (0.51) | (0.31) | (0.32) | |
| Education | -0.01 | -0.01 | -0.01 | |
| | (0.12) | (0.05) | (0.08) | |
| Child | -0.05 | -0.05 | -0.04 | |
| | (0.25) | (0.17) | (0.15) | |
| Constant | -0.79 | $-0.79^{**}$ | $-0.79^{**}$ | |
| | (0.63) | (0.39) | (0.39) | |

Notes: $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$. Robust Standard Errors in Parentheses. The ratio of explained or unexplained part relative to total difference in column (4) is calculated based on the pooled-two method.

Table 4.5 Continued: Blinder-Oaxaca Decomposition of Total Travel Time

| Panel C: 2003 - 2013 | | | | |
|---|---|---|---|---|
| | (1) Pooled-two | (2) Ref_1993 | (3) Ref_2003 | (4) Ratio |
| **Overall** | | | | |
| Survey_2013 | $8.29^{***}$ | $8.29^{***}$ | $8.29^{***}$ | |
| | (0.15) | (0.11) | (0.11) | |
| Survey_2003 | $9.03^{***}$ | $9.03^{***}$ | $9.03^{***}$ | |
| | (0.07) | (0.09) | (0.09) | |
| Difference | $-0.74^{***}$ | $-0.74^{***}$ | $-0.74^{***}$ | |
| | (0.17) | (0.14) | (0.14) | |
| Explained | -0.02 | -0.00 | -0.03 | 2.2% |
| | (0.02) | (0.03) | (0.03) | |
| Unexplained | $-0.73^{***}$ | $-0.74^{***}$ | $-0.71^{***}$ | 97.8% |
| | (0.17) | (0.14) | (0.14) | |
| **Explained** | | | | |
| Age | $-0.05^{***}$ | $-0.07^{***}$ | $-0.04^{**}$ | 7.4% |
| | (0.01) | (0.02) | (0.02) | |
| Work-Gender | $-0.06^{***}$ | $-0.05^{***}$ | $-0.07^{***}$ | 8.2% |
| | (0.01) | (0.01) | (0.01) | |
| Education | $0.11^{***}$ | $0.13^{***}$ | $0.10^{***}$ | -15.0% |
| | (0.01) | (0.02) | (0.02) | |
| Child | $-0.01^{*}$ | -0.00 | $-0.02^{**}$ | 1.6% |
| | (0.01) | (0.01) | (0.01) | |
| **Unexplained** | | | | |
| Age | 0.13 | 0.15 | 0.12 | |
| | (0.23) | (0.19) | (0.19) | |
| Work-Gender | 0.14 | 0.13 | 0.15 | |
| | (0.30) | (0.24) | (0.25) | |
| Education | -0.06 | -0.08 | -0.05 | |
| | (0.06) | (0.06) | (0.04) | |
| Child | 0.17 | 0.16 | 0.18 | |
| | (0.14) | (0.12) | (0.13) | |
| Constant | $-1.10^{***}$ | $-1.10^{***}$ | $-1.10^{***}$ | |
| | (0.42) | (0.35) | (0.35) | |

Notes: $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$. Robust Standard Errors in Parentheses. The ratio of explained or unexplained part relative to total difference in column (4) is calculated based on the pooled-two method.

### 4.4.3 Summary of Decomposition Results

We have the following main findings using Blinder-Oaxaca decomposition:

(i) Demographic shifts can explain roughly 45 percent of the increase in total travel time from 1975 to 1993, nearly 17 percent of the decline from 1993 to 2003, but have insignificant effect on the decline in total travel time from 2003 to 2013 due to compensating forces of shifts.

(ii) Shifts in the composition of education attainments play prominent roles in driving up the total travel time in two subperiods: 1975-1993 and 2003-2013, dominating other demographic factors in those two periods. Declines in education attainment also contribute to the decline in total travel time from 1993 to 2003.

(iii) Shifts across age and work-gender groups combined explain roughly 18 percent of the increase in total travel time from 1975 to 1993, about 11 percent of the decline from 1993 to 2003, and nearly 16 percent of the decline in the most recent decade.

(iv) From period 2003 to 2013, aggregate forces common to all demographic groups may be at work in driving down the total travel time.

Our analysis supports the view that although baby boomers going into retirement may contribute to the change in travel time in the future, it is unlikely the major reason for the decline in travel time from 2003 to 2013, or from 1993 to 2013. First, although people in their 50s travel less than those in their 30s, the travel of the senior age group actually increased in the past ten years, while the travel of those in the 30s declined over time, thus almost closing the gap between the two age groups. Second, drastic changes in the demographic shifts appeared after 2008, and showed strongly in the work travel. The intensified shift of population from working to nonworking population seems to be an important force behind the change in the travel pattern, and the shift to nonworking population is not unique to senior population. As the oldest cohort among the baby boomers reached the retirement age in 2011, changing age demographics may become more important in the coming decades, but it is not a major contributor to the decline in the total travel time in the past decade.

## 4.5 Travel Time as Part of Time Allocation

The previous analysis indicates that the portion not explained by demographic shifts also plays important roles, especially from 2003 to 2013. Equation (4.2) shows that the unexplained portion reflects variations in both time trends common to all demographic groups and within-cell means of demographic cells defined by a combination of demographic characteristics. As shown in Figure 4.2, there are similar time trends of total travel time within each demographic group, which indicate that aggregate forces common to all demographic groups may be at work driving the portion of variations in total travel time not explained by demographic shifts.

In this section we make use of the data on the time use of respondents on all activities, and treat travel time as part of the individual's time allocation. We ask the following questions: How travel time, both total travel time and disaggregated travel time, co-vary with other time use categories across all demographic groups? What can we say about aggregate forces behind fluctuations in total travel time, especially the decline after 2003?

In order to address these questions, we focus on three aspects of travel time allocation. First, we examine whether there are evidence for or against economizing on travel. Here economizing on travel is reflected in the decline of the ratio of travel to non-travel time related to the same category of activity, for example, the ratio of time spent on work travel to on market work. Economizing on travel is most likely caused by aggregate forces related to the transportation sector, such as fluctuation in gasoline prices, or changes in transportation technology. Second, we examine whether there are shifts of time among activities with different travel intensity. Even absent economizing on travel, a shift of time use from more travel-intensive to less travel-intensive activity may cause the total travel time to decline. Third, we study common complementary or substitutionary patterns of travel time with other time uses. Co-variation of travel time with other time use categories may be driven by forces within or outside the transportation sector. Examining these three aspects gives us a comprehensive picture of variations in travel time.

In the following analysis, we first focus on the short sample period from 2003 to 2013 before taking a long-run perspective on the entire sample period from 1975 to 2013. We focus on the period from 2003 to 2013 for two reasons: First, variations in total travel time in this sample period are dominated by factors other than demographic shifts, potentially aggregate forces that may last into future decades; Second, the time use data for this period are not only annual, but also most detailed and consistent across all time-use surveys. Consistency of disaggregated travel measures becomes an issue when we extend the sample period backward to include 1975, 1985 and 1993 time-use surveys. While the 2003-2013 time-use surveys contain 57 or more detailed measures of travel time, those in previous years contain only 9 or 10 measures. For consistency we have to use slightly different measures of travel time to track variations in disaggregated travel time over the entire sample period. Taking all the consideration together, we decide to examine the most recent decade first to make use of the rich data we have.

### 4.5.1 The Recent Decade: 2003-2013

As described in Section 4.2, we have relatively consistent measures of the following travel time categories: work travel, non-market work travel and leisure travel. Their corresponding non-travel time use activities are: market work, non-market work, and leisure. For this sample period we use the broadly based measure of leisure time that includes eating, sleeping, personal care and other religious and civil activities.

Tele-commuting and e-commerce are two primary means of economizing on travel. Based upon Census Bureau data (FRED, quarterly, seasonally adjusted), e-commerce retail sales only make up for about 1.5 percent of total sales at the beginning of 2003, and about 6 percent in 2014.

When there exists a decline in travel time, there are always issues of whether the decline is due to less travel time associated with each specific activity, or less time is allocated to travel-intensive activities even though the time needed for travel related to each activity remains unchanged. We examine the two possibilities below.

### Shift of Time Allocation or Economizing on Travel?

Figure 4.5 shows the composition of average time use out of 168 hours per week in 2003. The broad measure of leisure makes up 112.2 hours, followed by 24.9 hours for market work and 19.2 hours for non-market work. Work travel, non-market work travel and leisure travel respectively total 2.1, 3.5 and 2.9 hours per week.[56] The remaining 3.1 hours are for other time uses and related travel, including time use and travel related to education. As shown in the pie chart, non-market work is the most travel-intensive activity during the recent decade. The ratio of travel time over non-travel time related to non-market work ranges between 0.15 and 0.17. Non-travel leisure accounts for the highest amount of total time use. However, leisure is also the least travel-intensive activity, with the ratio of leisure-related travel and non-travel time at around 0.025. The ratio remains smallest even after we exclude sleeping time from leisure-related non-travel time use. Travel related to work is about 8 percent of total non-travel work time, for both the working population and the entire sample.

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[56] The average time of work travel is 3.14 hours per week for workers, and 2.14 hours per week for all, including nonworkers.

Market work is the second most travel intensive activity.

Figure 4.5: Composition of Average Time Use (2003)

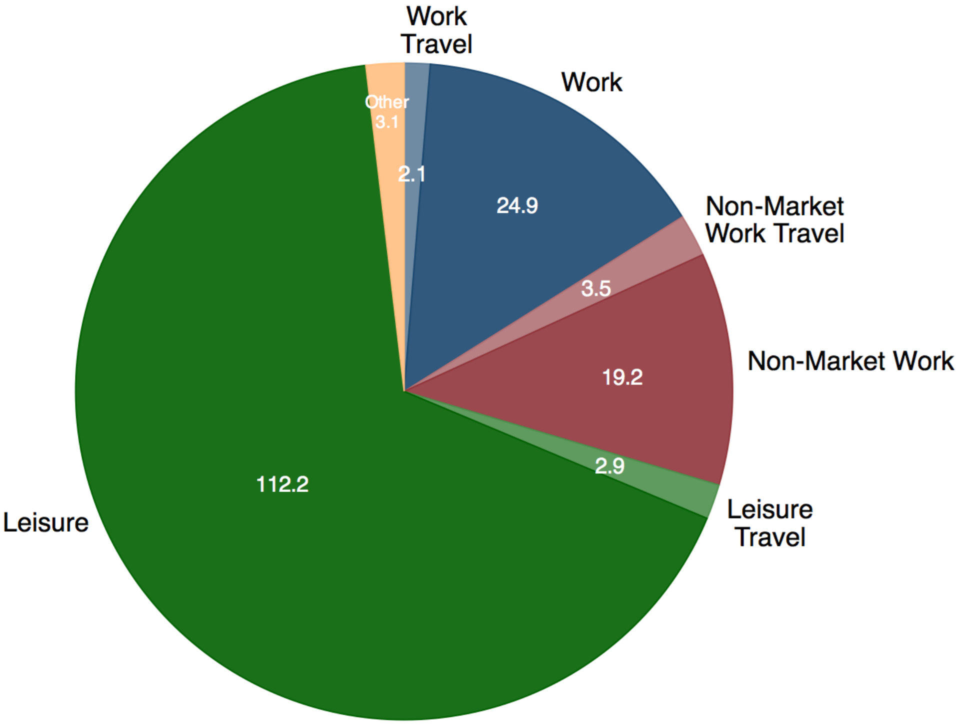


Table 4.6 reports average time spent on major time use categories as well as disaggregated categories from 2003 to 2013. Using the data from Table 4.6, Figure 4.6 shows the relationship between work travel, non-market work travel, leisure travel and the corresponding time use on market work, non-market work and leisure. The solid lines in all panels plot percentage changes of non-travel time, while the dashed lines plot those of travel time for each corresponding activity from 2003 to 2013, using 2003 as the base year.

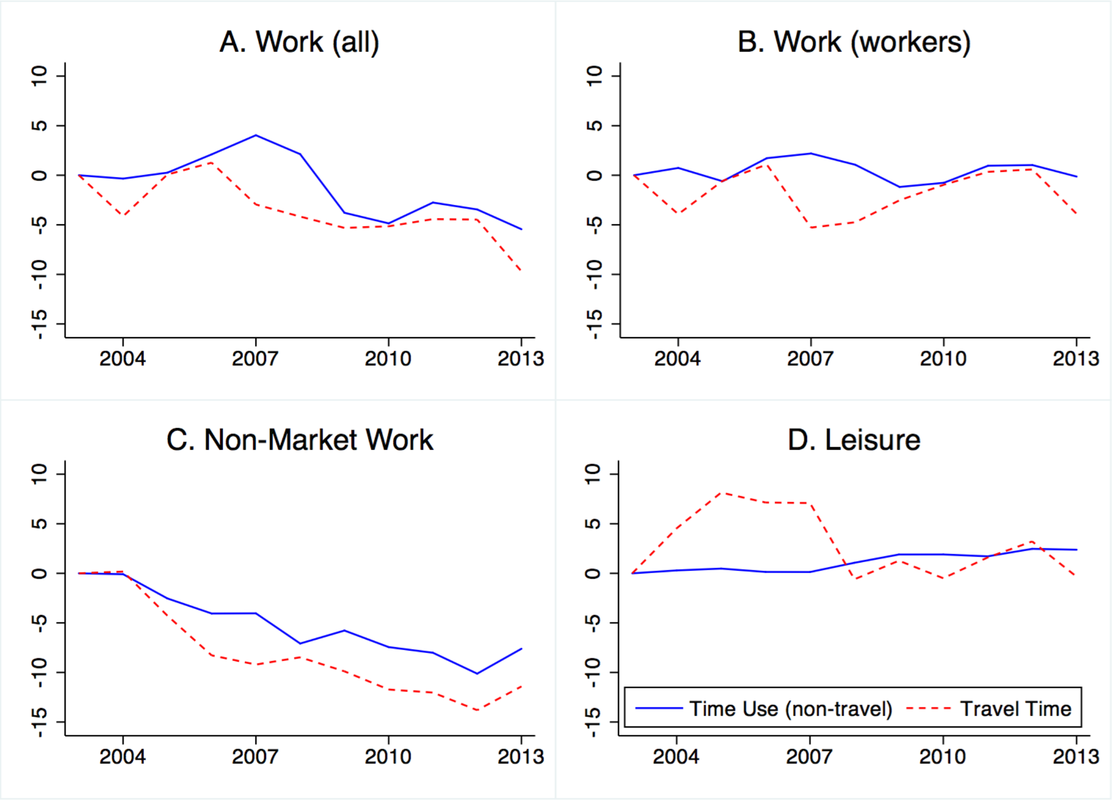
Panel A of Figure 4.6 shows percentage changes of market work versus those of work travel for the entire sample. Time spent on market work increased initially by 4.2 percent relative to that in 2003, declined to 4.7 percent below after the great recession, and stayed around that level till 2013. The change in market work, however,

Table 4.6: Disaggregated Time Use (Hours per Week) 2003-2013

| | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | Difference 2013-2003 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Panel A: Major Time Use Categories | | | | | | | | | | | | | |
| Work Travel | 2.14 | 2.05 | 2.14 | 2.16 | 2.07 | 2.05 | 2.02 | 2.03 | 2.04 | 2.04 | 1.93 | -0.21*** | -9.7% |
| Work | 24.88 | 24.79 | 24.94 | 25.40 | 25.88 | 25.41 | 23.94 | 23.67 | 24.19 | 24.02 | 23.52 | -1.35*** | -5.4% |
| Work Travel (workers) | 3.14 | 3.02 | 3.12 | 3.17 | 2.97 | 2.99 | 3.06 | 3.11 | 3.15 | 3.16 | 3.02 | -0.12 | -3.9% |
| Work (workers) | 36.89 | 37.15 | 36.69 | 37.53 | 37.70 | 37.28 | 36.46 | 36.61 | 37.25 | 37.27 | 36.84 | -0.05 | 0.1% |
| Non-Market Work Travel | 3.50 | 3.51 | 3.35 | 3.21 | 3.18 | 3.21 | 3.16 | 3.09 | 3.08 | 3.02 | 3.10 | -0.40*** | -11.4% |
| Non-Market Work | 19.22 | 19.21 | 18.74 | 18.44 | 18.45 | 17.86 | 18.11 | 17.79 | 17.68 | 17.28 | 17.76 | -1.46*** | -7.6% |
| Leisure Travel | 2.88 | 3.01 | 3.11 | 3.09 | 3.08 | 2.86 | 2.92 | 2.87 | 2.93 | 2.97 | 2.87 | -0.01 | -0.3% |
| Leisure | 112.25 | 112.58 | 112.78 | 112.41 | 112.39 | 113.44 | 114.38 | 114.38 | 114.17 | 115.02 | 114.92 | 2.68*** | 2.4% |
| Panel B: Time Use Categories in Non-Market Work | | | | | | | | | | | | | |
| Child Care Travel | 0.59 | 0.57 | 0.62 | 0.57 | 0.57 | 0.59 | 0.56 | 0.54 | 0.56 | 0.54 | 0.57 | -0.01 | -1.9% |
| Child Care | 3.74 | 3.74 | 3.69 | 3.56 | 3.57 | 3.68 | 3.61 | 3.46 | 3.43 | 3.42 | 3.51 | -0.24* | -6.4% |
| Other Care Travel | 0.66 | 0.64 | 0.53 | 0.44 | 0.44 | 0.45 | 0.44 | 0.46 | 0.43 | 0.43 | 0.44 | -0.23*** | -34.0% |
| Other Care | 1.09 | 1.15 | 0.81 | 0.82 | 0.76 | 0.79 | 0.74 | 0.78 | 0.75 | 0.64 | 0.71 | -0.37*** | -34.3% |
| Home Travel | 0.28 | 0.28 | 0.26 | 0.26 | 0.27 | 0.25 | 0.30 | 0.28 | 0.29 | 0.26 | 0.26 | -0.01 | -4.8% |
| Home Production | 11.05 | 10.95 | 10.91 | 10.71 | 10.89 | 10.27 | 10.70 | 10.51 | 10.49 | 10.34 | 10.56 | -0.49*** | -4.4% |
| Obtaining Travel | 1.98 | 2.02 | 1.94 | 1.95 | 1.90 | 1.92 | 1.86 | 1.82 | 1.79 | 1.80 | 1.83 | -0.15*** | -7.6% |
| Obtaining | 3.35 | 3.37 | 3.32 | 3.36 | 3.24 | 3.12 | 3.06 | 3.05 | 3.01 | 2.89 | 2.98 | -0.36*** | -10.8% |

$^{*}p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$

Figure 4.6: Percentage Change of Time Use from 2003



also reflects shifts out of the working status. In order to focus on time spent on work travel by those who work, we plot percentage changes in time spent on market work by workers only in Panel B. For those who work, the change in the time spent on market work from 2003 to 2013 is statistically insignificant. Thus the decline in time spent on market work after 2007 is driven by shifts out of work status, rather than the decline in work time of those who work. Panels A and B show similar patterns of work travel prior to year 2007. Although work travel for the entire sample population stays at 5 percent below the 2003 level from 2007 to 2012, time spent on work travel by those who work has gone up and reverted to the level in 2003 by 2010. Between 2010 and 2012, percentage changes in both market work and work travel are close to zero compared to 2003, implying that the ratio of work travel to market work in those years is close to that in 2003. Although time spent on work travel declined from

2012 to 2013 relative to market work for the working population, the difference in work travel between 2003 and 2013 is statistically insignificant for this group. In all, there is not strong evidence indicating economizing on work travel, that is, a decline in time spent on work travel relative to that on market work.

Panels C and D of Figure 4.6 show a steady shift of time use from non-market work to leisure during this decade. Non-market work time declined steadily over time in the sample period from 2003 to 2013. As shown in Table 4.6, time spent on non-market work is 1.94 hours per week less in 2012, and 1.46 hours less in 2013 as compared to that in 2003. Leisure time remained fairly stable prior to 2007, but increased by roughly 2 hours per week from 2007 to 2009, and then continued a slightly increase (around 0.5 hour) afterwards. Since 2007, there has also been a shift of time from market work time to leisure driven by the shift from working to nonworking population. Since leisure is the least travel-intensive activity, the shift of time use from travel-intensive non-market and market work to leisure may lead to a decline in travel time even without any economizing on travel.

Panel C shows that non-market work travel declined steadily over time, mirroring the decline in non-market work time. In 2012 it is 0.48 hours per week less than that in 2003, and in 2013 0.4 hours less. By contrast, travel time related to leisure has barely changed, as shown in Panel D. There is some evidence for economizing on travel in terms of a decline in the ratio of leisure travel to leisure time. However, since leisure travel registers no significant change from 2003 to 2013, economizing on leisure travel does not contribute to the decline in total travel time.

There is no strong evidence supporting economizing on travel for activities related to market work and leisure. There seems to be evidence for economizing on non-market work travel as Panel C shows the travel time declining more than the corresponding non-travel portion of non-market work. The larger decline in travel time may indicate economizing on travel, or shifts of time allocation within non-market work. A detailed analysis of non-market work supports the latter explanation.

Figure 4.7 displays the composition of non-travel and travel-related non-market activities. The chart shows that within non-market work category, obtaining goods and services and other care are the two most travel-intensive activities, while home production is the least travel-intensive activity. Travel time spent on obtaining goods and services make up around 57 percent of non-market work travel.

Figure 4.7: Composition of Average Non-Market Work Time (2003)

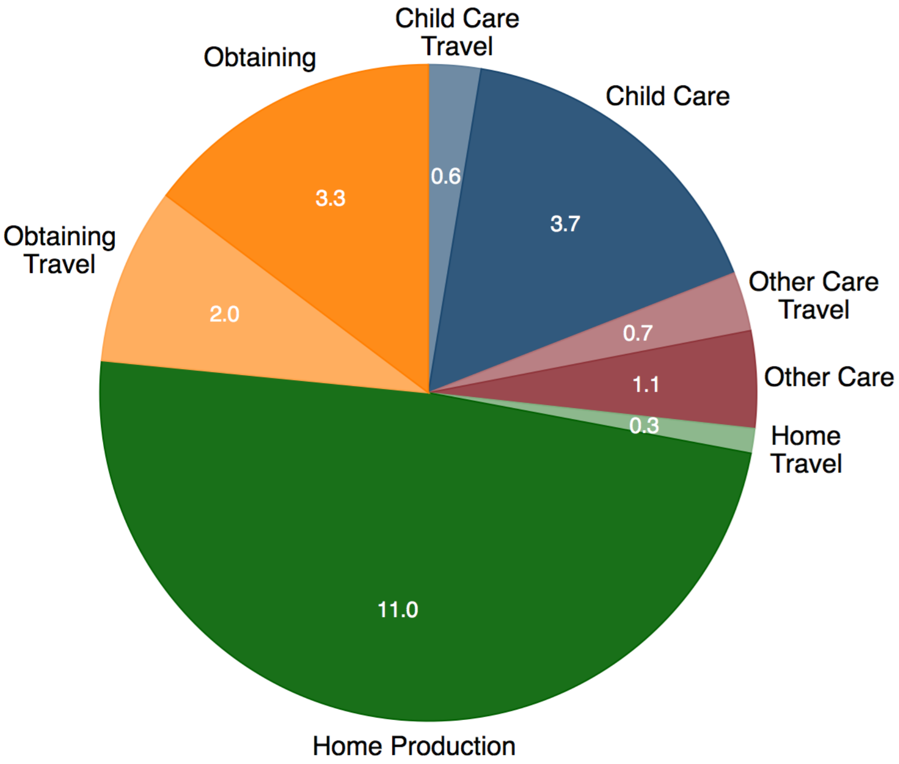
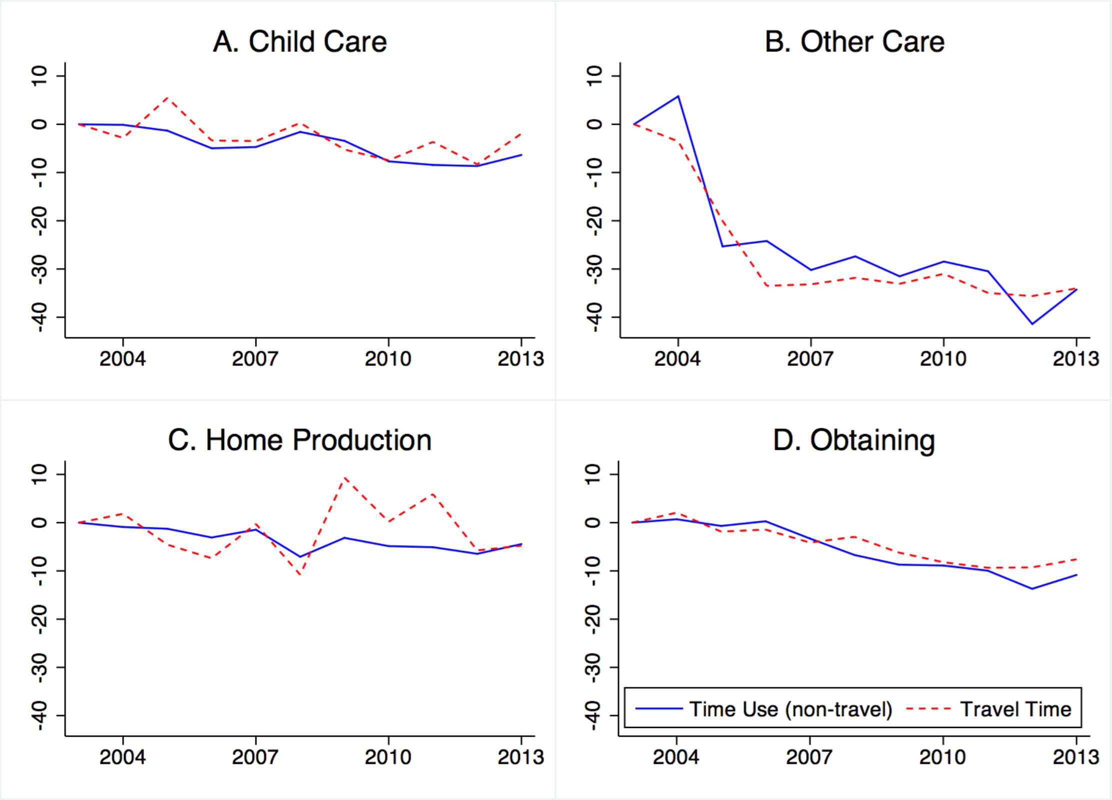


Figure 4.8 shows the evolution of non-travel and travel time related each category of non-market activities. Statistical tests show that time spent on child care travel and home production travel in 2013 is insignificantly different from that in 2003. The declines in travel time related to obtaining goods and services and other care are the main driving forces in the decline in travel time related to non-market work. Moreover, the ratio of travel to non-travel time related to obtaining goods and services and other

care have been relatively constant in the past decade. The relatively constant ratios indicate that there is no strong evidence on economizing on travel for non-market work activities.

Figure 4.8: Percentage Change of Time Use in Non-market Work from 2003



A careful examination of Figure 4.8 reveals a shift of time allocation from more travel-intensive activities such as obtaining and other care to less travel-intensive activity such as home production. Referring to Table 4.6, non-travel time related to obtaining and other care have shown statistically significant (1 percent) declines, proportional to declines in related travel time. The decline in home production is statistically significant at 5 percent level. The decline in non-market work travel is more likely due to shift of time allocation from more travel-intensive to less travel-intensive activity within the non-market work category, rather than economizing on travel.

### Decomposition of Disaggregated Travel Time

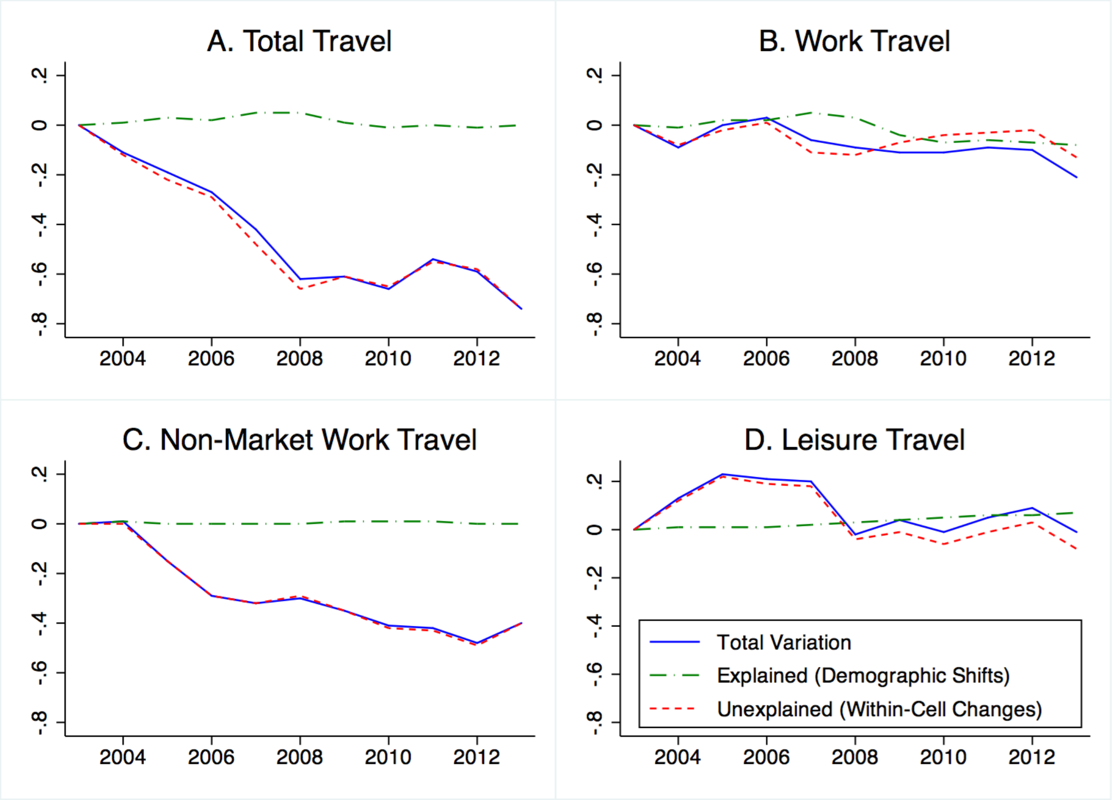
We conduct a Blinder-Oaxaca Style decomposition of the unconditional mean change in total and disaggregated travel for each year from 2004 to 2013, using 2003 as the base year. Since the change in leisure travel is statistically insignificant in this period, we focus on decomposition of market and non-market work travel.

Figure 4.9 plots total variations, the explained portion (contribution from demographic shifts) and the unexplained portion (contribution from time effects and changes in within-cell means) for total travel, work travel, non-market work travel, and leisure travel for each year, relative to their respective levels in 2003. Consistent with the decomposition results in Section 4.4, contribution from demographic shifts is close to zero throughout the 2003-2013 period. Prior to the great recession demographic shifts contribute little to variations in work travel, but after 2008, shifts in demographic composition have pushed work travel downward, while the unexplained portion has been reverting to its level in 2003. In the end, more than half of the 0.2 hour-per-week decline in work travel time is caused by demographic shifts, likely the shift out of working population in the 20-49 age group.

Figure 4.9 shows that similar to decomposition results of total travel time, demographic shifts also play negligible role in total variations of non-market work travel from 2004 to 2013.

Total travel time declined by around 0.74 hours per week between 2003 and 2013. A close look at the disaggregated travel time shows that the decline is driven by two main forces: First, shifts of time allocation, from more travel-intensive activities to less travel-intensive activities, are the major driving forces behind the decline in non-market travel time from 2003 to 2013. These shifts include shift of time from market and non-market work to leisure, and also from obtaining goods and services and other care to home production within the non-market work activities. Non-market work travel declined by 0.4 hours per week in the same period, accounting for around 54

Figure 4.9: Blinder-Oaxaca Decomposition of Travel Time Variations



percent of the total decline in travel time. These shifts are not caused by demographic shifts, but more likely explained by the shift of time allocation, which are common to all demographic groups.[57] Second, work travel time declined by 0.21 hours per week, accounting for around 28 percent of the total decline in travel time. More than half of the decline in work travel is caused by changing demographic composition after 2008, possibly declining work population. The declines in leisure and other travel make up equal shares of the rest of decline. There is no strong evidence on economizing on travel related to market (in particular commuting) or non-market work (in particular obtaining goods and services).

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[57] We have examined the shift of time allocation within each age and work-gender groups, and find that the shift of time allocation from non-market work to leisure is a common phenomenon for each group. Aguiar and Hurst (2007) have similar findings on the trend of increase in leisure and decrease in non-market work time.

### Substitutionary or Complementary: Co-variations of Travel Time Use with Other Time Uses

Previous sections identify the main contributor to variations in total travel time as forces that may be common to all demographic groups. Identification of reallocation patterns between total travel and other time uses common to various demographic groups may shed light on the aggregate forces at work. We divide the sample population into 120 demographic cells as described in Section 4.2.2 and use the sample weight in the surveys to compute the average of each time use for all cells. For each year we calculate average time use for each category and demographic cell.

To assess how forgone (augmented) travel time is reallocated across (from) different time use categories, for each time use category $j$ we estimate the following baseline regression:

$$\triangle H_{it}^{j} = \alpha^{j} + \beta^{j} \triangle H_{it}^{travel} + \varepsilon_{it}^{j}, \tag{4.5}$$

where $\triangle H_{it}^{j}$ is the change in hours per week spent on time use category $j$ for the average individual in cell $i$ between period $t-1$ and period $t$, and $\triangle H_{it}^{travel}$ is the change in total travel time for the average individual in cell $i$ between period $t-1$ and period $t$. Since annual data are available for the years from 2003 to 2013, the variable $t$ represents each calendar year.

Differences in time use across periods for each demographic cell represent within-cell variations, the portion not accounted for by demographic shifts. Thus our regression focuses on how within-cell variations in travel time and other time use categories are related. The coefficient $\beta^{j}$ measures the fraction of foregone (augmented) travel time allocated to (from) time use $j$, identified from cross-cell variations of changes in all time use categories. The estimated coefficient is not a structural parameter intended to identify a causal relation. Instead, it is an accounting device that measures how activity covaries with travel time across all demographic cells. A positive $\beta^{j}$ indicates that time use of category $j$ comoves with travel time, thus more likely complementary with travel. A negative $\beta^j$ indicates otherwise. We multiply the coefficients by 100 for easy interpretation.

Table 4.7 reports the regression results. Column 1 shows the sample average of time use on each category. For example, in each week an average individual in our sample spends around 24 hours on market work, 18 hours on non-market work, and 114 hours on leisure, including 60 hours on sleeping. We further divide leisure into leisure at home, leisure outside and other leisure, where leisure at home includes time spent on computer, TV, sleeping, and other home leisure, and leisure outside includes exercise and sports, socializing, entertainment and arts. Leisure at home makes up close to 80 percent of leisure time.

In column 2 we present the estimated coefficients from regression (4.5) using weighted least squares and in column 3 we present the associated standard errors. The samples are weighted by their respective cell weights. By weighting observations we put higher weight on larger cells to reduce sampling errors related to smaller cells. Columns 4, 6 and 8 present estimates when we control for demographic variables, estimates when we control for time dummies, and estimates when we control for demographics and time dummies simultaneously. Columns 5, 7 and 9 report the associated standard errors. As shown in Table 4.7, coefficients estimates obtained with additional control variables are close to those in the baseline regression. Henceforth we focus on the coefficient estimates that are significantly different from zero in the baseline regression.

Based on column 2, time spent on leisure and non-market work at home are strong substitutes for time spent on travel across all demographic cells. On average around 53 percent of foregone travel time is allocated to home entertainment on computer and TV, while the same amount of foregone travel time is allocated to sleeping. Time spent on other home-based leisure also increases in response to an increase in total travel time. Within non-market work, home production and child care absorb around

Table 4.7: Substitution Patterns across Time Use Categories (2003-2013)

| Time Use Category<br>(Non-Travel Time) | Sample<br>Average<br>(1) | Baseline<br>$\beta$<br>(2) | <br>S.E.<br>(3) | Demographics<br>$\beta$<br>(4) | <br>S.E.<br>(5) | Time Dummies<br>$\beta$<br>(6) | <br>S.E.<br>(7) | Demo + Time<br>$\beta$<br>(8) | <br>S.E.<br>(9) |
|---|---|---|---|---|---|---|---|---|---|
| **Work** | 24.39 | -9.75 | (7.24) | -9.80 | (7.27) | -10.01 | (7.20) | -10.05 | (7.22) |
| **Non-market Work** | 18.36 | -11.84$^{*}$ | (7.10) | -11.83$^{*}$ | (7.13) | -12.02$^{*}$ | (7.05) | -12.01$^{*}$ | (7.08) |
| - Child Care | 3.64 | -5.19$^{***}$ | (1.85) | -5.22$^{***}$ | (1.85) | -4.96$^{***}$ | (1.87) | -4.99$^{***}$ | (1.88) |
| - Other Care | 0.83 | 3.09 | (2.56) | 3.10 | (2.57) | 3.13 | (2.50) | 3.14 | (2.51) |
| - Obtaining Goods/Services | 3.14 | 12.45$^{***}$ | (2.61) | 12.46$^{***}$ | (2.63) | 12.47$^{***}$ | (2.64) | 12.49$^{***}$ | (2.65) |
| - Home Production | 10.75 | -22.19$^{***}$ | (5.05) | -22.18$^{***}$ | (5.08) | -22.66$^{***}$ | (5.05) | -22.65$^{***}$ | (5.07) |
| **Home Leisure** | 86.41 | -113.53$^{***}$ | (15.44) | -113.50$^{***}$ | (15.49) | -113.98$^{***}$ | (15.52) | -113.95$^{***}$ | (15.58) |
| - Computer + TV | 20.35 | -53.37$^{***}$ | (9.54) | -53.33$^{***}$ | (9.58) | -53.14$^{***}$ | (9.58) | -53.18$^{***}$ | (9.63) |
| - Sleeping | 60.33 | -53.37$^{***}$ | (10.17) | -53.34$^{***}$ | (10.22) | -53.90$^{***}$ | (10.16) | -53.88$^{***}$ | (10.21) |
| - Other Home Leisure | 5.73 | -6.87 | (4.19) | -6.82 | (4.21) | -6.93 | (4.19) | -6.89 | (4.21) |
| **Outside Leisure** | 9.71 | 17.76$^{*}$ | (9.23) | 17.80$^{*}$ | (9.26) | 17.75$^{*}$ | (9.29) | 17.79$^{*}$ | (9.33) |
| - Exercise and Sports | 2.06 | 10.33$^{***}$ | (3.52) | 10.34$^{***}$ | (3.53) | 10.24$^{***}$ | (3.53) | 10.24$^{***}$ | (3.54) |
| - Socializing | 7.06 | 5.94 | (8.40) | 5.98 | (8.43) | 6.01 | (8.38) | 6.05 | (8.41) |
| - Entertainment and Arts | 0.60 | 1.49 | (1.38) | 1.48 | (1.39) | 1.51 | (1.38) | 1.50 | (1.39) |
| **Other Leisure** | 17.57 | 17.77$^{***}$ | (5.95) | 17.75$^{***}$ | (5.98) | 18.42$^{***}$ | (5.90) | 18.40$^{***}$ | (5.93) |
| - Garden and Pet | 2.05 | -2.92 | (2.55) | -2.92 | (2.56) | -2.86 | (2.50) | -2.87 | (2.51) |
| - Eating | 7.85 | 5.53$^{**}$ | (2.54) | 5.54$^{**}$ | (2.47) | 5.52$^{**}$ | (2.45) | 5.53$^{**}$ | (2.46) |
| - Personal Care | 4.73 | 5.19$^{**}$ | (2.19) | 5.20$^{**}$ | (2.20) | 5.37$^{**}$ | (2.19) | 5.38$^{**}$ | (2.20) |
| - Self Care | 0.61 | 0.49 | (2.53) | 0.51 | (2.54) | 0.75 | (2.56) | 0.76 | (2.57) |
| - Own Medicare | 0.36 | 3.84$^{**}$ | (1.54) | 3.84$^{**}$ | (1.55) | 3.85$^{**}$ | (1.56) | 3.84$^{**}$ | (1.56) |
| - Civic | 1.97 | 5.63$^{**}$ | (2.50) | 5.59$^{**}$ | (2.51) | 5.79$^{**}$ | (2.48) | 5.75$^{**}$ | (2.49) |
| **Other** | 3.02 | -0.41 | (8.01) | -0.43 | (8.04) | -0.16 | (8.03) | -0.19 | (8.06) |
| - Education | 1.63 | -1.17 | (7.19) | -1.22 | (7.22) | -1.23 | (7.23) | -1.28 | (7.27) |
| - Other (excluding education) | 1.39 | 0.77 | (3.96) | 0.79 | (3.98) | 1.07 | (3.92) | 1.09 | (3.93) |

$^{*}p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$
Note: All coefficients are multiplied by 100.

27 percent of foregone travel time.

Column 2 shows that time spent on obtaining goods and services, other care, leisure outside, and other leisure are complementary with time spent on travel. For every hour reduction in total travel time, time spent on obtaining goods and services decline by 0.12 hours, and time spent on leisure outside home decline by 0.18 hours. Time spent on exercises and sports alone declines by 0.1 hour for every hour reduction in travel time.

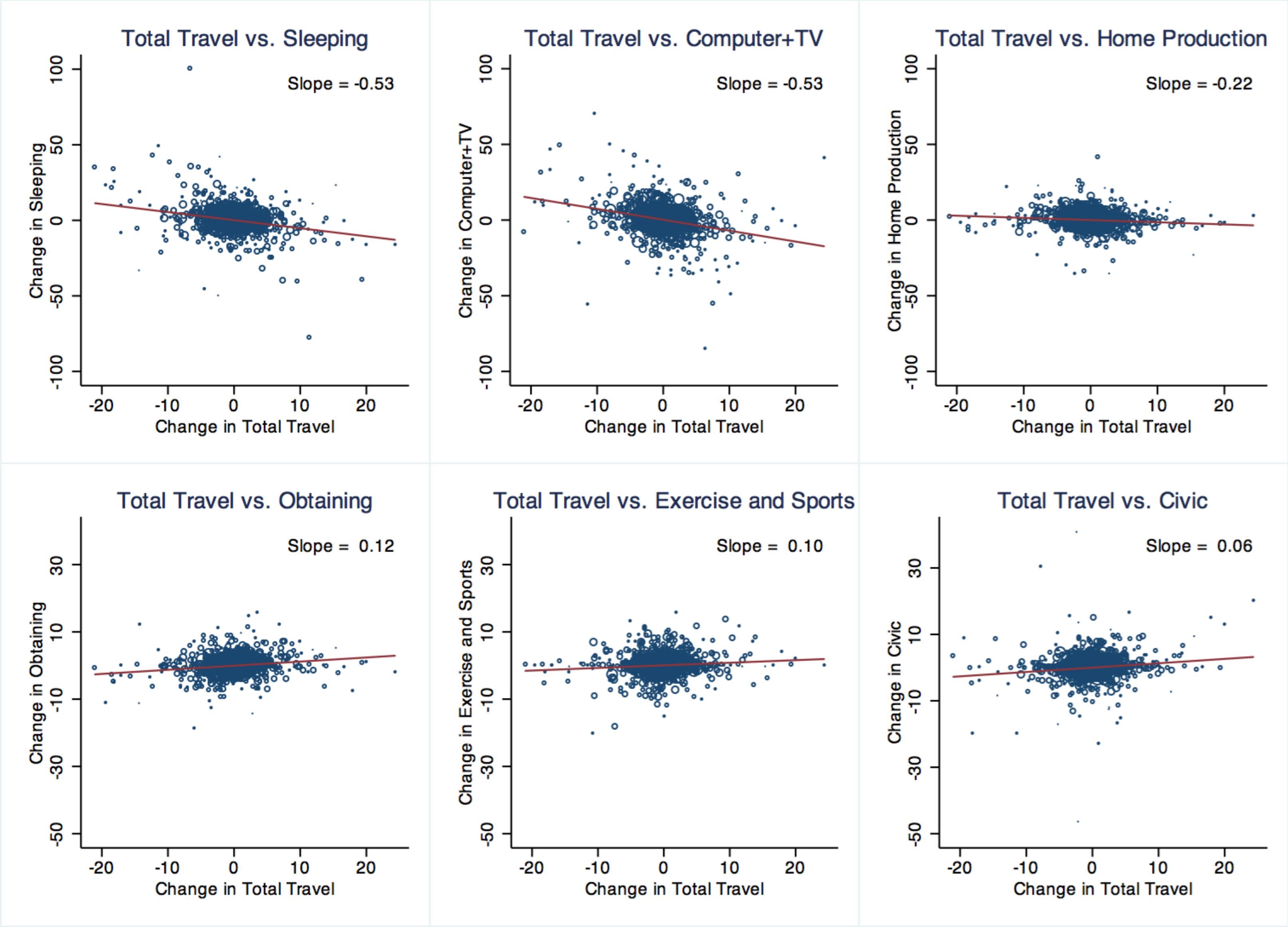
Figure 4.10 shows the scatter plots of $\triangle H_{it}^{travel}$ with change in six other time use categories, ordered by the degree of substitution and complement with travel time. The figure verifies that outliers are not driving our results.

From 2003 to 2013, there has been a shift of time allocation from time spent on travel, time spent on leisure outside home and time spent on obtaining goods and services to leisure and non-market work at home, in particular, to such activities as home entertainment on computer and TV, sleeping and home production.

### 4.5.2 The Longer Horizon: 1975-2013

When we extend our analysis to a longer horizon, measure consistency becomes an important issue. Since time-use surveys prior to 2003 have fewer travel time categories, we have to limit our travel pattern analysis to measures of time use that are present and comparable across all time use surveys. We focus on three categories of non-travel time use and their corresponding travel time. The categories are: market work and work travel (the same measure as post-2003 surveys), obtaining goods and services (17 percent of non-market work) and travel time spent on obtaining (56 percent of non-market work travel), and a core measure of leisure (32 percent of broad-based leisure) and related travel (53 percent of broadly defined leisure-related travel). The narrowed measure includes core leisure activities such as socializing, recreation and passive leisure, but does not include eating, sleep, personal care and organizational

Figure 4.10: Cross Cell Variation: Selected Activity Time Use vs. Travel Time

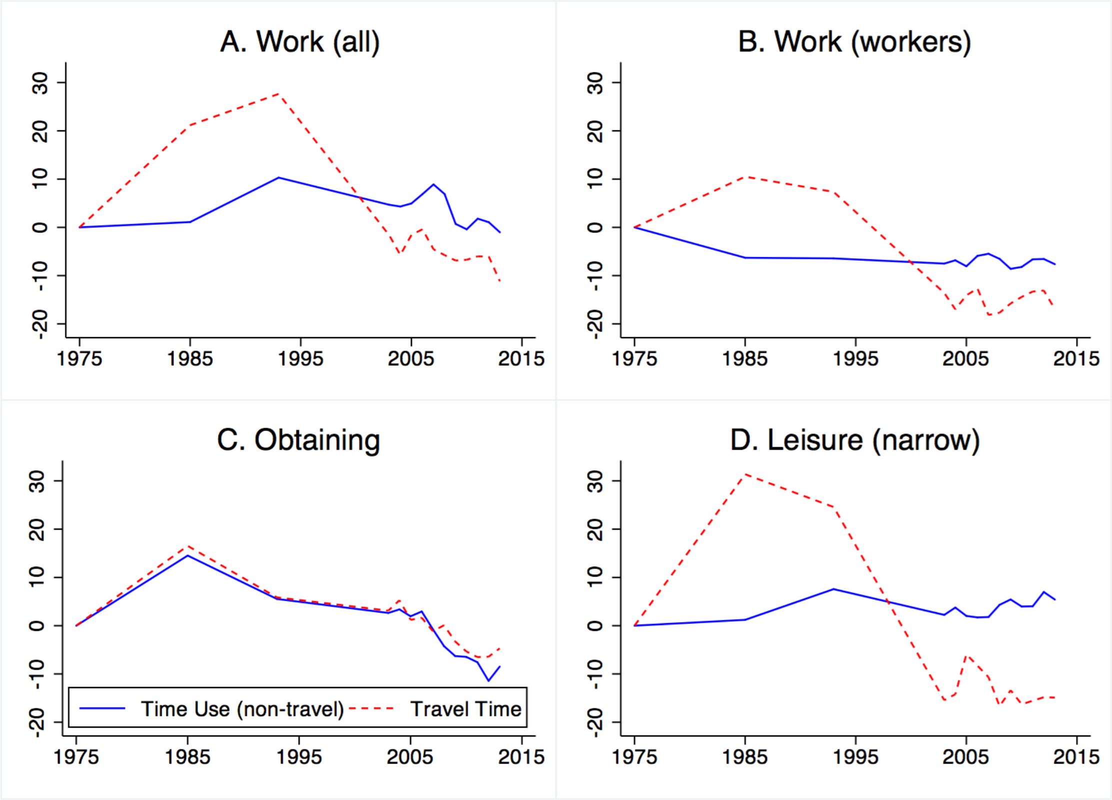


activities. In total, the three categories of non-travel time use and their corresponding travel time make up respectively 40 percent and 62-74 percent of non-travel and travel time use in 2003.

### Percentage Changes in the Three Time Use Categories

Figure 4.11 shows percentage changes of non-travel and travel time use of the above three categories as compared to corresponding values in 1975. The two panels in the upper row show percentage changes in market work and work travel for all the sample population and for those who work. A comparison of the two graphs in the upper row shows that shifts in and out of the work force play an important role for the total amount of market work of the entire sample population. When we restrict the sample to workers only, we observe time spent on market work declining from 1975 to 1985, and then remaining at around the same level since 1985. As also shown in Table 4.8,

Figure 4.11: Percentage Change of Time Use from 1975



time spent on work travel for the entire sample increased by close to 28 percent from 1975 to 1993. However, time spent on work travel increased by only 7 percent if we restrict the sample to those who work for the same time period.

The contrast between the two numbers indicates that the shift into the working population has played an important role in the increase in the work travel for the sample population. Between 1993 and 2003 time spent on work travel declined by around 20 percent for both the entire sample and workers only, despite a 5.3 percent decline in market work time for the sample population and statistically insignificant change in time spent on market work by workers. Although the narrow-based leisure has followed a steady upward trend, just as the broad-based leisure, travel time related to the narrow measure increased drastically from 1975 to 1993, and then plummeted from 1993 to 2003.[58] From 1975 to 1993, the ratio of time spent on work travel to that on market work and the ratio of time spent on leisure-related travel to leisure both increased, a phenomenon opposite to economizing on travel. From 1993 to 2003, the opposite happened with both ratios declining despite stable time spent on market work and steady increases in time spent on leisure.

To the contrary, the ratio of non-travel and travel time spent on obtaining goods and services have been approximately constant since 1975. Both travel and non-travel time related to obtaining goods and services have steadily declined since 1985, at an accelerating rate after 2003. There is no evidence for economizing on travel related to the activity of obtaining.

### Decomposition of Disaggregated Travel Time

Similar to the decomposition of total travel time, we also conduct decomposition of time spent on travel related to work, obtaining goods and services, and leisure to

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[58] Non-market work travel increased between 1993 and 2003, partly due to inclusion of travel related to other care and home production after 2003. However, the decline in leisure travel dominated the increase in non-market work travel for this period, thus resulting in the decline in total travel time.

Table 4.8: Disaggregated Time Use (Hours per Week) 1975-2013

| | 1975 | 1985 | 1993 | 2003 | 2013 | Difference 1993-1975 | | Difference 2003-1993 | | Difference 2013-2003 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Work Travel | 2.17 | 2.63 | 2.77 | 2.14 | 1.93 | 0.60*** | 27.7% | -0.64*** | -23.0% | -0.21*** | -9.7% |
| Work | 23.77 | 24.03 | 26.22 | 24.88 | 23.52 | 2.45*** | 10.3% | -1.34*** | -5.1% | -1.35*** | -5.4% |
| Work Travel (workers) | 3.63 | 4.02 | 3.90 | 3.14 | 3.02 | 0.27*** | 7.4% | -0.76*** | -19.5% | -0.12 | -3.9% |
| Work (workers) | 39.89 | 37.37 | 37.32 | 36.89 | 36.84 | -2.57*** | -6.4% | -0.43 | -1.1% | -0.05 | 0.1% |
| Obtaining Travel | 1.92 | 2.24 | 2.03 | 1.98 | 1.83 | 0.11** | 5.9% | -0.05 | -2.6% | -0.15*** | -7.6% |
| Obtaining | 3.26 | 3.73 | 3.44 | 3.34 | 2.98 | 0.18** | 5.5% | -0.09 | -2.7% | -0.36*** | -10.8% |
| Leisure(narrow) Travel | 1.80 | 2.37 | 2.25 | 1.53 | 1.54 | 0.44*** | 24.6% | -0.72*** | -32.1% | 0.01 | 0.5% |
| Leisure (narrow) | 34.40 | 34.82 | 37.01 | 35.17 | 36.26 | 2.61*** | 7.6% | -1.84*** | -5.0% | 1.09*** | 3.1% |

${}^{*}p < 0.10$, ${}^{**}$ $p < 0.05$, ${}^{***}$ $p < 0.01$

quantify the impact of demographic shifts and other forces for the three types of disaggregated travel.

Table 4.9 reports decomposition results using the pooled-two method. Columns (1) and (2) show the following decomposition results: (i) From 1975 to 1993, roughly 72 percent of the increase in work travel can be explained by demographic shifts, in particular shifts across work-gender groups (60 percent). The shift of females from nonworking to working status is among one of the most important contributors to the increase in work travel. (ii) Between 1993 and 2003, 15 percent of the decrease in work travel can be accounted for by demographic shifts, with changes in age composition (7.2 percent) equally important as in work-gender composition (7.5 percent). (iii) Consistent with our analysis in the previous sections, demographic shifts account for 38 percent of the decrease in work travel from 2003 to 2013, with the shifts among work-gender groups (44.1 percent), in particular the decline in the fraction of working population the main contributor to the decline in work travel. Shifts in education composition, despite being a prominent factor in evolution of total travel time, do not play a noticeable role in explaining the variations in time spent on work travel.

Columns (3) and (4) show decomposition results for travel related to obtaining goods and services. From 1975 to 1993, although changes in the work-gender composition, especially an increasing number of women in the work force, may have reduced the time spent on obtaining, changes in education composition completely offset the small negative effect. From 1993 to 2003, the shift toward lower education groups explains a small amount of decline in obtaining travel. From 2003 to 2013, demographic shifts, especially increases in educational attainment on average, push the time spent on obtaining to increase, albeit by a small amount. The small positive effect is dominated by forces related to time effects and changes in within-cell means, resulting in a decline in time spent on obtaining travel.

Columns (5) and (6) report decomposition results for travel related to the narrowly

Table 4.9: Blinder-Oaxaca Decomposition of Disaggregated Travel Time

| | Work Travel | | Obtaining Travel | | Leisure (narrow) Travel | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| | | | Panel A: 1975-1993 | | | |
| **Overall** | | | | | | |
| Survey_1993 | 2.77*** | | 2.03*** | | 2.25*** | |
| Survey_1975 | 2.17*** | | 1.92*** | | 1.80*** | |
| Difference | 0.60*** | | 0.11 | | 0.44* | |
| Explained | 0.43*** | 72.2% | 0.05 | 43.0% | 0.13** | 28.3% |
| Unexplained | 0.17 | 27.8% | 0.06 | 57.0% | 0.32 | 71.7% |
| **Explained** | | | | | | |
| Age | 0.04*** | 6.8% | 0.01 | 11.6% | 0.07*** | 16.0% |
| Work-Gender | 0.36*** | 60.1% | -0.09*** | -75.7% | -0.08*** | -17.4% |
| Education | 0.03 | 4.6% | 0.12*** | 109.9% | 0.09** | 21.1% |
| Child | 0.00 | 0.7% | -0.00 | -2.8% | 0.04** | 8.5% |
| | | | Panel B: 1993-2003 | | | |
| **Overall** | | | | | | |
| Survey_2003 | 2.14*** | | 1.98*** | | 1.53*** | |
| Survey_1993 | 2.77*** | | 2.03*** | | 2.25*** | |
| Difference | -0.64*** | | -0.05 | | -0.72*** | |
| Explained | -0.09*** | 15.0% | -0.02 | 25.9% | -0.05*** | 5.8% |
| Unexplained | -0.55*** | 85.0% | -0.04 | 74.1% | -0.68*** | 94.2% |
| **Explained** | | | | | | |
| Age | -0.04*** | 7.2% | -0.00 | 6.9% | -0.03*** | 4.2% |
| Work-Gender | -0.05** | 7.5% | 0.01 | -8.6% | 0.01*** | -2.0% |
| Education | 0.00 | -0.5% | -0.02*** | 32.8% | -0.01* | 1.6% |
| Child | -0.00 | 0.7% | 0.00 | -5.3% | -0.02*** | 2.1% |
| | | | Panel C: 2003-2013 | | | |
| **Overall** | | | | | | |
| Survey_2013 | 1.93*** | | 1.83*** | | 1.54*** | |
| Survey_2003 | 2.14*** | | 1.98*** | | 1.53*** | |
| Difference | -0.21*** | | -0.15** | | 0.01 | |
| Explained | -0.08*** | 38.1% | 0.03*** | -19.7% | 0.01 | |
| Unexplained | -0.12* | 61.9% | -0.18** | 119.7% | -0.00 | |
| **Explained** | | | | | | |
| Age | -0.01 | 2.9% | -0.00 | 0.7% | -0.03*** | |
| Work-Gender | -0.10*** | 44.1% | 0.00 | -2.6% | 0.01*** | |
| Education | 0.02*** | -7.6% | 0.03*** | -19.0% | 0.02*** | |
| Child | 0.00 | -1.2% | -0.00 | 1.1% | 0.01*** | |

$^{*}p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$

Notes: The decomposition results in this table are based on pooled-two method. Columns (2), (4), and (6) are ratios of explained and unexplained parts relative to the total difference of each disaggregated travel time use respectively. The details of unexplained part are suppressed due to mostly insignificance.

defined leisure. From 1975 to 1993, roughly 28 percent of the increase in leisure travel can be explained by demographic shifts. Increases in the educational attainment, the fraction of people in their 20s to 50s, and the fraction with no children, contribute positively to the increase in leisure travel. However, the shift from nonworking to working status during this period offsets part of the increase. From 1993 to 2003, demographic shifts explain around 6 percent of the decline in leisure travel, with aging of baby boomers, decreases in education attainment and increases in the fraction of people with children all contributing to the decrease. The decline in the fraction of working population in this period, however, exerts a positive but small effect on the time spent on leisure travel. From 2003 to 2013, the change in leisure travel is statistically insignificant. Among the small combined effects of demographic shifts, the increase in education attainment, the shift out of work status and the decline in the fraction with children push up leisure travel, only to be countered by the impact of an aging population.

In all, similar to decomposition results of total travel time, decomposition of disaggregated travel time shows strong impact of demographic shifts in the 1975-1993 subperiod, but much smaller, and even negligible effect in the 1993-2003 and 2003-2013 subperiods. Shifts across work-gender groups play an important role for variations in work travel in all subperiods, while changes in education composition play prominent roles for changes in obtaining and leisure travel. Relating decomposition results with the percentage changes in both travel and non-travel time, it is clear that work travel and leisure travel change more than their corresponding non-travel time in the period before 2003, even conditional on demographic shifts. The decomposition results again point to the importance of the portion not explained by demographic shifts.

In the following subsection we examine substitutionary and complementary patterns between travel time and other time uses for the long horizon. Common patterns across all demographic cells may shed light on aggregate forces behind the changes in time allocation.

### Substitutionary and Complementary Patterns over the Long Horizon

We run the same regression as equation (4.5) to examine reallocation patterns between 1975 and 2013. Since annual data are not available before 2003, we redefine each period as representing ten years. As a result, we examine changes in time use for 120 cells over the following periods: 1975-1985, 1985-1993, 1993-2003, and 2003-2013.[59]

Table 4.10 shows the regression results. Column (1) shows sample averages of time use categories. An average individual spends similar amount on market work over the long horizon as in the recent decade. Column (2) shows the baseline regression using weighted least square and column (3) shows associated standard errors. Columns (4), (6) and (8) report regression results controlling respectively demographics only, time dummies only and both demographics and time dummies. Columns (5), (7) and (9) report associated standard errors. In contrast to the role of time dummies in the same regression for annual data from 2003 to 2013, controlling time dummies has strong impact on some regression estimates. The importance of time dummies indicate large ten-year differences in various time use categories across the four decades we examine.

For the long horizon regression, we focus on column (6), in particular those coefficient estimates significantly different from zero. Column (6) shows that for every one hour reduction in total travel time, on average around 56 percent of foregone travel time is allocated to sleeping, a similar amount as in the year-to-year regression for the period 2003 to 2013. Since data on computer use are only available after 1993, we separate leisure at home into TV and other home leisure. Around 40 percent of foregone travel time is allocated to TV watching, and another 25 percent allocated to other types of home leisure. Sleeping, Watching TV and other home-based leisure are the three most prominent destinations of time substituted out of travel use.

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[59] We multiply the changes in time use from 1985 to 1993 by $\frac{10}{8}$ to account for the shorter gap in this period compared to others.

Table 4.10: Substitution Patterns across Time Use Categories (1975-2013)

| Time Use Category (Non-Travel Time) | Sample Average | Baseline | | Demographics | | Time Dummies | | Demo + Time | |
|---|---|---|---|---|---|---|---|---|---|
| | | $\beta$ | S.E. | $\beta$ | S.E. | $\beta$ | S.E. | $\beta$ | S.E. |
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| **Work** | 24.94 | -19.80 | (12.02) | -20.98$^{*}$ | (12.44) | -13.25 | (13.05) | -14.38 | (13.53) |
| **Non-market Work** | | | | | | | | | |
| - Child Care | 2.80 | -5.40 | (5.93) | -5.39 | (6.18) | -0.99 | (5.78) | -0.90 | (6.07) |
| - Obtaining Goods/Services | 3.35 | 10.35$^{**}$ | (4.28) | 10.62$^{**}$ | (4.41) | 9.19$^{*}$ | (4.96) | 9.45$^{*}$ | (5.14) |
| **Home Leisure** | 83.81 | -116.69$^{***}$ | (21.40) | -116.40$^{***}$ | (22.04) | -120.05$^{***}$ | (19.98) | -119.85$^{***}$ | (20.54) |
| - TV | 17.53 | -29.59$^{**}$ | (12.09) | -30.20$^{**}$ | (12.49) | -39.74$^{***}$ | (11.22) | -40.62$^{***}$ | (11.57) |
| - Sleeping | 58.75 | -68.56$^{***}$ | (13.42) | -67.94$^{***}$ | (13.58) | -55.60$^{***}$ | (14.33) | -54.69$^{***}$ | (14.60) |
| - Other Home Leisure | 7.52 | -18.54$^{**}$ | (7.45) | -18.26$^{**}$ | (7.62) | -24.71$^{***}$ | (7.85) | -24.54$^{***}$ | (7.97) |
| **Outside Leisure** | 10.42 | 32.47$^{***}$ | (9.29) | 31.73$^{***}$ | (9.50) | 27.05$^{***}$ | (9.59) | 26.13$^{***}$ | (9.80) |
| - Exercise and Sports | 2.30 | 15.20$^{***}$ | (5.25) | 15.15$^{***}$ | (5.38) | 8.84 | (5.63) | 8.67 | (5.80) |
| - Socializing | 7.55 | 9.87 | (10.36) | 8.93 | (10.55) | 11.00 | (10.53) | 9.98 | (10.71) |
| - Entertainment and Arts | 0.57 | 7.40$^{***}$ | (2.27) | 7.65$^{***}$ | (2.31) | 7.21$^{***}$ | (2.49) | 7.47$^{***}$ | (2.54) |
| **Other Leisure** | | | | | | | | | |
| - Civic | 1.93 | 17.07$^{**}$ | (8.47) | 17.41$^{**}$ | (8.70) | 20.59$^{**}$ | (9.43) | 21.04$^{**}$ | (9.70) |
| **Other** | | | | | | | | | |
| - Education | 1.70 | 0.02 | (7.17) | -0.35 | (7.43) | -2.29 | (7.45) | -2.74 | (7.73) |

$^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$
Note: All coefficients are multiplied by 100.

Column (6) shows that leisure outside home, and time spent on obtaining goods and services are complementary with time spent on travel. As total travel time declines by one hour, time spent on leisure outside home declines by around 0.27 hours, time spent on civil activities declines by 0.21 hours, and time spent on obtaining goods and services declines by around 0.09 hours.

Despite quantitative differences, the substitutionary and complementary patterns of total travel time with other time use categories are similar between the long horizon and the short horizon of the recent decade.

## 4.6 Discussion and Conclusion

In this essay we document that total travel time increased between 1975 and 1993, reached a peak some time between 1993 and 2003, and has declined ever since for at least a decade. As a result, an average individual spends similar amount of time on travel in 2013 as in the 1960s and 1970s. We use the Blinder-Oaxaca method to decompose changes in the unconditional mean of total travel time into the portion explained by demographic shifts and the portion explained by changes in within-cell means and time effects. We find that changes in education composition play a prominent role in the increase in total travel time from 1975 to 1993, even more important than shifts among age, work and gender groups. Shifts across work-gender groups play a dominant role among demographic shifts when we focus on variations in work travel for the 1975-1993 period.

After 1993, demographic shifts play a small role in the evolution of total travel time, even more so during the recent decade. We find that a shift of time allocation from more travel-intensive market and non-market work to less travel-intensive leisure is the main driving force behind the decline in travel time from 2003 to 2013.

We also examine how travel time covaries with other time use categories. We find that the decline in travel time is associated with reduction in time spent on leisure outside home, time spent on obtaining goods and services, and time spent on civil activities. Leisure at home, especially entertainment using computer and TV and sleeping, are the major alternative time uses coupled with a decline in total travel time. Effectively, in addition to a shift of time allocation from market and non-market work to leisure, there is an increasing allocation of time to leisure at home compared to leisure outside.

Covariations of travel time with other time use categories, although not causal, can provide insight on the aggregate forces affecting total travel time. There are two hypotheses. The first hypothesis relates to fluctuations in gasoline prices. Since vehicle travel remains the primary travel mode for Americans, it is possible that fluctuations in gasoline prices directly impact the demand for travel, and thus affect time allocation between more travel-intensive and less travel-intensive activities. The second hypothesis is based on unbalanced growth rates of productivity in market, non-market work, leisure and transportation sectors. Changes in either the efficiency of transportation or the productivity of any activities substitutionary with travel may cause reallocation of travel time and other time uses.

The period from 1975 to 1993 witnessed a 24-percent decline in gasoline prices, as well as a 20-percent increase in total travel time, where about 55 percent of the increase is not explained by demographic shifts. The period from 2003 to 2013 witnessed a 73-percent increase in gasoline prices, accompanied by only 9 percent decline in total travel time, mostly unexplained by demographic shifts. Total travel time declined by 11 percent from 1993 to 2003, with a possible peak in between, which is the largest decline seen within a decade. However, that decade is the time period with not only stable but also low gasoline prices compared to other subperiods.

The decline in gasoline prices from 1980 to 1993 may have fueled the increase in total travel time from 1975 to 1993. Due to absence of data on annual travel time between 1993 and 2003, it is difficult to identify a turning point at which total travel time embarks on a declining trend. We also cannot rule out that the turning point in total travel time actually coincides with that in gasoline prices. Thus it is possible that changes in gasoline prices may be a trigger for declines in travel time among other possible causes. The increase in gasoline prices seems to have less impact on travel time during the period from 2003 to 2013 compared to the first subperiod. Despite the dramatic increase in gasoline prices, both work travel for workers and leisure travel barely change significantly. The decline in non-market work travel is in lockstep with the decline in time allocated to non-market work, thus it is hard to attributing that decline to increases in gasoline prices. Although time spent on obtaining goods and services may be sensitive to gasoline price changes, the decline in time spent on obtaining has started even before 1993. Thus it is difficult to establish a convincing connection between increases in gasoline prices and declines in total travel time after 2003.[60]

There are studies on uneven growth rates of market and non-market work. Earlier work by Greenwood and Hercowitz (1991), Ngai and Pissarides (2008) and Bridgman (2013) find that there has been a shift of time allocation from non-market work to market work. They argue that as the growth rate of productivity is higher in the market than non-market sector, the substitutionary nature of market goods and home goods leads to a decline in time spent on non-market work. Since non-market work is travel-intensive, the decline in non-market work may cause non-market work travel, and total travel to decline as well.

Another change in the growth rate of productivity pertains to the the transportation sector. Traffic congestion and deterioration of road conditions may both make travel a not efficient way to use time compared to other time use categories, thus leading to less travel time. Our substitution patterns point to substitution of travel time toward home entertainment on computer and TV. Such patterns imply an in-

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[60] We have also examined whether differences in travel time across states are related to cross-state variations in gasoline prices. The effect of gasoline price change is not significant.

crease in efficiency of leisure time in generating utility, which may persuade people to spend more time at home instead of travel.

Both fluctuations in gasoline prices and unbalanced growth rates across relevant sectors are possible explanations for evolutions of total travel time, in addition to demographic shifts. We have measured the contribution of demographic shifts in the present study. In a companion study, Wei (2015) models optimal time allocation in an environment with fluctuations in gasoline prices and unbalanced growth rates across sectors. The structural model may help us to quantitatively evaluate the validity of each hypothesis.

# Chapter 5: Discussion and Conclusions

Migration and seawall protection are two major adaptation actions to SLR undertaken by individuals and governments, respectively. Given that there is a linkage between these two adaptation actions, the first two essays in this dissertation examine the outcome and efficiency of individual and government adaptation for different decision-making schemes.

The first essay investigates the optimal adaptation outcome via a two-region model, and examines the efficiency of decentralized government adaptation outcome. The model assumes that the probability of damage for a location decreases as the distance between the location and the shoreline increases. Equalization of wage rates across locations is the driving force for migration. The analysis shows that population distribution is altered by SLR risk: the shoreline faces the highest damage probability, and thus has the smallest population; population then increases at an increasing rate as one moves farther away from the shoreline, until the damage boundary is reached.

Analyzing the impacts of migration and a seawall on both the coastal region the inland region, I show that the incentives facing the two local governments and the central government for building a seawall differ. If the government's objective is to maximize output, then, in most cases, the local government of the coastal region will choose to build a higher seawall than the central government. In contrast, the local government of the inland region has no incentive to build a seawall because the inland region always benefits from migration. If the government's objective is to maximize the wage rate, the two local governments have the same incentive to build a seawall. In this case it is plausible that they will cooperate and share the construction cost of a seawall. However, they will choose a lower seawall height than the central government. Thus, in general, the seawall height determined by the local governments will be either too high or too low compared to the socially optimal height. Introducing a linear congestion cost caused by migration does not alter this conclusion. Simulation results confirm this conclusion–the local governments' decisions in general yield higher loss rates, and show that the central and local government decisions can also differ as to when the corner solution of "no seawall" is optimal.

Therefore, with free migration, local provision of adaptation in general cannot achieve the socially optimal outcome. This conclusion is different from the result presented in the public economics literature, namely, that with perfect household mobility, local public good provision is efficient. The fundamental reason for this difference is that the negative shock of sea-level rise is spatially asymmetric. The coastal region has a spatial disadvantage due to this shock, which triggers immigration to the inland region. The shock makes the inland region either better off by raising output or worse off by reducing the wage rate. Due to migration, the benefits of a seawall cannot be fully borne by each region, which results in either over-provision or under-provision of local adaptation. The externality associated with migration cannot be resolved without other institutional arrangements.

The conclusion of this essay implies that, although adaptation is primarily local, the central government might play an essential role to correct for over-provision or under-provision of local adaptation. The over-provision of local government adaptation due to pursuing local economic growth can be seen in China's seawall construction. According to Ma et al. (2014), China's seawall mileage has more than tripled over the past two decades and now covers 60 percent of the mainland coastline. This new "Great Wall" has caused a dramatic decline in internationally shared biodiversity and associated ecosystem services and will threaten regional ecological security and sustainable development. Local governments in China prefer to obtain more land for supporting rapid economic development via constructing seawalls, in contrast, the central government has realized the importance of wetland conservation. A lack of national legislation and an overemphasis on economic growth at the local level cause massive seawall construction.

Although this essay uses SLR and seawall construction to motivate the analysis, the analysis can be easily adapted to other negative shocks that are spatial in nature (for example, droughts, hurricane, wildfire, etc.) and can be mitigated by providing local public goods. In addition to negative shocks, there might be positive shocks. For example, if better climate primarily in the coastal region is predicted. The coastal region will experience higher productivity and induce immigration. The inland region is then in a disadvantaged position and will experience emigration. If maximizing output is the objective, the local government of the inland region might provide a local public good or service that can raise productivity (such as better irrigation system) to prevent emigration. Therefore, regardless of the direction of the shock, it is the disadvantaged region that has the incentive to provide the local public good.

The first essay, like other studies in the literature of local public good provision, implicitly assumes that governments make decisions first, and that households respond to the governments' decisions via migration. The second essay, in contrast, assumes that the inverse decision-making order, i.e., households make migration decisions first, is also possible, considering that the governments' policy-making procedures are rather long or uncertain. The second essay starts with a basic model adapted from the theory of local public goods, one in which the local government maximizes per capita utility and allocates private and public consumption according to the Samuelson rule. Again in a two-region setting, viewing the choices of the government and households as a sequential game, this essay examines how the decision-making sequence affects adaptation outcomes. To ensure the existence of a stable two-region equilibrium, both regions are assumed to be over-populated in this essay.

The analysis reveals that when a local government makes the seawall decision, the local government being the first mover yields a lower seawall and more migration than when it is the second mover. When the central government makes the seawall decision, the central government being the first mover yields a higher seawall and less migration than when it is the second mover. Simulation results further show that, although the first-best optimum cannot be obtained by any decision-making scheme as long as free migration is allowed, having the central government making the seawall decision and being the first mover is socially preferable. Therefore, this essay verifies that social optimum under free migration is achieved when the central government makes adaptation decisions and moves first, which is treated as an implicit assumption in the first essay and in the literature of local public goods. If the local (central) government determines seawall height, households moving first (second) generates higher social welfare. In particular, households moving before the local government yields only slightly lower welfare than the central government moving first. This result indicates that, although local adaptation in general cannot achieve the social optimum, having households move before the local government can largely reduce loss of welfare.

Recall that in the first essay, when there is a congestion cost in production, the two local governments choose a lower seawall than the central government. The assumption of overpopulation in the second essay plays a similar role and yields a consistent result–the local government of the coastal region chooses lower seawall height than the central government given the government being the first mover. However, the second essay shows that if households move first, the local government will build a higher seawall than the central government, which highlights the importance of the decision-making sequence.

From these two essays, we can conclude that depending on the local government's objective, local government adaptation can either be too much or too little. Other studies of local public good provision claim that, when considering migration responses, regional governments take into account the effects of their actions not only on their own residents' utility but also on the welfare of nonresidents. Therefore, interregional household mobility provides an incentive for regional governments to choose an efficient allocation. The two essays in this dissertation both show that this result does not hold if local public good provision and free migration are adaptive responses to climate risk. A seawall is not a normal local public good, because the construction of a seawall is triggered by potential productivity loss rather than normal consumption demand. The productivity shock alters the original relationship between the two regions and triggers migration directly given all other aspects of the economy do not change. Unlike other local public goods that can attract individuals to move into a region directly, a seawall itself does not provide utility directly, and cannot attract residents from the risk-free region to the at-risk region. Therefore, in the adaptation scenario, free migration does not promote efficiency for decentralized adaptation. Although the specific illustration in these two essays is regarding SLR threat, the analysis can be extended to any negative productivity shocks that are spatial in nature and can be mitigated by providing a local public good.

If in practice the local government must be responsible for making adaptation decisions, one might ask what kinds of institutional arrangements can be made to reduce social welfare loss. The second essay shows that households making decisions before the local government is one way to reduce welfare loss. Further research can be done to explore the role of other institutional arrangement, including interregional government policies, or different tax schemes to finance the seawall. Also, incorporating ambiguity and differing expectations between households and government to the model might have other implications about the optimal decision-making scheme.

In reality, migration incurs costs. Therefore, one might want to extend the model by relaxing the assumption that migration is costless. There are mainly two types of migration costs specified in the literature. Mansoorian and Myers (1993) introduce the "attach-to-home" type of migration costs. An individual has a different degree of attachment to different regions, the region of strongest attachment being defined as 'home'. They show that all equilibrium allocations resulting from the Nash behavior of regional authorities are efficient, and there is no efficiency role for a central authority. Other works, including Wellisch (1994), Ludema and Wooton (2000), Petchey (2000), and Ogura (2006), also use this type of migration costs.

In contrast, Myers and Papageorgiou (1997) assume all residents, regardless of their place of origin, face an identical and fixed migration cost. They show that decentralized equilibrium allocations may not be first-best efficient but are federally efficient.[61] Hercowitz and Pines (1991) use the same specification in a dynamic, stochastic model. Using the same assumption that migration costs are the same for everyone, Bucovetsky (2011) shows that conditional on the direction of migration, interests of different communities are still perfectly aligned. Wildasin (1991) considers fixed migration costs in generalizing a model but assumes only a fraction of agents are mobile. Barnett and Webber (2010) state that the number of people who cannot migrate in response to climate change (for reasons of poverty, remoteness, illness, or age) may actually far exceed the number of those who do. Therefore, migration might not be an adaptation option for some individuals, and the assumption that some agents are immobile is reasonable in this case.

The third essay documents the average travel time for U.S. adults. We find that there have been dramatic changes in travel time over the past five decades. Total travel time (hours per week) increased by nearly 19 percent from 1965 to 1993 for an average individual between 19 and 65 years old. If we expand the sample to those 18 and up, average travel time increased from 8.43 hours per week in 1975 to 10.1 hours per week in 1993, a roughly 20 percent increase. Average travel time reached a peak some time between 1993 and 2003. By 2003, average travel time per adult has

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[61] In the first-best problem, the central planner can assign individuals both to a residence and to a level of consumption. In contrast, federal efficiency is characterized by the second-best problem, because in the federalism literature, governments in a federation typically cannot impose immigration quota or force emigration, and cannot discriminate by taxing or subsidizing individuals according to their place of origin.

already declined to 9.03 hours per week, a decline of nearly 11 percent since 1993. The decline has continued throughout the following decade. In 2013 average travel time per adult was 8.29 hours per week, registering a decline of 18 percent compared to that in 1993. As a result, an average individual in the U.S. spends similar amount of time on travel in 2013 as in the 1960s and 1970s, even though there have been dramatic changes in all aspects of the U.S. economy since 1965

We use the Blinder-Oaxaca method to decompose changes in the unconditional mean of total travel time into the portion explained by demographic shifts and the portion explained by changes in within-cell means and time effects. We find that demographic shifts explain roughly 45 percent of the increase in total travel time from 1975 to 1993. Increases in educational attainment alone contribute to 28 percent of the increases, followed by 18 percent contributed by changes in age, work and gender composition. However, demographic shifts play a much smaller role in the evolution of total travel time afterwards. Variations in total travel time from 2003 to 2013 are dominated by time effects that are common to all demographic groups. In particular, the shift of time allocation from more travel-intensive non-market work to less travel-intensive leisure accounts for roughly 50 percent of the decline in total travel time. There are no strong evidence for economizing on travel during the recent decade.

We also examine how travel time covaries with other time use categories. We find that the decline in travel time is associated with reduction in time spent on leisure outside home, time spent on obtaining goods and services, and time spent on civil activities. Leisure at home, especially entertainment using computer and TV and sleeping, are the major alternative time uses coupled with a decline in total travel time. Covariations of travel time with other time use categories can provide insight on the aggregate forces affecting total travel time. There are two hypotheses. The first hypothesis relates to fluctuations in gasoline prices. Since vehicle travel remains the primary travel mode for Americans, it is possible that fluctuations in gasoline prices directly impact the demand for travel, and thus affect time allocation between more travel-intensive and less travel-intensive activities. The second hypothesis is based on unbalanced growth rates of productivity in market, non-market work, leisure and transportation sectors. Changes in either the efficiency of transportation or the productivity of any activities substitutionary with travel may cause reallocation of travel time and other time uses.

The decline in gasoline prices from 1980 to 1993 may have fueled the increase in total travel time from 1975 to 1993. The increase in gasoline prices seems to have less impact on travel time during the period from 2003 to 2013 compared to the 1975-1993 subperiod. Despite the dramatic increase in gasoline prices, both work travel for workers and leisure travel barely change significantly. Thus it is difficult to establish a convincing connection between increases in gasoline prices and declines in total travel time after 2003.

Earlier studies on uneven growth rates of market and non-market work by Greenwood and Hercowitz (1991), Ngai and Pissarides (2008), and Bridgman (2013) find that there has been a shift of time allocation from non-market work to market work. Since non-market work is travel-intensive, the decline in non-market work may cause non-market work travel, and total travel to decline as well. Another change in the growth rate of productivity pertains to the the transportation sector. Traffic congestion and deterioration of road conditions may all make travel a not efficient way to use time compared to other time use categories, thus leading to less travel time. Our substitution patterns imply an increase in efficiency of leisure time in generating utility, which may persuade people to spend more time at home instead of travel.

We have measured the contribution of demographic shifts in the present study. In a companion study, Wei (2015) models optimal time allocation in an environment with fluctuations in gasoline prices and unbalanced growth rates across sectors. The structural model may help to quantitatively evaluate the validity of each hypothesis.

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# Appendix A: Chapter 2

## A.1 Proof of Proposition 2.2

The effective length of land is

$$M(g) = (2L - x_0) + \int_0^{x_0} [1 - \theta(x)k(g)]^{\frac{1}{1-\alpha}} dx. \tag{A.1}$$

The derivative of effective length with respect to seawall height is

$$\frac{\partial M(g)}{\partial g} = -\frac{k'(g)}{1-\alpha} \int_0^{x_0} [1 - \theta(x)k(g)]^{\frac{\alpha}{1-\alpha}} \theta(x) dx. \tag{A.2}$$

Recall that $k'(g) < 0$, and $k''(g) > 0$, therefore $\frac{\partial M(g)}{\partial g} > 0$. The second-order derivative is

$$\begin{aligned} \frac{\partial^2 M(g)}{\partial g^2} = & - \frac{k''(g)}{1-\alpha} \int_0^{x_0} [1 - \theta(x)k(g)]^{\frac{\alpha}{1-\alpha}} \theta(x) dx \\ & + \frac{\alpha[k''(g)]^2}{(1-\alpha)^2} \int_0^{x_0} [1 - \theta(x)k(g)]^{\frac{2\alpha-1}{1-\alpha}} \theta^2(x) dx. \end{aligned} \tag{A.3}$$

Without a functional form for $k(g)$, one cannot determine the sign of $\frac{\partial M^2(g)}{\partial g^2}$. I assume a linear relationship $\theta(x) = (x_0 - x)\theta_0$, where $\theta_0$ is a parameter between 0 and $\frac{1}{2L}$. I also assume that $k(g)$ takes the form of the power function, $k(g) = (kg + b)^{-j}, j > 0$. Therefore, $k'(g) = -jk(kg + b)^{-j-1}, k''(g) = j(j + 1)k(kg + b)^{-j-2}$. Substituting the functional forms of $\theta(x)$ and $k(g)$ into (A.2) yields

$$\frac{\partial M(g)}{\partial g} = -\frac{jk(kg + b)^{j-1}\{(1-\alpha) - [1 - x_0\theta_0 k(g)]^{\frac{1}{1-\alpha}}[x_0\theta_0 k(g) + 1 - \alpha]\}}{(2-\alpha)\theta_0}. \tag{A.4}$$

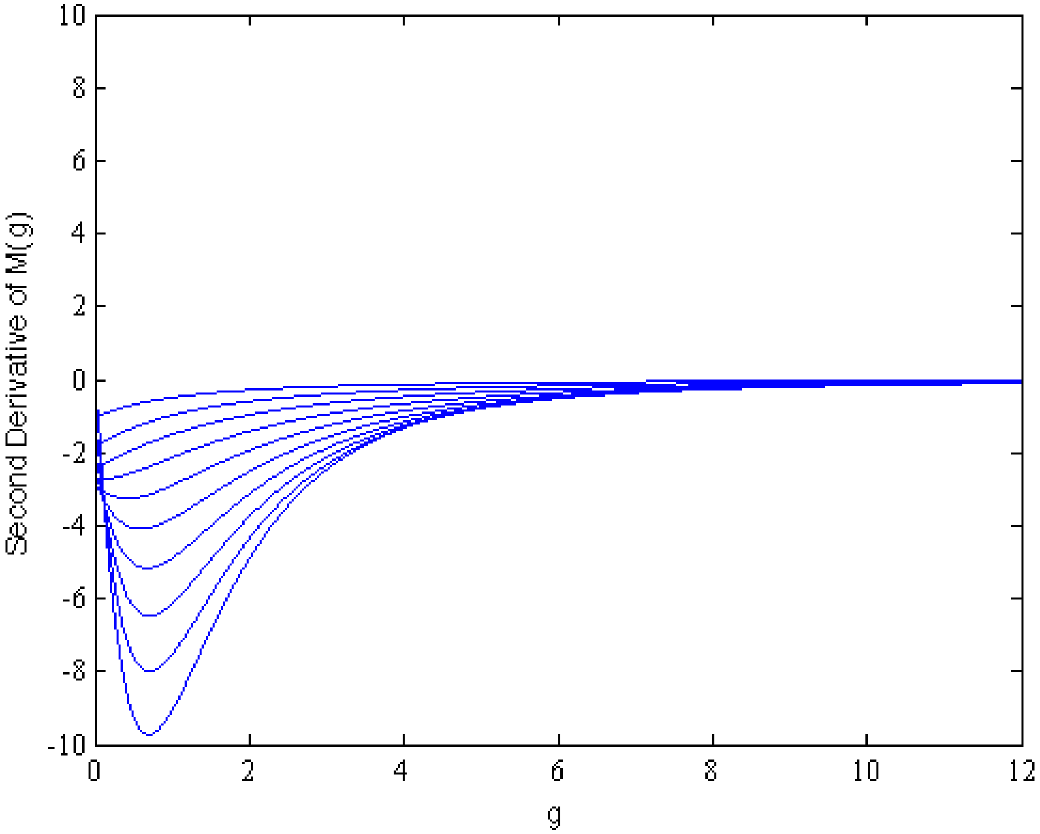
The second-order derivative is

$$\frac{\partial M^2(g)}{\partial g^2} = \frac{k(j-1)}{kg+b}\frac{\partial M(g)}{\partial g} - \frac{{x_0}^2\theta_0 j^2 k^2 [1 - \theta(x)k(g)]^{\frac{\alpha}{1-\alpha}}}{(1-\alpha)(kg+b)^{2j+1}} \tag{A.5}$$

It is clear that the sign of (A1.4) is ambiguous. A sufficient but not necessary condition for $\frac{\partial M^2(g)}{\partial g^2} < 0$ to hold is $j \leq 1$. To obtain more insight about how $j$ affects the sign of $\frac{\partial M^2(g)}{\partial g^2}$, I simulate $j \in [0.2, 10]$ with the interval of 0.2. I set $x_0 = 75, \theta_0 = 0.008, b = 0.5$, and $\alpha = 0.75$, to keep consistency with parameter values set in Section 2.5.

Figure A.1 shows when $j \in [0.2, 2]$, $\frac{\partial M^2(g)}{\partial g^2} < 0$. Figure A.2 shows when $j \in [2.2, 10]$, $\frac{\partial M^2(g)}{\partial g^2}$ is initially positive, but falls quickly to negative. Therefore, we can say that $\frac{\partial M^2(g)}{\partial g^2} < 0$ is negative except for in the small interval close to zero. For simplicity, I assume $j \leq 1$ for the discussion in this essay, so that $\frac{\partial M^2(g)}{\partial g^2} < 0$ holds for all $g$, and I specially assume $j = 1$ for the simulation in Section 2.5.

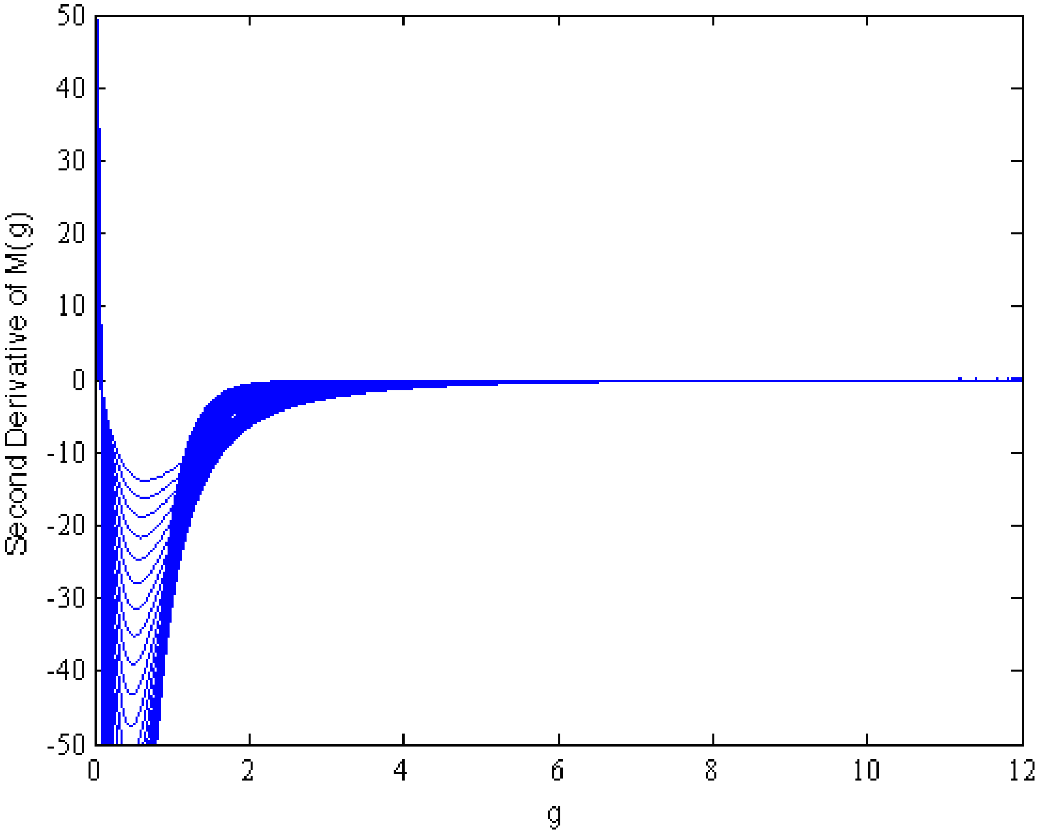
Figure A.1: Second Derivative When $j \in [0.2, 2]$



According to (2.11b), we have, $n_{x_0} = \frac{2N}{M(g)}$. Therefore,

$$\frac{\partial n_{x_0}(g)}{\partial g} = -\frac{2N}{M(g)^2}\frac{\partial M(g)}{\partial g} = -\frac{n_{x_0}(g)}{M(g)}\frac{\partial M(g)}{\partial g} < 0,$$

Figure A.2: Second Derivative When $j \in [2.2, 10]$



and,

$$\frac{\partial^2 n_{x_0}(g)}{\partial g^2} = -\frac{4N}{M(g)^3}\left[\frac{\partial M(g)}{\partial g}\right]^2 - \frac{2N}{M(g)^2}\frac{\partial^2 M(g)}{\partial g^2}.$$

Hence, we have proved the results in Proposition 2.2.

## A.2 Proof of Lemma 2.4 and Proposition 2.5

The effective length for each region defined in (2.22) is

$$m_1(g) = \int_0^L [1-\theta(x)k(g)]^{\frac{1}{1-\alpha}}dx; m_2(g) = \int_L^{x_0} [1-\theta(x)k(g)]^{\frac{1}{1-\alpha}}dx + (2L - x_0).$$

The derivatives of effective length with respect to seawall height for the two regions are

$$\frac{\partial m_1(g)}{\partial g} = -\frac{k'(g)}{1-\alpha} \int_0^L [1-\theta(x)k(g)]^{\frac{\alpha}{1-\alpha}} \theta(x) dx; \tag{A.6a}$$

$$\frac{\partial m_2(g)}{\partial g} = -\frac{k'(g)}{1-\alpha} \int_L^{x_0} [1-\theta(x)k(g)]^{\frac{\alpha}{1-\alpha}} \theta(x) dx. \tag{A.6b}$$

Recall that $\theta(x) = (x_0 - x)\theta_0$. In order to compare $\frac{\partial m_1(g)}{\partial g}$ with $\frac{\partial m_2(g)}{\partial g}$, I define a function: $z(x) = [1-\theta(x)k(g)]^{\frac{\alpha}{1-\alpha}}(x_0 - x)\theta_0$. The first-order derivative of $z(x)$ with respect to x yields,

$$z'(x) = \frac{\theta[1-\theta(x)k(g)]^{\frac{2\alpha-1}{1-\alpha}}[(x_0-x)\theta_0 k(g) - (1-\alpha)]}{1-\alpha}. \tag{A.7}$$

The sign of $z'(x)$ is ambiguous. A sufficient but not necessary condition for $\frac{\partial m_1(g)}{\partial g} > \frac{\partial m_2(g)}{\partial g}$ to hold is $z'(x) < 0$, or

$$(x_0 - x)\theta_0 k(g) < (1-\alpha). \tag{A.8}$$

Recall that $m_1(g) < m_2(g)$, using Definition 2.2, we know that if $\frac{\partial m_1(g)}{\partial g} > \frac{\partial m_2(g)}{\partial g}$, then $\rho_1 > \rho_2$. Applying this to (2.25a) and (2.25b), we have $B_{1g} > B_{2g}$. It is clear that a relatively small $x_0$ (but keep in mind that it still must be larger than $L$, because it falls in region 2 in this case) increases the chance of (A.8) to hold. However, (A.8) is only a sufficient but not necessary condition. Because the integral interval in (A.6a) is larger than that in (A.6b), if $x_0$ is not too large, even if $z'(x) > 0$, $\frac{\partial m_1(g)}{\partial g} > \frac{\partial m_2(g)}{\partial g}$ can still hold. Furthermore, $\frac{\partial m_1(g)}{\partial g} > \frac{\partial m_2(g)}{\partial g}$ is also only a sufficient but not necessary condition for $B_{1g} > B_{2g}$ to hold. We must rely on simulation to obtain more insights.

As one can see in (A.8), the key parameters to determine the properties of the function are $x_0, \alpha$ and $\theta$. I use the same values of other parameters as that in Section 2.5. I first set $\theta_0 = 0.008$, and $x_0 = 2L = 100$, which is the maximum value of $x_0$. I let

$\alpha$ change from 0.05 to 0.95, with the interval of 0.05, and see how $\alpha$ affects $B_{1g}$ and $B_{2g}$. The results show that there are three different patterns. Figure A.3 shows that if $\alpha \in [0.05, 0.45], B_{2g} > 0$, which is corresponding to Figure 2.5. Figure A.4 shows that if $\alpha \in [0.5, 0.75], B_{2g} < 0$, which is corresponding to Figure 2.4 . A.5 shows that if $\alpha \in [0.8, 0.95]$, $B_{2g}$ is positive initially, and then falls to negative. This is a rather special pattern which only happens when $x_0$ is very large.

If one sets $x_0 = 75$, the pattern in Figure A.3 holds for $\alpha \in [0.05, 0.15]$, and the pattern in Figure A.4 holds for $\alpha \in [0.2, 0.95]$. Furthermore, one can verify that a smaller $\theta_0$ increases the chance of the pattern in Figure A.4 to hold. Therefore, we can conclude that as long as $x_0$ is not too large, and $\alpha$ is not too small, $B_{2g} < 0$, and $B_{1g} > B_g$ holds. Also, we can see that even when the local government of region 2 has an incentive to build a seawall, it will choose a lower seawall height than the local government of region 1, which induces it to free ride.

Figure A.3: Marginal Benefit Comparison When $\alpha \in [0.05, 0.45]$

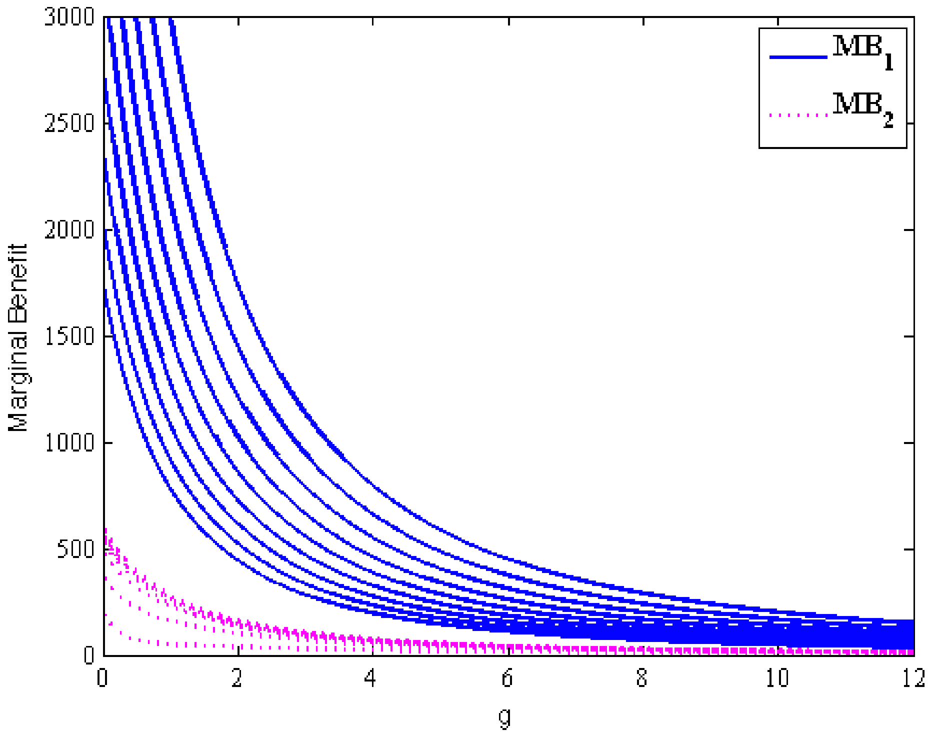


Figure A.4: Marginal Benefit Comparison When $\alpha \in [0.5, 0.75]$

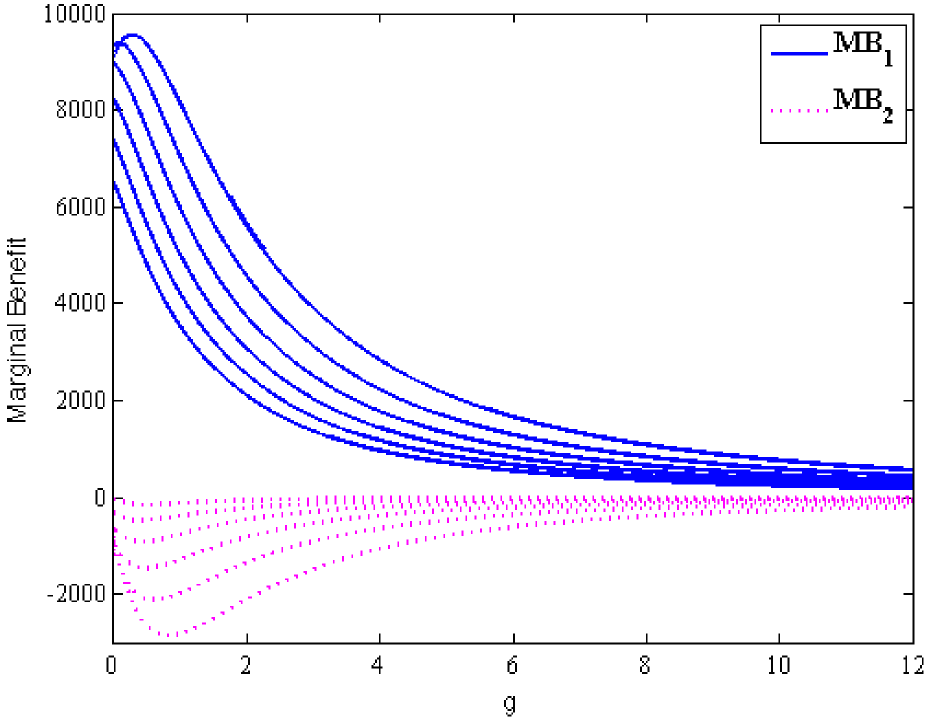
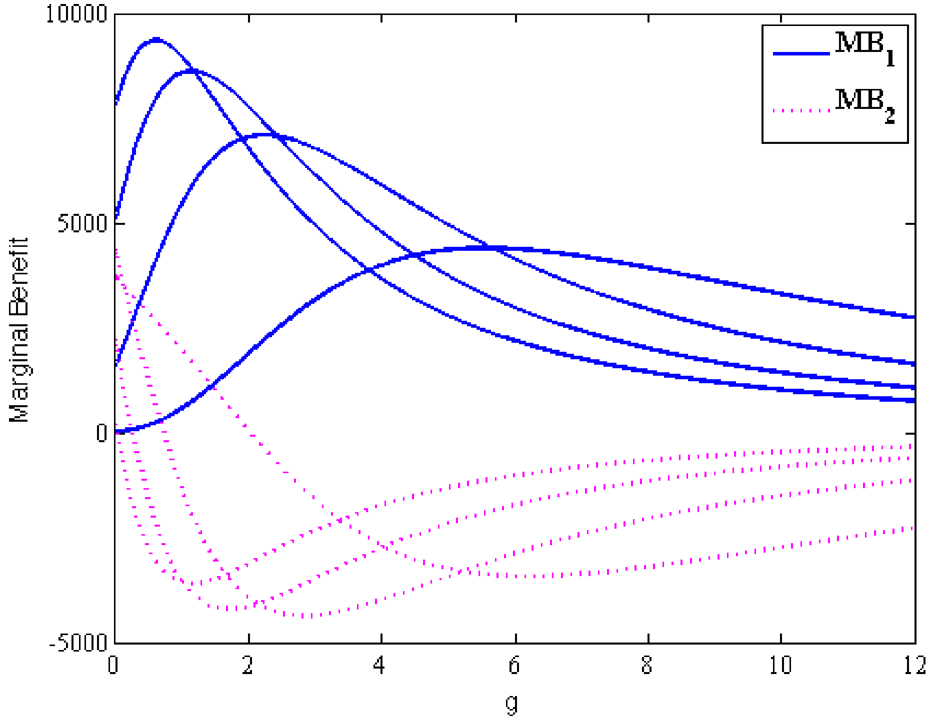


Figure A.5: Marginal Benefit Comparison When $\alpha \in [0.8, 0.95]$



### A.3 Supplementary Tables and Figures of Simulation Results

Figure A.6 shows net total output curves for both no seawall (baseline) decision and building a seawall decision (seawall) made by the central government, with both the high and low damage probabilities. Since there is no seawall investment in the baseline case, net total output does not vary with seawall height. Therefore, the two horizontal lines in the Figure A.6 represent net total output in the baseline. The higher line is associated with the low damage probability while the lower line is associated with the high damage probability. For the seawall case, the optimal choice is always at the peak of each curve. Notice that for both scenarios, once the seawall investment decision is made, net total output can never reach the no-seawall level in the baseline due to the relatively high fixed cost of the seawall. Hence, in each of these two scenarios, the interior solution yields a local maximum but not a global maximum, and the corner solution of no seawall protection is socially preferable.

Figure A.6: Net Total Output Comparison

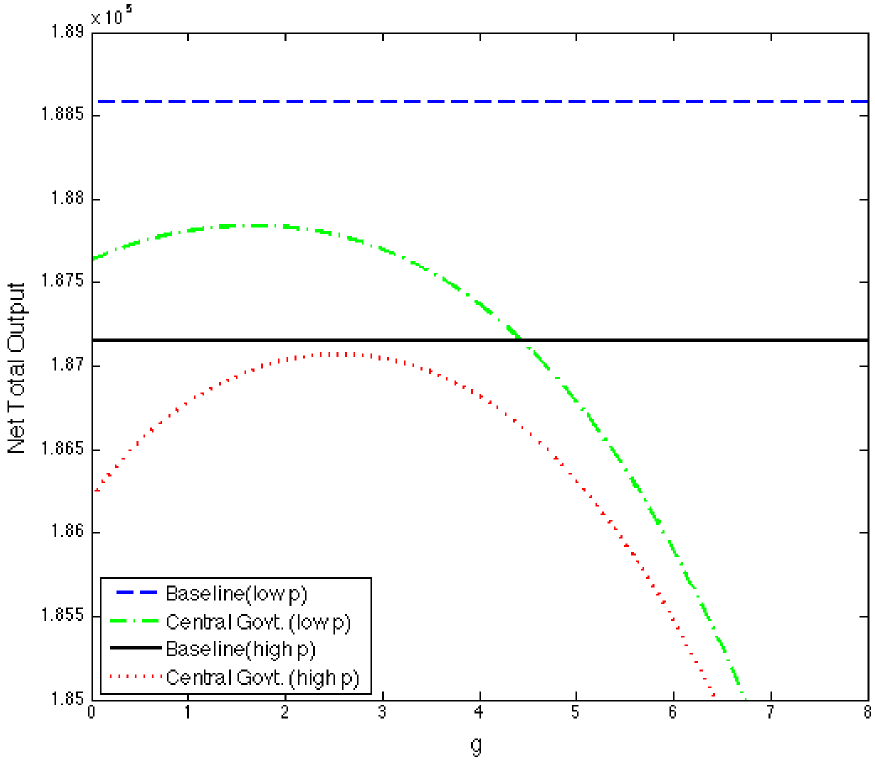


Table A.1: Damage Boundary in Region 1 and Low Fixed Cost

| | | Scenario 3 | | |
|---|---|---|---|---|
| $\overline{\theta} = 0.2$ | Baseline | Central Govt. | Local (Output) | Local (Wage) |
| | (1) | (2) | (3) | (4) |
| Seawall Height | 0 | 2.56 | 3.46 | 2.03 |
| Seawall Cost | 0 | 261.85 | 507.53 | 177.75 |
| Wage Rate (P1) | 34.7155 | 35.1034 | 35.1594 | 35.0596 |
| After-tax Wage | 35.4653 | 35.3671 | | 35.3987 |
| Net Total Output | 187149.16 | 187921.37 | 187824.91 | 187888.65 |
| Net Output in R1 | 89444.08 | 91869.48 | 92005.5 | 91653.76 |
| Average Wage | 35.0904 | 35.2353 | | 35.2291 |
| Loss Rate | 2.11% | **1.30%** | 1.40% | 1.33% |
| | | Scenario 4 | | |
| $\overline{\theta} = 0.05$ | Baseline | Central Govt. | Local (Output) | Local (Wage) |
| | (1) | (2) | (3) | (4) |
| Seawall Height | 0 | 1.67 | 2.28 | 1.31 |
| Seawall Cost | 0 | 141.3 | 213.38 | 116.98 |
| Wage Rate (P1) | 35.2526 | 35.3472 | 35.3637 | 35.3346 |
| After-tax Wage | 35.4653 | 35.4123 | | 35.4214 |
| Net Total Output | 188580.16 | 188692.14 | 188664.06 | 188682.75 |
| Net Output in R1 | 93145.08 | 93642.49 | 93681.24 | 93581.82 |
| Average Wage | 35.359 | 35.3798 | | 35.378 |
| Loss Rate | 0.60% | **0.48%** | 0.51% | 0.49% |

Table A.2: Damage Boundary in Region 2 and High Fixed Cost

| | Scenario 5 | | | |
|---|---|---|---|---|
| $\overline{\theta} = 0.6$ | Baseline | Central Govt. | Local (Output) | Local (Wage) |
| | (1) | (2) | (3) | (4) |
| Seawall Height | 0 | 4.96 | 6.29 | 4 |
| Seawall Cost | 0 | 2164.3 | 3438.58 | 1585.34 |
| Wage Rate (P1) | 29.7844 | 33.3529 | 33.6678 | 33.0504 |
| After-tax Wage | 35.4653 | 34.6537 | | 34.8708 |
| Net Total Output | 173999.16 | 181350.81 | 180916.3 | 181123.32 |
| Net Output in R1 | 59958.08 | 80296.48 | 80896.83 | 79052.63 |
| Average Wage | 32.6249 | 34.0033 | | 33.9606 |
| Loss Rate | 16.02% | **8.24%** | 8.70% | 8.49% |

| | Scenario 6 | | | |
|---|---|---|---|---|
| $\overline{\theta} = 0.15$ | Baseline | Central Govt. | Local (Output) | Local (Wage) |
| | (1) | (2) | (3) | (4) |
| Seawall Height | 0 | 3.4 | 4.27 | 2.73 |
| Seawall Cost | 0 | 1338.68 | 1724.06 | 1149.76 |
| Wage Rate (P1) | 33.6068 | 34.7447 | 34.8424 | 34.646 |
| After-tax Wage | 35.4653 | 34.9633 | | 35.0342 |
| Net Total Output | 184192.16 | 185887.92 | 185763.27 | 185813.87 |
| Net Output in R1 | 83974.08 | 89224.21 | 89390.31 | 88854.59 |
| Average Wage | 34.5361 | 34.854 | | 34.8401 |
| Loss Rate | 5.24% | **3.45%** | 3.58% | 3.53% |

# Appendix B: Chapter 3

## B.1 Proof of Proposition 3.3

To prove this proposition, rewrite equation (3.28)

$$-\frac{V_t C'(g)}{2\overline{Y}} - \frac{\beta n_2}{2n}(V^1_{n_1} + V^2_{n_2})\frac{\partial n_1}{\partial g} = \beta\theta'(g)V^1_\theta[n_1(g), \theta(g)]. \tag{B.1}$$

Compare (3.25) with (B.1), the RHS, the marginal social benefit is identical. Subtracting the LHS of (3.25) from (B.1) and letting $Q$ denote the difference gives

$$Q = \beta\Big\{\frac{n_1}{2n}V^1_{n_1}[n_1(g), \theta(g)] - \frac{n_2}{2n}V^2_{n_2}[n_2(g), \theta(g)]\Big\}\frac{\partial n_1}{\partial g}. \tag{B.2}$$

Since $n_2 > n_1, V_(n_i) < 0$, and $V_{n_i n_i} < 0$, thus, $\frac{n_1}{2n}V^1_{n_1} > \frac{n_2}{2n}V^2_{n_2}$. Therefore, $Q$ is positive, i.e., when the central government moves first, the marginal social cost is lower.

# Appendix C: Chapter 4

## C.1 Travel Definitions and Coding Rules

### C.1.1 Travel Classifications

Table C.1 presents classifications and definitions of travel time use. We categorize travel time into four main categories, including work travel, non-market work travel, leisure travel, and other travel. We further divide non-market travel into four subcategories, including child care travel, other care travel, home production travel, and obtaining travel. For leisure travel, there are two different measures based on narrow and broad measures of leisure. One is narrow leisure travel, which is travel time related to core leisure activities (for example, sports, recreation, socializing, relaxing, and arts and entertainment). The other one is other leisure travel, which is travel time related to other broadly defined leisure activities (for example, eating and drinking, personal care, own medical care, religious, and spiritual). The American Time Use Survey (2003-2013) have consistent measures on the first three main categories. However, for earlier surveys, we do not have consistent measures on non-market work travel and leisure travel. We instead focus on subcategories of travel time use that have consistent measures for the sample period. In particular, we focus on obtaining travel and the narrow measure of leisure travel when examining the disaggregated travel time over the long horizon.

### C.1.2 Coding Rules

Table C.2 lists the coding rules of traveling from 2003 ATUS Coding Rules Manual. Table C.3 lists the coding rules of traveling from Time Use in Economic and Social Accounts, 1975-1976. We can see that the coding rules are generally consistent between these two surveys. The general rule in 2003 ATUS is to code all travel, except homebound trips, look ahead to the next activity or destination before coding

Table C.1: Travel Time Use Classifications

| Travel Time Use Classification | Examples of Travel Activities Included |
|---|---|
| **Work Travel** | Travel related to work, such as commuting to/from work, and work-related travel, not commuting. |
| **Non-Market Work Travel** | Home Production Travel, Obtaining Travel, Child Care Travel and Other Care Travel |
| – Child Care Travel | Travel related to helping and caring for household and nonhousehold children |
| – Other Care Travel | Travel related to helping and caring for household and nonhousehold adults |
| – Home Production Travel | Travel related to household activities such as meals, vehicle maintenance and other housework |
| – Obtaining Travel | Travel related to consumer purchases, household and government services, professional and personal care services except medical, |
| **Leisure Travel** | Narrow leisure travel and Other Leisure Travel |
| – Narrow Leisure Travel | Travel related to sports, exercises, recreation, socializing and communicating, hosting and attending social events, relaxing and leisure, arts and entertainment, and telephone calls |
| – Other Leisure Travel | Travel related to eating and drinking, personal care, own medical care, religious, spiritual, volunteering and other leisure activities |
| **Other Travel** | Travel related to education, security procedures related to traveling, and traveling not elsewhere classified |

a travel episode. Homebound travel episodes are coded by looking look backwards to the previous activity. The coding rules for some special cases are also specified. For instance, for multiple destination trips, each travel episode of a multiple destination trip is coded according to each destination. For example, driving from home to work is coded as traveling related to work (commuting), from work to the bank as traveling related to financial services and banking, from the bank to the grocery store as traveling related to consumer purchases, and from the grocery store to home as traveling related to consumer purchases. Another important travel time use is travel as part of a job. For taxi drivers, bus drivers, and other workers who travel as an essential part of their jobs, the rule is to code their travel time as work and work-related activities, unless travel reason is clearly not work.

Table C.2: Coding Rules of Traveling (2003)

| | |
|---|---|
| General rule | To code all travel except homebound trips, look ahead to the next activity/destination before coding a travel episode. To code the homebound travel episode, look backwards to the previous activity. |
| Single destination trips | Direct trips to/from a destination: Code as Traveling/Related to [relevant destination/activity].<br>Multi-leg trips: Code all legs associated with one destination according to the trip destination. |
| Multiple destination trips | Code each travel episode of a multiple destination trip according to each destination. |
| Trips home | Code according to the last stop. |
| Waiting for bus/train | Code any waiting related to travel as part of the travel episode. |
| Commuting or work-related travel | Code home to work and work to home (including multi-leg trips) as commuting, provided there are no intervening activity stops. Code travel undertaken after arriving at work according to the next activity destination. If such activities have an M or O in the work column, then code the travel as work-related, not commuting. Travel to return to work after leaving work for another activity should be coded according work-related travel, not commuting. |
| Walking someplace | Code as Traveling/Related to [relevant activity]. Exceptions: Walking for exercise should be coded as sports and exercise. Walking the dog should be coded as pet care under household activities. Walking a child to [the child's event] should be coded as traveling related to childcare. Walking around as part of another activity should be coded as part of the main activity. |
| Travel as part of job | For taxi drivers, bus drivers, chauffeurs, traveling sales workers, and other workers for whom travel is an essential part of their job, code travel time as Work and Work-Related Activities/Working/Work, main job or work, other job unless travel reason is clearly not work. |
| Using a taxi | Code as Traveling/Related to [activity], not as Consumer Purchases. |
| Warming up the car | Code as part of the next travel episode (traveling related to xx), even if the respondent does other activities before the traveling episode. |
| Travel with no destination | If the respondent reports driving, but changes his or her mind and returns home before reaching a destination, code as Traveling, n.e.c (not elsewhere classified). |
| Airport, train station, or bus depot travel activities | Code activities associated with travel (such as "picking up baggage") as Traveling, n.e.c. |
| Security procedures | If respondent reports undergoing security procedures (such as "being searched at security checkpoint") related to traveling, code as Security Procedures Related to Traveling. |

Source: 2003 ATUS Coding Rules Manual, p31-33.

Table C.3: Coding Rules of Traveling (1975)

| | |
|---|---|
| General rule | Travel can never be a secondary activity. When travel is reported as a secondary activity and it is a non-concurrent activity:<br>1. Circle it out and move it to the primary column under the primary it was listed with.<br>2. Split the time according to travel time not reported rules.<br>3. Edit item 4 to "transit".<br>4. Assume item 5 is the same as for the associated primary unless noted otherwise.<br>5. Assume there is no secondary activity. |
| Purpose of trip | Travel is generally associated with the purpose of the trip, both going to and coming back from. |
| Multiple purpose trips | In the case of a trip that had multiple purposes, code each travel segment as travel related to the next primary activity, then code the last segment of the trip as travel time related to the last activity. |
| Pleasure driving | Code "driving around," "out for a ride," etc. as 817, under sports and active leisure. |
| Travel while work | Code travel while working as work time. |
| Travel shopping | Code "picked up friend to go shopping" as travel shopping (not social). |
| Picking up others | In general, code the travel time related to the purpose of the trip, e.g.,"taking someone else to work" (if r is not going to work), code 498, travel (helping). |
| Work travel | Travel related to work (code 099) is to capture only the time r spends commuting to get to his/her work place and to get back home from the work place (at the end of r's work day). Any intervening trips are to be coded as travel related to the purpose of the activity (e.g., travel to and from lunch will be coded as travel related to personal care). |
| Interrupted work travel | Since many respondents do not go directly to work or directly home afterwards:<br>A. First, ascertain if one of the travel times (to or from work) is direct. When one of the times is direct, use that as the travel time for commuting the other way. Any left over minutes should be divided among the travel time related to other activities along the way (use work travel code 099).<br>B. If both the trip to and from work include activities along the way, start with the trip to work: subtract 5 minutes from the total travel time for each different travel activity (but must have at least five minutes left for commute work time) once you have subtracted for stops use the remaining (trip to work) total time for computing the base time for the trip home from work, and divide remaining time equally between other activities on the way home. |
| Trip within a trip | If there is a clear trip within a trip, then code travel to and from as you would if r went there and back from home. |

Source: Time Use in Economic and Social Accounts, 1975 - 1976, Codebook p44-48.

### C.2 Blinder-Oaxaca Decomposition (Sample 2)

Table C.4 presents the Blinder-Oaxaca decomposition of total travel time for three subperiods: 1965-1993, 1993-2003, and 2003-2013. As in Table 4.5, the first columns reports decomposition results using the ”pooled-two” method, while the second and third columns report results using starting and ending years as references. The last column gives the ratio of explained or unexplained part relative to total difference.

Panel A shows that travel time increased by 1.63 hours per week from 1965 to 1993. About 30 percent of the increase can be explained by demographic shifts. Advances in education attainment alone contribute to 25 percent of the increase, which is close to our 1975-1993 decomposition result (28 percent) using the first sample. Shifts across work-gender groups contribute to 6 percent of the increase, whereas the declines in the proportion of population with children pushes travel time down by 5 percent. Finally, different from the result in our main sample, changes in age composition play little role here. Because the second sample excludes those older than 65, shifts of age composition, especially the aging of baby boomers, cannot be fully captured.

Panel B shows that total travel time declined by 0.89 hours per week from 1993 to 2003. Demographic shifts can only explain about 3 percent of the decline. Shifts in age and education respectively contribute to 3.5 and 3.8 percent of the decline, whereas shifts across work-gender groups push total travel time up about 3 percent. The effect of increases in the fraction of people with children is not significant.

Panel C shows that total travel time declined by 0.8 hours per week from 2003 to 2013. Consistent with the result in the main sample, contribution from demographic shifts is statistically insignificant, due to countering forces of demographic shifts. Changing composition across age, work-gender and population with and without children explain about 12 percent of the total decline in this period. However, increases fractions of people with higher education pushes travel time up about 11 percent and offset the impact of the other three demographic shifts.

Table C.4: Blinder-Oaxaca Decomposition of Total Travel Time (Sample 2)

Panel A: 1965 -1993

| | (1)<br>Pooled-two | (2)<br>Ref_1993 | (3)<br>Ref_2003 | (4)<br>Ratio |
|---|---|---|---|---|
| **Overall** | | | | |
| Survey_1993 | 10.40$^{***}$ | 10.40$^{***}$ | 10.40$^{***}$ | |
| | (0.11) | (0.17) | (0.17) | |
| Survey_1965 | 8.77$^{***}$ | 8.77$^{***}$ | 8.77$^{***}$ | |
| | (0.32) | (0.16) | (0.16) | |
| Difference | 1.63$^{***}$ | 1.63$^{***}$ | 1.63$^{***}$ | |
| | (0.33) | (0.23) | (0.23) | |
| Explained | 0.42$^{***}$ | 0.52$^{***}$ | 0.31$^{*}$ | 25.9% |
| | (0.11) | (0.15) | (0.17) | |
| Unexplained | 1.20$^{***}$ | 1.11$^{***}$ | 1.32$^{***}$ | 74.1% |
| | (0.36) | (0.27) | (0.30) | |
| **Explained** | | | | |
| Age | -0.00 | -0.01 | 0.01 | -0.2% |
| | (0.01) | (0.01) | (0.01) | |
| Work-Gender | 0.10$^{***}$ | 0.12$^{***}$ | 0.06$^{**}$ | 6.0% |
| | (0.03) | (0.04) | (0.03) | |
| Education | 0.41$^{***}$ | 0.52$^{***}$ | 0.29$^{**}$ | 25.1% |
| | (0.08) | (0.12) | (0.14) | |
| Child | -0.08 | -0.10 | -0.06 | -4.9% |
| | (0.07) | (0.09) | (0.09) | |
| **Unexplained** | | | | |
| Age | 0.43 | 0.44 | 0.41 | |
| | (0.70) | (0.44) | (0.44) | |
| Work-Gender | -1.19$^{**}$ | -1.21$^{***}$ | -1.15$^{***}$ | |
| | (0.54) | (0.41) | (0.38) | |
| Education | 0.05 | -0.06 | 0.16 | |
| | (0.14) | (0.11) | (0.12) | |
| Child | -0.09 | -0.07 | -0.12 | |
| | (0.46) | (0.20) | (0.33) | |
| Constant | 2.01$^{*}$ | 2.01$^{***}$ | 2.01$^{***}$ | |
| | (1.04) | (0.65) | (0.65) | |

Notes: $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$. Robust Standard Errors in Parentheses. The ratio of explained or unexplained part relative to total difference in column (4) is calculated based on the pooled-two method.

Table C.4 Continued: Blinder-Oaxaca Decomposition of Total Travel Time (Sample 2)

| Panel B: 1993 - 2003 | | | | |
|---|---|---|---|---|
| | (1) Pooled-two | (2) Ref_1993 | (3) Ref_2003 | (4) Ratio |
| **Overall** | | | | |
| Survey_2003 | 9.50$^{***}$ | 9.50$^{***}$ | 9.50$^{***}$ | |
| | (0.07) | (0.10) | (0.10) | |
| Survey_1993 | 10.40$^{***}$ | 10.40$^{***}$ | 10.40$^{***}$ | |
| | (0.31) | (0.17) | (0.17) | |
| Difference | -0.89$^{***}$ | -0.89$^{***}$ | -0.89$^{***}$ | |
| | (0.32) | (0.19) | (0.19) | |
| Explained | -0.03 | -0.00 | -0.06$^{*}$ | 3.2% |
| | (0.03) | (0.05) | (0.04) | |
| Unexplained | -0.87$^{***}$ | -0.89$^{***}$ | -0.84$^{***}$ | 96.8% |
| | (0.32) | (0.21) | (0.20) | |
| **Explained** | | | | |
| Age | -0.03$^{**}$ | -0.02 | -0.05$^{***}$ | 3.5% |
| | (0.01) | (0.03) | (0.02) | |
| Work-Gender | 0.02$^{**}$ | 0.02$^{*}$ | 0.02$^{**}$ | -2.7% |
| | (0.01) | (0.01) | (0.01) | |
| Education | -0.03$^{**}$ | -0.03 | -0.04$^{**}$ | 3.8% |
| | (0.02) | (0.03) | (0.02) | |
| Child | 0.01 | 0.02 | 0.01 | -1.4% |
| | (0.02) | (0.03) | (0.02) | |
| **Unexplained** | | | | |
| Age | -0.60 | -0.61 | -0.59 | |
| | (0.56) | (0.37) | (0.38) | |
| Work-Gender | 0.21 | 0.21 | 0.21 | |
| | (0.60) | (0.38) | (0.37) | |
| Education | 0.04 | 0.03 | 0.05 | |
| | (0.16) | (0.08) | (0.10) | |
| Child | -0.06 | -0.07 | -0.05 | |
| | (0.29) | (0.20) | (0.16) | |
| Constant | -0.46 | -0.46 | -0.46 | |
| | (0.84) | (0.55) | (0.55) | |

Notes: $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$. Robust Standard Errors in Parentheses. The ratio of explained or unexplained part relative to total difference in column (4) is calculated based on the pooled-two method.

Table C.4 Continued: Blinder-Oaxaca Decomposition of Total Travel Time (Sample 2)

Panel C: 2003 - 2013

| | (1)<br>Pooled-two | (2)<br>Ref_1993 | (3)<br>Ref_2003 | (4)<br>Ratio |
|---|---|---|---|---|
| **Overall** | | | | |
| Survey_2013 | 8.70$^{***}$ | 8.70$^{***}$ | 8.70$^{***}$ | |
| | (0.18) | (0.12) | (0.12) | |
| Survey_2003 | 9.50$^{***}$ | 9.50$^{***}$ | 9.50$^{***}$ | |
| | (0.07) | (0.10) | (0.10) | |
| Difference | -0.80$^{***}$ | -0.80$^{***}$ | -0.80$^{***}$ | |
| | (0.19) | (0.16) | (0.16) | |
| Explained | -0.01 | 0.02 | -0.03 | 0.7% |
| | (0.02) | (0.03) | (0.03) | |
| Unexplained | -0.80$^{***}$ | -0.82$^{***}$ | -0.77$^{***}$ | 99.3% |
| | (0.19) | (0.16) | (0.16) | |
| **Explained** | | | | |
| Age | -0.03$^{***}$ | -0.04$^{**}$ | -0.02 | 3.6% |
| | (0.01) | (0.01) | (0.02) | |
| Work-Gender | -0.06$^{***}$ | -0.05$^{***}$ | -0.06$^{***}$ | 7.0% |
| | (0.01) | (0.01) | (0.01) | |
| Education | 0.09$^{***}$ | 0.11$^{***}$ | 0.08$^{***}$ | -11.4% |
| | (0.01) | (0.02) | (0.02) | |
| Child | -0.01$^{*}$ | 0.00 | -0.02$^{**}$ | 1.5% |
| | (0.00) | (0.01) | (0.01) | |
| **Unexplained** | | | | |
| Age | 0.23 | 0.24 | 0.23 | |
| | (0.48) | (0.39) | (0.39) | |
| Work-Gender | 0.15 | 0.14 | 0.15 | |
| | (0.38) | (0.31) | (0.32) | |
| Education | -0.04 | -0.06 | -0.02 | |
| | (0.10) | (0.08) | (0.07) | |
| Child | 0.22 | 0.21$^{*}$ | 0.23 | |
| | (0.18) | (0.14) | (0.15) | |
| Constant | -1.35$^{**}$ | -1.35$^{**}$ | -1.35$^{**}$ | |
| | (0.69) | (0.56) | (0.56) | |

Notes: $^{*}$ $p < 0.10$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$. Robust Standard Errors in Parentheses.

The ratio of explained or unexplained part relative to total difference in column (4) is calculated based on the pooled-two method.

### C.3 Blinder-Oaxaca Decomposition Details

In this section, we briefly explain the “pooled-two” method and the “pooled-all” method in Blinder-Oaxaca decomposition. Recall that the decompositions shown in (4.2) and (4.3) use the starting and the end year of coefficient estimates to weigh demographic shifts, respectively. In the following decomposition, we use the coefficient estimates from pooled models.

$$\overline{Y}_{t_1} - \overline{Y}_{t_0} = \left(\overline{X}_{t_1} - \overline{X}_{t_0}\right)' \widehat{\beta^*} + \left[\overline{X}'_{t_1}(\widehat{\beta}_{t_1} - \widehat{\beta^*}) + \overline{X}'_{t_0}(\widehat{\beta^*} - \widehat{\beta}_{t_0})\right]. \tag{C.1}$$

The first term is the “explained” portion, and the term in brackets is the “unexplained” portion. For “pooled-two” method, we pool the observations of both periods to run the regression (4.1), and $\widehat{\beta^*}$ represents the least-square estimate of $\beta$ in the two-year pooled model. For “pooled-all” method, we pool all observations available, from 1975 to 2013, to run the regression (4.1). $\widehat{\beta^*}$ represents the least-square estimate of $\beta$ in the all-year pooled model.