Valuing public investments to support bicycling

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Abstract

We develop a framework for assessing the net benefits of investments to promote bicycling, which explicitly accounts for internal costs of bicycling. We apply our model to eight Swiss cities using data from the Swiss national travel survey and find that increasing the level of bicycling by reducing internal costs leads to inframarginal benefits that exceed the net benefits from the additional bicycling. We further find that Swiss cyclists only partially internalize health benefits, which affects the benefits from infrastructure investments but also implies that there is scope for "soft" measures that would inform users about health benefits of bicycling.

JEL H43, H76; Q51; R41, R42.

Keywords: Cost-benefit analysis, health impact assessment, bicycle, valuation, internal cost, health benefit, VSL

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1. Introduction

Transport and urban planning branches of many local, regional and sometimes federal governments in industrialized countries have offices responsible for designing and carrying out bicycle-friendly policies, usually in coordination with other planning activities such as road construction or public transportation. The role of government to design and finance bicycle policies can be justified by the public-good character of bicycle infrastructures and their substantial fixed costs, but also by societal benefits associated with bicycling compared to other modes of transportation, such as a reduction in mortality and morbidity due to increased physical activity, reduction of congestion, and reduction in air pollution (WOODCOCK et al., 2009). Public interventions to increase the level of bicycling have often been successful (PUCHER, DILL AND HANDY, 2010).

In principle, there is nothing different about valuing bicycle-related investment, relative to investments in other types of transportation modes, and therefore standard cost-benefit principles based on consumer surplus should be employed. There are two empirical problems with this: First, computing the consumer surplus associated with bicycling requires knowledge about the generalized costs of bicycling, which are difficult to estimate because of the lack of a readily observable monetary cost component (abstracting from the fixed cost of the bicycle purchase). And second, it requires knowledge about the degree of internalization of personal health benefits, which constitute a major part of the benefits associated with bicycling. It is not clear that people fully internalize these benefits: The link between regular physical exercise and longevity may not be obvious because the benefits usually accrue many years in the future, and even if people are aware of cycling being healthy, translating this accurately into a quantitative sense for the long-term health benefits associated with bicycling, not to mention their monetary value, is extremely challenging. Last but not least, commitment issues could yet prevent them from choosing their optimal level of exercise (BERNHEIM and RANGEL, 2007). The share of personal health benefits not considered by cyclists should then be treated like an external benefit, because they are not traded off against internal costs.

Most existing studies about the value of bicycle investment abstract from internal costs altogether and equate the benefits associated with an increase in bicycling with the resulting gross benefits to marginal riders, mostly in the form of health benefits, and report high benefit-cost ratios (CAVILL et al., 2009; GOTSCHI, 2011; KRIZEK et al., 2007; WANG et al., 2005). While such a "gross benefits" approach overstates the consumer surplus associated with the increase in bicycling, it neglects the benefit to existing cyclists, such that the direction of the bias is not clear.

BORJESSON et al. (2012), to our knowledge, provide the only published attempt at estimating the consumer surplus of bicycling in a survey of commuter cyclists in Stockholm. They find that transportation time savings are valued higher for bicycling than for other modes, indicating that bicycling is associated with a direct disutility. Their results further imply that cyclists consider health effects when choosing among several competing transport options. However, these observations do not necessarily imply that internalization of health benefits is complete.

In this paper we develop a valuation method based on consumer surplus that accounts for the internal (generalized) costs of bicycling and apply it to eight Swiss cities using data from the Swiss national travel survey. By including monetary savings of bicycling relative to other modes of transportation in our generalized cost estimation, we can monetize these costs and compare them with the health benefits of bicycling, which we monetize independently using estimates for the reduction in mortality risk due to exercise and the Value of a Statistical Life (VSL). Our estimates suggest that Swiss bicyclists internalize around half of the health benefits when making transportation choices, although the results are sensitive to the VSL estimate employed (the higher the VSL, the lower the degree of internalization). We further find that due to the reduction in costs for existing riders, the total consumer surplus from bicycle spending turns out to be greater than the gross health benefits for new riders, a measure which has been used to value bicycle investments in the past to value public investments in bicycling.

The relationship between changes in internal costs and the resulting level of cycling on the one hand, and the degree of internalization of health benefits on the other, allows us to conceptualize the interaction between "hard" and "soft" policy measures, which is a longstanding question in the promotion of bicycling. "Hard" measures, such as investments in infrastructure, are aimed at reducing the internal costs (i.e., the disutility) associated with bicycling, whereas "soft" measures, such as informational and educational campaigns highlighting benefits of bicycling enable people to realize and hence internalize benefits in their decision making. Taking our results at face value, they suggest that there remains scope for soft bicycle measures in Swiss cities due to imperfect internalization of personal health benefits. However, because of the complexity of assessing internal costs of bicycling and the inherent limitations of the available data, our results primarily serve illustrative purposes and need to be interpreted with caution. For example, information about characteristics of chosen routes, longer or repeated assessments within subjects, more detailed information about attitudes and perceptions and various other types of data would likely improve the estimation of the internal cost function.

2. The costs and benefits of bicycling

In this section we briefly discuss the costs and benefits associated with bicycling identified by the literature. We separate health benefits from other benefits because of their quantitative importance, and because the degree of their internalization is the focus of our empirical analysis.

2.1 Health benefits

Bicycling is associated with a number of positive and negative health effects, and a literature has developed on the subject with the aim of defining, quantifying and sometimes monetizing various costs and benefits. The most important effects identified in the literature in terms of magnitude are a.) decreased risk of mortality and various morbidities as a result of physical activity (OJA et al., 2011), b.) increased injury risk as a result of exposure to motorized traffic (DE GEUS et al., 2012), and c.) increased mortality and morbidity due to exposure to air pollutants (INT PANIS et al., 2010). Most studies find that the first of these effects far outweighs the second two, leading to net health benefits of bicycling (DE HARTOG ET AL., 2010; DE NAZELLE ET AL., 2011; HOLM, GLÜMER AND DIDERICHSEN, 2012; RABL AND DE NAZELLE, 2012; ROJAS-RUEDA ET AL., 2011; WOODCOCK ET AL., 2009). Benefits from physical activity are the focus of most valuation studies, and they also feature prominently in our approach.

2.2 Internal costs and the determinants of the bicycle mode share

Abstracting from leisure trips that serve no purpose of transportation, getting from A to B conveys disutility to people in the form of money, time, effort, fear of accidents and other costs, the sum of which are usually referred to as generalized costs. In the context of bicycling, the internal costs are almost exclusively nonmonetary. The existence of internal costs follows from the fact that without an offsetting element, the presence of positive health benefits would make the bicycle the dominant transportation choice for all trips up to a certain distance.[1] However, the bicycle mode share in Swiss cities is around 5%, with few reaching more than 10% (Federal Statistical Office, 2007, 2012), and similar or lower numbers apply to other countries (PUCHER ET AL., 2010). Even

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[1] Experience from Dutch cities and Copenhagen suggests that there is no “law of nature” capping bicycle mode share anywhere close to what is observed in most cities without a long history of systematic bicycle investments.

though the presence of internal costs of bicycling may seem obvious, they are usually not considered when valuing the benefits of bicycle policies. Naturally, bicycling also conveys utility gains for some trips (i.e., negative costs), but the relatively low bicycle mode share implies that for many trips that could theoretically be carried out by bicycle, but are not, the internal costs are positive.

The tradeoff between costs and benefits is implicit in the literature devoted to identifying the determinants of bicycle mode choice and/or mode share,[2] most of which are not monetary in nature. RIETVELD and DANIEL (2004) use generalized costs as a predictor variable, in which they include measures such as "costs of effort" or fear of accidents. Similarly, HUNT and ABRAHAM (2007) report that bicyclists choose routes that are least "onerous",[3] and BROACH et al. (2012) find that cyclists avoid high volumes of motorized traffic. In the following, we separate the determinants that have been empirically identified to affect the propensity to bicycle into the following groups:

a.) <u>The general environment</u>

Factors that have been shown to influence the propensity to bicycle include weather (temperature and precipitation), topography, city size, cultural and neighborhood characteristics including land use (PUCHER AND BUEHLER, 2012; SAELENS, SALLIS AND FRANK, 2003; WARDMAN, TIGHT AND PAGE, 2007). General determinants that may be more easily influenced by city planners are the prices of alternative modes of transportation including parking costs.

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[2] Whereas the mode choice describes the discrete decision between two or several competing transportation modes, the mode share is the proportion of all trips carried out by a particular mode and therefore also depends on trip distances. In the literature reviewed here, the mode share is usually the dependent variable.

[3] SMITH (1991) finds that psychological costs of bicycling are a significant predictor of bicycle mode choice, but does not provide an explicit link between mode choice determinants and psychological costs.

b.) Route and destination characteristics

Bicycle mode choice/share is influenced by the presence of bicycle lanes/paths; the lane width, the volume and speed of motorized traffic; competition for space between drivers and cyclists; the number of stops, traffic lights or other obstacles; the number of intersections and their characteristics, accident risk; and qualitative aspects about bike lanes such as continuity and connectivity or the presence of on-street parking (Berrigan, Pickle and Dill, 2010; Broach, Dill and Gliebe, 2012). Menghini et al. (2010) conclude that trip length is the dominant factor for route choice, which is consistent with high time costs and/or costs of physical exertion.[4] This category may also include trip end facilities such as locking stations or the presence of showers at work (Wardman, Tight and Page, 2007).

c.) Personal characteristics

In terms of personal characteristics, the choice of bicycling is influenced by a person's age, race, gender, education, car ownership, aversion to driving, and the perception of bicycle-friendliness of the traffic environment or environmental preferences (Bauman et al., 2012; Heinen and Handy, 2012; Li et al., 2012). Furthermore, the translation between external factors and route characteristics into (dis-) utility of bicycling may vary across people: For example, the physical effort associated with a significant elevation gain may deter older people more than younger ones, all else equal. This means that even mode choice determinants that are the same for everybody can have a person-specific influence on the propensity to bicycle.

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[4] This study is based on GPS data of actual routes taken in Zurich, which are compared to constructed non-chosen alternative routes. The main result is that the observed bicyclists are willing to make only slight detours in order to improve along another dimension (such as the presence of a bike trail or fewer stops), implying large time and effort costs of bicycling.

2.3 Externalities

A share of the benefits from improved personal health accrue to the population as a whole in the form of lower health care costs, which leads to lower tax rates in nationalized health care systems or reduced insurance payments in systems relying on private health insurance. Better health may also increase the productivity of workers, which may be captured only partially by a wage increase. To the extent that bicycling substitutes for motorized traffic, it is also associated with a number of positive externalities, or more precisely, with the avoidance of negative externalities. These external effects include a reduction in air pollution, noise and congestion, lower demand for parking spaces, less wear and tear on roads, and intangible effects such as “livability” (DUMBAUGH, 2005; ELLISON and GREAVES, 2011; LITMAN, 2004; THAKURIAH et al., 2012).

3. Consumer surplus from public investments in bicycling

The social value of bicycle investment is shown in Figure 1. On the horizontal axis we measure cumulative bicycle-km Q in a population that take place in a given time period (e.g., a year). MC refers to the per-km net internal cost of bicycling, which we define to include all costs and benefits with the exception of health benefits. We ordered bicycle trips by their internal costs, such that the MC curve is increasing by construction. Bicycle-km on the left are associated with negative costs (i.e. benefits), representing the bicycle trips with the highest utility. As we expand the level of bicycling, the internal costs increase as more trips take place during inclement weather, over hilly terrain, or are carried out by people with a stronger aversion to physical exercise or accident risk.

Health benefits per bicycle-km are given by HB, which we assume to be constant across bicycle-km.[5] The equilibrium level of bicycling is given by Q_0; beyond this point, the internal costs of an

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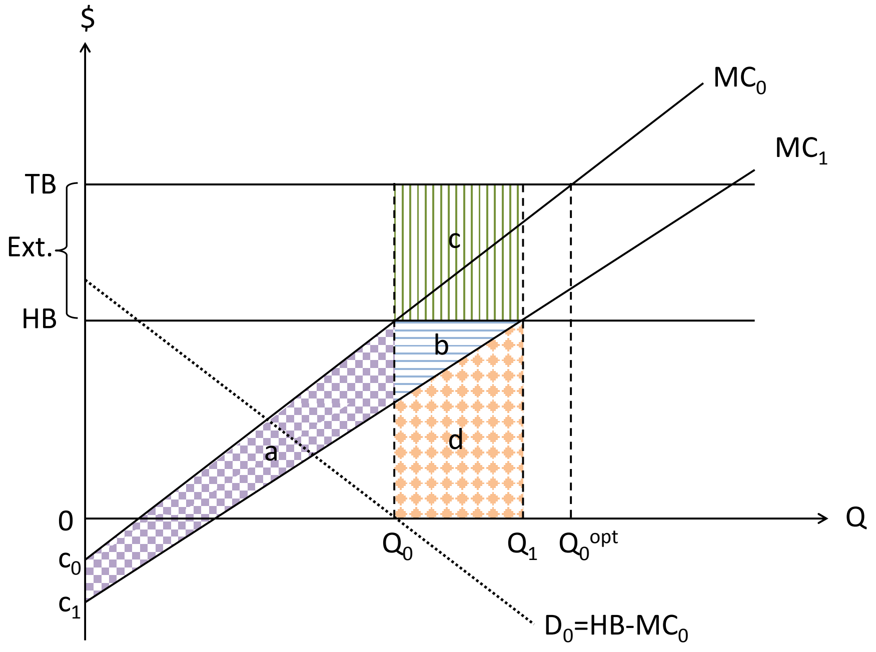
[5] Such a linear relationship between km of cycling and health benefits requires the assumption that cycling – more specifically cycling trips of different utility-is fairly evenly distributed with regards to overall activity levels of

additional bicycle-km are larger than health benefits, and vice versa. The same solution could be obtained in a more traditional demand and supply framework by defining the demand curve for bicycling as D=HB-MC (dotted line), and intersecting this curve with the infinitely elastic supply of bicycling at a price of zero. We chose to separate health benefits from the remaining costs and benefits because we want to focus on their degree of health benefits internalization.

Figure 1: Costs and benefits from bicycling



In addition to internal costs and benefits, there also exist external benefits of bicycling as discussed in Section 2.3, and which are represented by the difference between health benefits HB and total

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cyclists, which arguably may be the case for utilitarian urban cyclists. This assumption, however, is unlikely to hold for occasional leisurely rides or long distance rides, and subjects which are either entirely inactive or extremely fit. To include these extremes of the dose-response curve, a non-linear relationship reflecting lower benefits per additional km (within subject) would better reflect the nature of the effect (WOODCOCK et al., 2011). However, subject specific health benefit assessment would be beyond the scope of this analysis.

benefits TB. For simplicity and lack of knowledge about how the likely magnitude of externalities changes with internal costs, we assume that these are constant on a per-km basis. According to standard economic theory, consumers exclude all external effects but fully consider all internal effects, but there is evidence that some people choose to cycle out of environmental concern (ERIKSSON and FORWARD, 2011).

In theory, the social optimum Q_0^{opt} could be achieved by placing a Pigovian subsidy equal to marginal external benefits on every bicycle-km travelled. Assuming that a per-km subsidy of bicycling is not feasible due to asymmetric information and enforcement constraints, the government has to resort to other measures. For example, it can carry out policies that increase the "bicycle-friendliness" of a city by reducing the internal costs of bicycling from MC_0 to MC_1, leading to an increase in the level of bicycling from Q_0 to Q_1. Examples include the expansion of bicycle infrastructure, driver education programs to raise awareness about sharing the street, rule changes such as a reduction in the speed limits for motorized traffic or subsidies for firms to install showers and locker rooms for their staff.

The social value of reducing MC_0 to MC_1 is the sum of net benefits associated with the increase in Q (area b), the benefit increase for inframarginal bicycle-km (area a), and the corresponding external benefits (area c). This is a restatement of the so-called "rule-and-a-half", (JARA-DÍAZ AND FARAH, 1988) the only difference being that the cost decrease varies across inframarginal travelers.[6]

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[6] The rule-and-a-half is an approximation for surplus under the assumption of linear demand curves and constant costs across consumers (e.g., the price of using public transportation) and abstracts from externalities. It states that the benefit from a cost decrease from C_0 to C_1 that increases transport demand from Q_0 to Q_1 is given by the sum of inframarginal benefits $Q_0(C_0-C_1)$, plus the benefits to new riders. The latter cannot exceed C_0-C_1 (otherwise, these trips would have taken place before the cost reduction), but they have to be positive (otherwise, they would not take

In contrast, the gross benefits associated with the increase in bicycling, which commonly have been used as an approximation of the value of bicycle investment, (e.g. GOTSCHI, 2011; RUTTER et al., 2013; WOODCOCK et al., 2009) are given by internal gross benefits (area b+d) plus external benefits (area c). Whether this is an over- or an underestimate of net benefits depends on the relative magnitudes of areas a and d. In our application to Swiss cyclists, we find that inframarginal benefits exceed internalized costs.

Bicyclists may not fully internalize health benefits because an important share of the benefits materialize only with a significant delay in the form of a decrease in mortality risk. If bicyclists only internalize $HB_p < HB$, the equilibrium level of bicycling is given by Q_0 in Figure 2. This could be a motivation for the government to engage in "soft measures", e.g. information or educational campaigns that aim to raise awareness about the personal health benefits from exercise that accrues to bicyclists, but which do not change the cost function. In practice, effective promotion of bicycling requires a broad mixture of policies, including "hard measures" such as infrastructure improvements as well as soft measures (KRIZEK, FORSYTH AND BAUM, 2009; PUCHER, DILL AND HANDY, 2010).

Suppose that the government engages in an information campaign that is fully successful in the sense that it causes people to exactly internalize the health benefits from bicycling. The new equilibrium will be at Q_1, leading to an increase in overall benefits by area b_1 (internal benefits to additional riders) plus c_1 (external benefits). If the government instead chooses to achieve Q_1 by means of hard measures that lower the cost function to MC_1, the corresponding benefits are the

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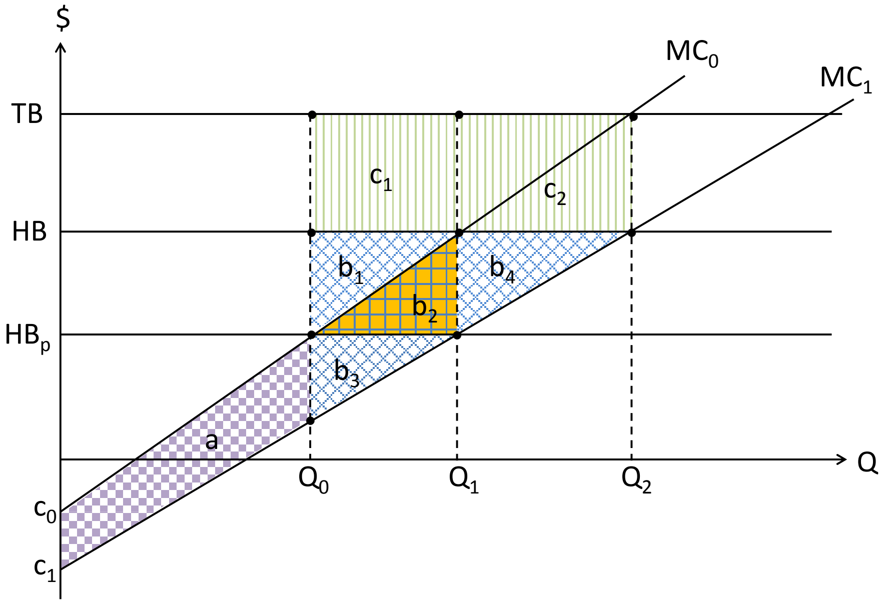
place even after the cost reduction). The rule-and-a-half assumes that on average, the additional benefits are $(C_0-C_1)/2$, such that total benefits are given by $Q_0(C_0-C_1) + (Q_1-Q_0)(C_0-C_1)/2 = (Q_0+Q_1)(C_0-C_1)/2$ (see e.g. Jara-Díaz and Farah, 1988). If the shift from MC_0 to MC_1 is parallel, this corresponds to areas a+b.

sum of areas a (benefits to inframarginal riders), b_3 (benefits to marginal riders), b_1+b_2 ("quasi"-externalities to marginal riders, which are technically internal benefits but are not considered by consumers in their mode choice), and the external benefits c_1. The difference in benefits consists of area $a+b_2+b_3$, the change in costs accruing to current plus new cyclists. This suggests that the substitution of hard for soft measures to reach a given level of ridership only makes sense to the extent that the latter is cheaper than the former.

Figure 2: Incomplete internalization of benefits



If the government decides to invest both in infrastructure and an information campaign, it can achieve an equilibrium level of bicycling at Q_2, with the corresponding benefits given by the inframarginal benefits a, benefits to marginal riders ($b_1+b_2+b_3+b_4$), plus external benefits (c_1+c_2). More generally, any level of bicycling between Q_0 and Q_2 could be achieved by a mix of hard and soft policy instruments, with the corresponding benefits as discussed above. Depending on the relative costs, the policy maker would then choose the optimal policy mix, characterized by the highest benefits/cost ratio.

4. Data and empirical model

We now apply our valuation framework to eight Swiss cities, using an econometric specification that fits the situation depicted in Figures 1-2, and which allows us to estimate the benefits of public spending that leads to a given reduction in the internal cost function.

4.1 Data

We use data from the Swiss national household travel survey (Federal Statistical Office, 2007, 2012), a large population-based survey conducted approximately every five years. For methodological comparability we restrict our analysis to data from the surveys from 1994, 2000, 2005 and 2010. As part of the computer assisted telephone interview (CATI), subjects are asked to provide information on one day of travel, tracking their mobility stage by stage. Travel mode, distance, duration, trip purpose and additional variables are captured for each stage. Earlier surveys (1994 and 2000) captured start and endpoints of stages by address only, more recent surveys recorded geo-coordinates using mapping software to assist CATI. Numerous additional variables are available at the levels of trip, travel day (e.g. weather), subject (e.g. public transport pass or car ownership), and household (e.g. number of vehicles available, including bikes). Not coded, however, are the actual routes chosen by the respondents.

We used Mapquest's address search feature and GIS software to identify direct routes between start and endpoints, which we overlaid with topographic data to derive elevation gains for each trip stage. We extracted the number of fatal and severe accidents from annually published accident statistics.

We compiled data for the 10 largest cities in Switzerland. We included all trips that originated or ended within the limits of our sample cities. Because Lausanne and Lugano had very few observed bicycle trips, we limited our analysis to the cities of Basel, Bern, Biel, Geneva, Luzern, St. Gallen, Winterthur and Zurich. Because we want to focus on stages for which the bicycle provides a feasible choice over other means of transportation, we focus on stage distances covering the central 98% of observed bicycle distances, which limits our sample to stages of 0.14-20.0km for all modes. Summary statistics of transportation mode choice in our sample are given in Table 1.

Table 1: Transportation choices at the stage level

	Stages	Stages (%)	Km	Km (%)	Respondents[a]
All modes	70'058	100.0%	142'831	100.0%	14'269
Walk	35'341	50.4%	27'636	19.3%	10'670
Pub. transport	16'487	23.5%	46'856	32.8%	5'883
Motor vehicle	12'197	17.4%	54'870	38.4%	4'716
Bicycle	4'678	6.7%	9'390	6.6%	1'644
Other	1'355	1.9%	4'080	2.9%	620

a: The same person may carry out trips using several different transport modes

4.2 Econometric specification

In order to estimate the relationship between internal costs and the quantity of bicycling on the population level, we have to overcome two problems: First, the internal cost of bicycling is unobserved, requiring the use of instrumental variables. Second, since bicycling is a choice and most trips are carried out by other means of transportation, we have to control for self-selection, for which we use Heckman's approach (HECKMAN, 1979).

Let q_{is}^{b} denote the distance travelled by bicycle (i.e., the observed demand for bicycling) by person i on stage s. Although all trip stages are recorded for all respondents, we observe the demand for bicycling only for people who choose to use a bicycle. The decision to use or not use a bicycle for a particular trip stage depends on a person's preferences and characteristics specific to the general environment and the route as discussed in Section 2.2. We model the decision to use a bicycle using a linear function given by

$$b_{is}^{*} = Z_{is}\gamma + u_{is} \tag{1}$$

where Z_{is} is a vector of mode choice variables, γ is a vector of coefficients, b_{is}^{*} is a latent variable, and u_{is} is an error term. Assuming that $u_{is} \sim N(0,1)$ leads to the Probit model. The sample rule is that we observe q_{is}^{b} only if $b_{is}^{*} > 0$. Let b_{is} be a dummy that takes the value of one if person *i* carries out stage *s* by bicycle, and zero otherwise. Defining $\Phi(\cdot)$ as the cumulative density function of the standard normal distribution, the probability that person *i* chooses a bicycle for stage *s* is then given by

$$\text{Prob}(b_{is} = 1) = \text{Prob}(u_{is} < Z_{is}\gamma) = \Phi(Z_{is}\gamma) \tag{2}$$

We specify the demand for bicycle-km as a linear function of variables Y_{is} that determine the quantity of bicycling via internal costs, and additional variables X_{is} that influence the level of bicycling via different mechanisms:

$$q_{is}^{b} = X_{is}\beta - \delta \cdot Y_{is}\Gamma + \varepsilon_{is} \qquad \text{(observed if } b_{is} = 1\text{)} \tag{3}$$

Here, β and Γ are vectors of coefficients, $Y_{is}\Gamma$ are monetized internal net costs of bicycling (including all internal costs and benefits with the exception of health benefits), and δ translates these costs into bicycle-km and therefore has the unit km/money. Since both Y_{is} and in Z_{is} contain variables related to the internal costs of bicycling, there will be considerable overlap between these vectors.

The error terms in (1) and (3) are jointly distributed according to a bivariate normal distribution:

$$(u_{is}, \varepsilon_{is}) \sim \text{biv. N}\,[0, 0; 1, \sigma_{\varepsilon}; \rho_{u\varepsilon}] \tag{4}$$

We estimate (2) and (3) jointly by full information maximum likelihood (FIML), allowing for clustering of the errors on the individual level such that they are independent between individuals, but not necessarily for different stages carried out by the same person. Note that by clustering on the individual level we also allow for clustering on the trip level.

Estimating (3) individually leads to inconsistent estimates if $\rho_{u\varepsilon} \neq 0$, which is a natural assumption in the context of bicycling. To provide some intuition, suppose that person *i* choses to use the bicycle for stage *s,* and that the observable mode choice determinants indicate that this person-stage combination is associated with high internal costs (e.g., the trip takes place during rainy weather and covers a significant elevation gain, and person *i* is a senior citizen). This translates to $Z_{is}\hat{\gamma} << 0$ in (1), which means person *i* must have a large positive error in the mode choice decision for stage *s* in order for b^{*}_{is} to be positive. We can therefore interpret u_{is} as a measure of innate affinity for person *i* to use the bicycle for stage *s*, which can be related to particular characteristics of person *i* and/or of stage *s*. Suppose further that $Z_{i's'}\hat{\gamma} > 0$ for person *s'* and stage *t'*, such that even moderately negative values of $u_{i's'}$ are consistent with $b^{*}_{i's'} > 0$.

Turning to the main equation, a large error term implies that person *i* cycles a longer distance q^{b}_{is} than what would be expected based on the observed covariates. A natural interpretation of ε_{is} is therefore something like bicycle endurance.[7] The question now is whether we expect that people

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[7] Both bicycle affinity and bicycle endurance can refer to characteristics of person *i*, of stage *s*, or a combination. The person-level interpretation is consistent with our error clustering.

who have a high expected bicycle affinity also have an above-average bicycle endurance.[8] Intuition suggests that this should be the case, and this is supported by our application where we obtain a positive estimate for $\rho_{u\varepsilon}$, and for its influence on q_{is}^{b}.

4.3 Variables

For the decision whether to use a bicycle or not for a particular stage, we use as the dependent variable the dummy b_{is} that takes the value of one if person *i* carries out stage *s* by bicycle, and zero otherwise. As continuous explanatory variables, we include steepness (elevation gain in m divided by distance in km) and its square; the risk for accidents resulting in fatalities or severe injuries involving bicyclists; the daily fare for public transportation within the city; and the age of the respondent. In addition, we include dummies indicating ownership of a public transportation pass (implying no or a reduced cost for a daily pass); gender; nationality (one if the respondent is Swiss, zero otherwise); education level (to proxy for income, which is unavailable in this dataset for the early years); access to a parking space at the trip destination; continuous access to a car or to a bicycle; precipitation (i.e. whether it rained or snowed during the stage); trip purpose; city dummies to capture the general bicycle environment that remains stable (e.g. climate, topography, city dispersion, culture, etc.); and year dummies to capture differences in sampling frequency and changing attitudes towards bicycling. To account for the possibility that the effect of some mode

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[8] Suppose that $Z_{i's'}\hat{\gamma} > 0$ for person *s'* and stage *t'*, such that even moderately negative values of $u_{i's'}$ are consistent with $b^{*}_{i's'} > 0$. Since we only observe $Z_{is}\hat{\gamma}$ but not the error, it is possible that $u_{i's'}$ exceeds u_{is} even if $Z_{is}\hat{\gamma} << Z_{i's'}\hat{\gamma}$. However, the fact that both trips are carried out by bicycle means that $E[u_{is} \mid \mathrm{Z}_{is}; b_{is} = 1] > E[u_{i's'} \mid Z_{i's'}; b_{i's'} = 1]$.

choice determinants varies by gender and age, we also include interaction terms involving these variables.

The dependent variable in the main equation is the distance of stage *s* carried out by person *i* using a bicycle (in km). As explanatory variables that influence the quantity of bicycling directly (the vector X_{is} in eq. (3)) we use a constant and year dummies, as well as the nonselection hazard (also known as "inverse Mills ratio"; this term corrects for self-selection). As determinants that affect the demand for bicycling via the cost function $Y_{is}\Gamma$, we use a subset of the variables included in the selection equation (elevation gain, elevation gain squared, accident risk and age, plus dummies for gender, nationality, education level, precipitation and trip purpose). We also include city dummies, which we interpret as a proxy for a city's general bicycling environment (e.g., the extent and quality of the bicycle lane network, culture, hilliness, dispersion etc.).

We further include variables representing the money savings (MS_{is}) and time savings (TS_{is}) of using the bicycle for stage *s*, relative to other modes of transportation. We define money savings as the weighted average of the price of competing modes of transportation, where we use as weights the probabilities that person *i* carries out stage *s* by that mode:

$$MS_{is} = \frac{\text{Prob}(pt_{is}) \cdot p_i^{pt} + \text{Prob}(car_{is}) \cdot p^{car}}{\text{1-Prob}(b_{is})} \tag{5}$$

$$\text{with} \qquad p_i^{pt} \equiv \overline{p}^{pt} \cdot \left(\text{Nopass}_i + 0.75 \cdot \text{Redfare}_i \right)$$

We compute the probabilities of mode choice using a multinomial Probit estimation that determines the choice of the five modes shown in Table 1, using the selection variables listed above plus stage distance, and distance squared (results not shown).

As the marginal cost of public transportation is p_i^{pt} we use the average price per km (full day fare divided by the average number of km traveled per day, or short-trip fare if person *i* travels less than 1 km by bicycle on that day), and adjust it for ownership of monthly or annual passes: Nopass$_i$ is a dummy indicating that person i holds no transportation pass, whereas Redfare$_i$ indicates that person *i* holds a reduced fare pass.[9] We set p_i^{pt} to zero for people who hold an annual or monthly pass that allows them to use public transportation at no marginal cost, and also if they used public transportation on the same day that they chose to use the bicycle for stage *s*.[10] We further assume a cost of CHF 0.50 per km for car travel[11], and of zero for the modes "walk" and "other" is zero.

For time savings, we compute the difference between the minutes needed per km when person *i* uses the bicycle for stage *s* (m_{is}), and the average time required when using a competing transportation mode ($\bar{m}^k$), again weighted by the probability that this mode is chosen:

$$TS_{is} = \frac{\sum_{k \neq b} \Pr(k_{is}) \cdot \bar{m}^k}{1 - \Pr(b_{is})} - m_{is} \tag{6}$$

We allow the average time requirements for different modes to differ across cities, therefore allowing for differences in the traffic situation or the quality of the public transportation network.

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[9] These are known as "half-fare travelcards" (Halbtax in German and abonnement demi-tarif in French) and are held by a large share of the Swiss population. As implied by their name, they convey the holder the right to purchase a fare at a 50% discount for long-distance travel. For city travel, however, the discount is typically only 25%.

[10] This reflects the assumption that if a person has used, or is intending to use, public transportation during this day and thus had/has to buy a day fare in any case, there is no money cost to replacing stage *s* with public transportation.

[11] Touring Club Switzerland computes a cost of CHF 0.76/km, but some of these are fixed costs; www.tcs.ch, last accessed in December 2013.

Table 2: Summary statistic of included variables

		Full sample (N=70,058))		Bicycle stages (N=4,678)	
Variables	Unit	Mean	St. Dev	Mean	St. Dev
Distance	km	2.04	2.67	2.01	1.77
Steepness	m/km	12.53	14.56	11.67	12.98
Accident risk	1/mio km	0.75	0.34	0.66	0.32
PT price	CHF/km	1.40	0.45	1.45	0.43
Money savings	CHF/km	0.27	0.24	0.27	0.24
Time savings	min/km			0.76	4.33
Age	years	45.43	19.96	38.73	15.03
Dummies	Unit	Share with value=1		Share with value=1	
Rain	(1/0)	0.20		0.17	
Commute	(1/0)	0.31		0.41	
Female	(1/0)	0.57		0.48	
Swiss	(1/0)	0.75		0.82	
High school	(1/0)	0.30		0.29	
University degree	(1/0)	0.27		0.38	
Car available	(1/0)	0.61		0.75	
Parking available	(1/0)	0.18		0.18	
Bicycle available	(1/0)	0.56		0.82	
Reduced fare pass	(1/0)	0.25		0.51	
Full pass	(1/0)	0.55		0.31	
Basel	(1/0)	0.09		0.15	
Bern	(1/0)	0.22		0.26	
Biel	(1/0)	0.03		0.04	
Geneve	(1/0)	0.19		0.12	
Luzern	(1/0)	0.06		0.08	
St. Gallen	(1/0)	0.06		0.03	
Winterthur	(1/0)	0.07		0.13	
Zürich	(1/0)	0.29		0.18	
1994	(1/0)	0.20		0.16	
2000	(1/0)	0.15		0.19	
2005	(1/0)	0.19		0.20	
2010	(1/0)	0.45		0.45	

Summary statistics of all included variables are shown in Table 2. There are a number of mode choice determinants for which we have no data. Perhaps the most important information that we are lacking is the chosen route itself, which implies that we cannot match them with route-specific attributes such as the presence of bicycle lanes, the number and type of intersections, traffic volume, etc., even if these latter variables were available. However, such information is not readily available anyway and would therefore be missing even if the travel survey recorded the exact routes. The lack of route information with sufficiently high spatial resolution naturally affects the explanatory power not only of our model, but of empirical models of active transport in general.

4.4 Identification

Without any further restriction it is clear from (3) that the components of Γ cannot be identified separately from δ, since $\delta \cdot \Gamma = \alpha\delta \cdot \Gamma / \alpha$ for any value of α. To identify Γ and δ, we fix the coefficient on money savings at -1 (money savings are negative costs). This identification strategy allows us to interpret $Y_{is}\Gamma$ as the monetized generalized net costs of bicycling, including all costs and benefits with the exception of private health benefits and external benefits. A different identification strategy would be to set $Y_{is}\hat{\Gamma} = HB$, but this would impose full internalization of health benefits ex-ante.

5 Results

Estimates from jointly estimating (2) and (3) are presented in Table 3. The left side contains the parameters in $\hat{\gamma}$ pertaining to the selection equation, and the right side the parameters in $\hat{\Gamma}$, which are computed by dividing the coefficient estimates from the main equation by the negative of the coefficient on cost savings (which becomes our estimate for δ). Most of the mode share determinants have the expected sign and are statistically significant. For example, an increase in accident risk, rain or age of the respondent lowers the probability that this person chooses the bicycle (Probit equation) and increases the internal cost of bicycling (main equation), all else equal. The results further suggest that people are more likely to choose the bicycle, and are willing to ride longer distances, if the observed stage is part of the daily commute (finding a good bicycle route can take some time, such that commuting trips may be associated with more attractive bicycle routes and thus with higher utility), or if the respondent is Swiss or has a higher education (cultural effects). Generalized internal costs are translated into bicycle-km via δ, implying that an increase in internal costs by CHF 1 is associated with a bicycle demand decrease by 3.96 km.

Table 3: Regression estimates (joint estimation by FIML)

	Probit equation (N=70,058)		Main equation (N=4,678)	
	Dep. var.: b_{is} (1/0)		Dep. Var.: q^{b}_{is} (bicycle-km)	
	Coef	t^{*}	Coef**	t^{*}
Steepness	0.0069	2.90	-0.0063	-3.90
Steepness sq.	-0.00005	-1.81	0.00007	3.14
Risk	-0.1728	-2.16	0.1268	2.46
PT price	0.1204	4.05		
Moneysave			-1	n/a
Timesave			-0.0009	-1.31
Age	-0.0082	-9.25	0.0426	4.21
Age · Steepness	-0.00015	-3.60	-0.32794	-4.04
Rain	-0.1238	-3.50	-0.0001	-2.99
Commute	0.1515	6.48	0.0001	2.60
Female	-0.0125	-0.20	0.0923	4.13
Female · Risk	-0.1286	-1.58	-0.0727	-4.60
Swiss	0.2175	5.98	0.0242	0.61
Secondary degree	0.1766	4.58	0.0943	1.79
University degree	0.3479	9.99	-0.1535	-6.22
Car available	0.0424	2.60		
Car parking	-0.2699	-3.10		
Car parking*Car avail.	0.2231	2.57		
Bicycle avail.	0.1699	8.17		
Reduced fare pass	0.0536	2.99		
Full pass	-0.3158	-11.22		
δ			3.9621	37.24
$\rho_{u\varepsilon}$			0.9938	843.27
σ_{ε}			2.4675	20.61
λ			2.2145	20.22

*: Standard errors clustered by respondent

**: The estimated coeff. on cost savings is δ; all other coeff. have been divided by $-\delta$

Additional variables included: Constant, city and year dummies

The total effect of steepness (elevation gain divided by distance) depends on the level of the variables at which it is evaluated. At the sample means of steepness and age, an increase in steepness decreases the propensity to bicycle, as expected, but it also decreases the internal costs of bicycling and thus increases the demand for bicycling. However, the relationship between steepness and bicycle demand is nonlinear, and costs increase as the stage becomes steeper, and as the age of the respondent increases. Evaluated at age=60 and the sample mean for steepness, the latter has a positive effect on internal costs.

Lastly, the coefficient on time savings has the expected sign, but is not significant. This could be explained by our lack of information about non-chosen alternatives, such that our time savings variable is a poor proxy for the actual time difference between competing modes for a particular stage. Alternatively, within the range of the analyzed trip distances, the time differences between modes may not be substantial enough to be detected by our model.

4.4 Computation of net benefits

We calculate the private health benefits from bicycling using the World Health Organization's Health Economic Assessment Tool (HEAT) for cycling (RUTTER et al., 2013; WHO, 2008). The tool has been developed in an expert consensus process and has been used widely. It uses state of the art science to provide a fairly simple tool for economic valuation of health benefits from cycling primarily aimed at transport planners without in depth economic or epidemiologic knowledge. The tool uses a relative risk estimate for all-cause mortality from a large cohort study (ANDERSEN et al., 2000) to estimate avoided number of deaths from a certain level of observed cycling. We then monetize the reduction in mortality using the value of a statistical life (VSL) of $7.4 Mio (million, measured in 2006 dollars) used by the US Environmental Protection Agency, which is equivalent to CHF 9.33 Mio (2010 francs). This leads to an average estimate for the value of bicycling one kilometer of CHF 0.40. Note, however, that this estimate is directly proportional to the VSL, for which there is no consensus, and for which a range of estimates has been proposed in the literature.

For example, the default value VSL in HEAT based on a European report from 1990 is only CHF 3.19 Mio (NELLTHORP et al., 2001), which would result in health benefits of CHF 0.15/km.[12]

We use daily bicycle-km as our dependent variable in the main equation, which requires multiplying the survey values by 365. We work with annual rather than daily numbers because the computation of health benefits presumes sustained long-term behavior. As we are ultimately interested in the benefits to the population rather than the sample, we scale all distances by dividing by the fraction of the total population that was sampled in that year and city.

The left curve in Figure 3 shows the net internal cost associated with bicycling plotted against cumulative bicycle-km in ascending order, which is the numerical equivalent of MC_0 in Fig. 1. The pre-intervention level of bicycling is given by Q_0=232 Mio km/y, which corresponds to 203 bicycle-km per person and year using 2010 populations. The right curve shows the internal costs associated with current riders' expected level of bicycling after a hypothetical policy intervention that reduces accident risk by 90%. Intuition suggests, and our regression results confirm, that a reduction in accident risk increases both the propensity to use a bicycle, as well as the quantity of km travelled by bike conditional on the bicycle being chosen as the means of transportation. The latter leads to additional bicycle-km of current riders, which is the cause of the outward shift of the MC curve to a level of bicycling given by Q_{1i}, whereas the former produces bicycle-km carried out by "new", i.e. marginal, riders, which are not reflected in Figure 3.

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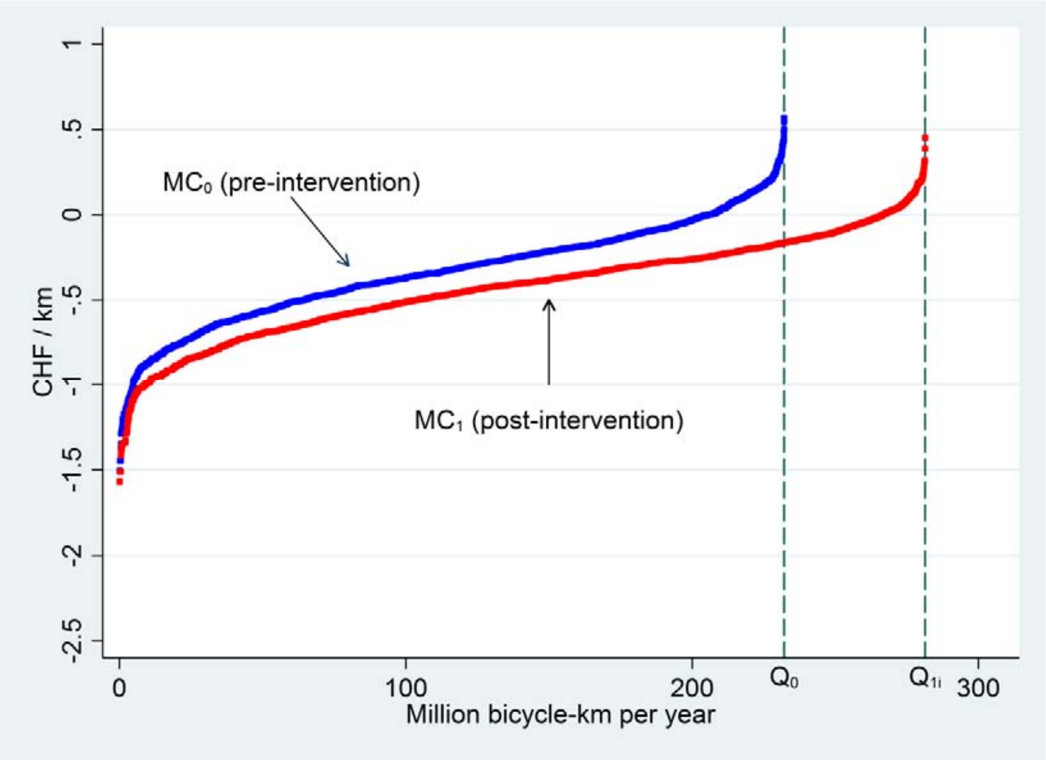
[12] Another issue is the transferability of VSL derived from labor market data involving US blue collar workers to cyclists in Switzerland, especially considering our finding that education is positively related to the propensity to choose the bicycle as a transport mode.

Figure 3: Generalized cost curves



Before we move on to the issue of marginal riders, we focus on the shape of the MC curves for inframarginal riders. The first bicycle-km are associated with negative internal costs, i.e. benefits. These bicycle-km are the low-hanging fruit associated with mode choice characteristics that favor bicycling (e.g. nice weather, not much elevation gain, young riders, commuting, etc.). As we increase the total level of bicycling, more and more "onerous" bicycle-km are carried out such that we move up the MC curve. Over a significant range, the relationship between internal costs and cumulative bicycle-km is approximately linear, but there is a sharp upwards trend in the beginning and at the very end. These areas are determined by extreme combinations of explanatory variables. For example, one cyclist in the sample is 99 years of age, and multiplying this number by the coefficients involving age yields a very high internal cost. The same applies to other variables or their combination: The stages with the highest marginal costs are associated with higher age of the riders, greater steepness, worse weather, less time and money savings etc., all of which are measured with error such that the most extreme observations can be expected to over-state the true costs. The positive error term from the Probit regression can only mitigate, but not remove this problem.

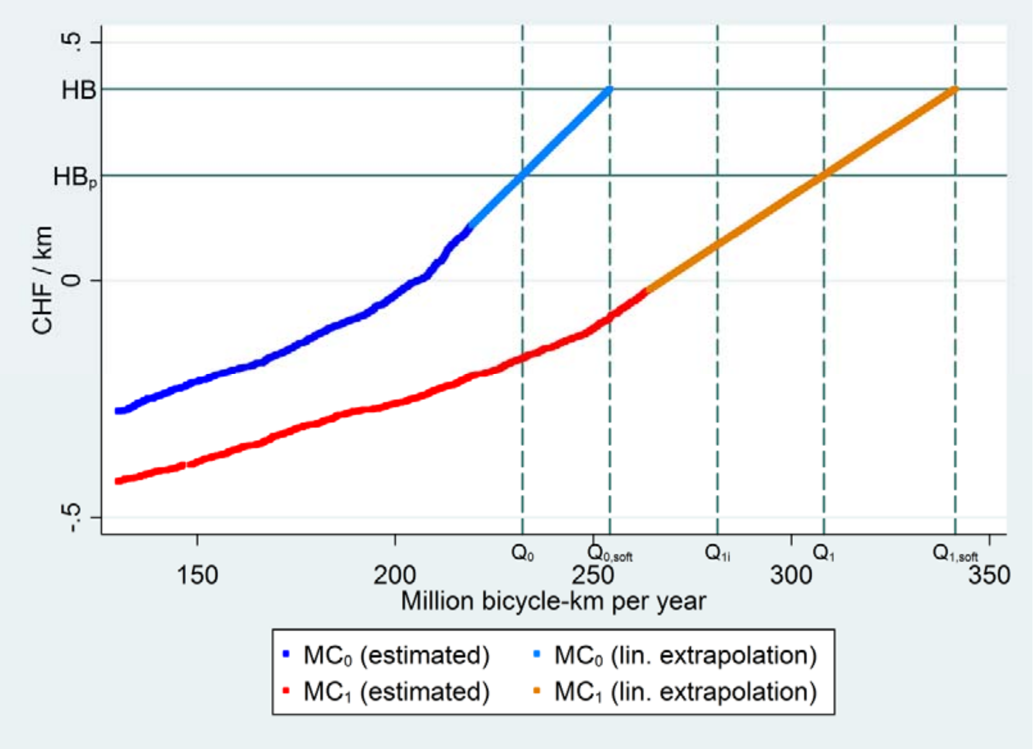
We believe that it makes little sense to base our estimate of the internalized share of health benefits on these tail observations since we are interested in the degree to which a representative person internalizes health benefits from an ex-ante perspective. We therefore chose to adjust the last decile of the MC function by linearly extrapolating the slope between the 8th and 9th decile. Although the same logic could be used to extrapolate for the first decile, the shape of the MC function at the lowest costs is of little empirical consequence because it applies to both cost functions such that the error is differenced out.

A second reason for the adjustment is that some of the most extreme costs may not have been anticipated by the riders. For example, riders may not know exactly how much elevation gain is associated with a stage, or they may not anticipate rain. When assessing the internal costs from an ex-post perspective we may over-estimate people's willingness to incur internal costs for the sake of bicycling.

Figure 4 shows the region around Q_0 in more detail. The straight part in MC_0 replaces the last 10% of observed bicycle-km. The intersection of this line with Q_0 gives us an adjusted estimate for internalized costs of 0.22 CHF/km, which is considerably lower than the unadjusted value and about half our estimate for gross health benefits HB of CHF 0.40.

One way to identify the "new" riders would be to rely on the estimates from the Probit regression to compute the increase in the likelihood that a particular non-bicycle would switch to bicycling, and use some spline function to ensure that the internal cost estimates of the new trips continue where the MC_1 function ends at Q_{1i}. However, we believe that this would place undue weight on the distributional assumption for u_{ij}, and there may also be further problems associated with outliers and differences between ex ante- vs. ex post assessments, requiring further extrapolations. To avoid these issues, we determine the extensive margin of bicycling by simply extrapolating the internal cost curve beyond Q_{1i} to the intersection with HB_p, using the same slope as for the last two deciles.[13]

Figure 4: Expected increase in bicycling based on linear extrapolation of costs



Conditional on our choice for the VSL, our results imply that bicyclists do not fully internalize health benefits, raising the scope for soft measures such as information campaigns with the aim to increase the awareness about positive health effects from bicycling. Depending on their cost and

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[13] The question of who would likely start to cycle is important when determining the health benefits associated with "new" bicycling. However, since we lack information such as personal fitness, time gain relative to other modes of transportations etc., we cannot really address this question. The lack of relevant details pertaining to a person's exercise level is the reason why we assume that health benefits are constant.

effectiveness, such campaigns could be welfare-improving, and be used as substitutes or complements for hard measures.

In the absence of any hard measures, a nationwide information campaign that is fully successful in the sense that people become fully aware of the health benefits of cycling would lead to a new level of bicycling given by Q_{0soft} (the intersection of the extrapolated MC0 curve with health benefits). If such a campaign were undertaken in addition to hard measures, the resulting equilibrium would be at Q_{1soft}. As discussed in the context of Figure 2, any level of bicycling between Q_0 and this level could be reached by a combination of hard and soft measures.

Table 4 lists the net benefits from the hypothetical policy intervention that reduces the risk of accidents involving bicyclists resulting in death or severe injury by 90%, abstracting from the cost of such a policy. Note that we do not consider any externalities here; the entries in Table 4 only represent internal net benefits for new and inframarginal riders.[14] For the full sample, such a policy intervention would lead to an increase of about 76 Mio bicycle-km, of which about two thirds are due to an increase in riding by current riders (ΔQ_i), and the remainder is due to "new" cyclists (ΔQ_m). The resulting gross health benefits are around CHF 31 Mio per year.

Using our valuation approach we compute an increase in internal benefits of CHF 39.7 Mio/y associated with inframarginal bicycle-km, and of CHF 15.7 Mio/y for the new km (these numbers correspond to areas a and b_3 in Figure 2). Another CHF 13.8 Mio/y accrue in the form of "pseudo-

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[14] In addition to the environmental benefits (conditional on mode substitution) and external benefits via the public health system, there may be externalities associated with the reduction in traffic deaths as a result of the policy. Cutting the accident risk by 90% and increasing the level of bicycling from currently 232 million to the new estimate of 308 million km per year (see Table 4) leads to an expected 0.56 deaths and 20.03 severe injuries per year, corresponding to 3.64 statistical lives and 131.37 severe injuries saved. The value of the risk reduction that personally accrues to riders in the form of a higher utility is reflected in the net benefits listed in Table 4, but any societal benefits would be additional.

externalities", i.e. the part of internal health benefits not internalized by riders, leading to total net benefits of CHF 69.2 Mio/year. If we exclude pseudo-externalities, which would be the consequence of imposing the restriction of full internalization of health benefits ex-ante, the resulting benefits are still almost twice as large as gross health benefits due to the large benefits associated with inframarginal km, which outweigh the internal costs associated with the additional km (areas a vs. d in Figure 1).

Table 4: Annual internal net benefits from a policy that reduces accident risk by 90%

	Unit	All cities	Basel	Bern	Biel	Geneve	Luzern	St.Gallen	Wint.	Zurich
Pop. (2010)	1'000	1'143	166	123	50	186	77	73	99	369
Q_0	Mio km	232.0	46.4	30.6	15.1	18.3	20.1	11.3	27.7	62.6
Hard measure[a]										
ΔQ_i	Mio km	49.2	12.5	7.5	5.5	6.2	2.6	1.0	2.3	11.6
ΔQ_m	Mio km	26.9	11.0	4.4	2.4	2.9	1.0	0.7	1.3	8.7
Q_1	Mio km	308.0	70.0	42.5	23.0	27.4	23.7	13.0	31.3	82.9
HB	CHF/km	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
HBp	CHF/km	0.22	0.03	0.22	0.02	0.30	0.04	0.24	0.05	0.23
$HB \cdot \Delta Q$	Mio CHF	30.6	9.5	4.8	3.2	3.7	1.4	0.7	1.5	8.2
NBi (inframarg)	Mio CHF	39.7	8.6	6.1	3.5	4.4	2.3	0.7	1.6	10.4
NBm (marg.)	Mio CHF	15.7	3.7	2.5	1.9	1.9	0.5	0.2	0.3	3.3
Pseudoext.	Mio CHF	13.8	8.8	2.1	3.0	1.0	1.3	0.3	1.3	3.4
Net benefit	Mio CHF	69.2	21.0	10.7	8.5	7.2	4.0	1.2	3.3	17.1
Soft measure[b]										
$Q_{0,soft}$	Mio km	254.1	62.5	33.5	19.2	20.2	23.9	12.0	33.4	70.6
$Q_{1,soft}$	Mio km	341.1	98.2	47.4	28.5	29.7	28.3	14.1	38.9	93.7
Net benefit (Q_0)	Mio CHF	2.0	2.7	0.3	0.7	0.1	0.7	0.1	1.0	0.7
Net benefit (Q_1)	Mio CHF	3.0	0.1	0.4	0.3	0.1	0.8	0.1	1.3	0.9

a: Reduction in accident risk involving bicyclists by 90%; b: campaign that makes people internalize full HB

Table 4 also shows the benefits from a soft policy measure in the status quo of CHF 2 Mio/y, and of CHF 3 Mio/y in combination with hard measures. These numbers are evidently much smaller than the benefits from hard measures, but the cost of informational campaigns is likely just a fraction of the cost of hard measures that reduce the accident risk by 90%.

Applying the estimates from the full sample regressions to individual cities yields internal cost curves by city. Figure 5 shows internal cost curves for the five largest cities in Switzerland. In order to facilitate a comparison, we divide cumulative km by the total population to arrive at bicycle-km per capita and year. The resulting slope of the MC function varies considerably across cities. It is flattest in Basel and Winterthur, which have relatively well developed bicycle infrastructures and a fairly flat topography. On the other hand, the MC curve in Zurich and Bern are much steeper, which may reflect the influence of topography (both cities are hillier than either Winterthur or Basel), or less complete networks of bicycle infrastructure. Increasing the level of bicycling in the latter cities will therefore require a more concerted/stronger policy effort than in the former, because the additional km are more costly from bicyclists' point of view. The slope of the MC curve is steepest in Geneva, which suggests an even less bicycle-friendly environment, possibly due to traffic conditions. The pattern of the modeled cost curves is remarkably consistent with results from a survey among cyclists rating their cities for a range of indicators of bicycle friendliness.[15]

The degree of internalization using the same linear extrapolation procedure as for the full sample, as well as the associated net benefits of a policy that reduces the accident risk by 90%, and a soft policy that leads to full awareness of health benefits, are presented in the city-specific columns of Table 4. Because the slope between the 8th and 9th decile differs across cities, the sum of the city-specific increases in bicycling and the corresponding net benefits is not equal to the net benefits for all cities combined.

A reduction in accident risk would increase the total level of bicycling by between 1.7 Mio km/year (St. Gallen) and 21.7 Mio km/year (Basel), and the range of net benefit from the policy intervention

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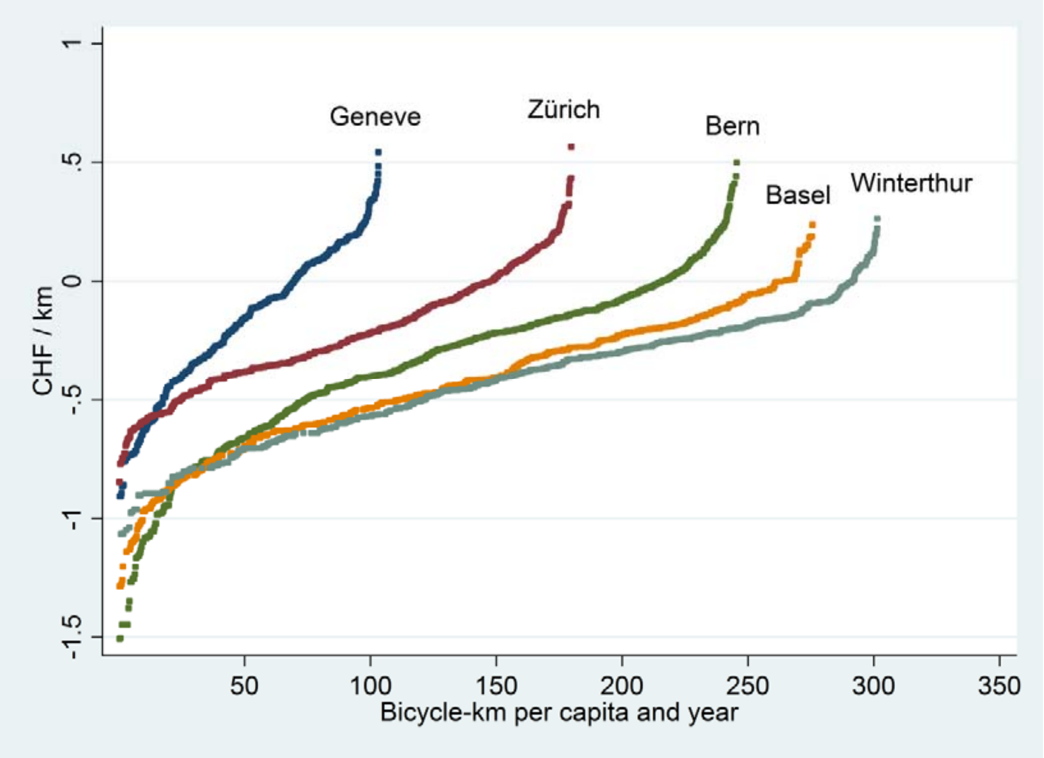
[15] http://www.velostaedte.ch, last accessed in December 2013.

is also determined by these two cities. Note that these are total rather than per-capita values, which explains the relatively modest increases in small cities like St. Gallen and Luzern. On the other hand, Basel has the highest expected gain despite being only third largest city in Switzerland in terms of population. The large increase in bicycling and the resulting benefit gains in Basel are due to the flat MC function combined with a large current bicycle share. In comparison, the benefits accruing in Zurich are lower despite its much larger population and city size, and a policy of equal risk reduction presumably more costly.

Figure 5: Internal costs by city vs. cumulative bicycle-km per capita and year



4.5 Sensitivity of the results

Our results are sensitive to our model and parameter assumptions. Whereas we were guided by the literature about bicycle mode choice determinants and the availability (or lack) of data for the selection of the variables in eqs. (2) and (3), other choices are more difficult to justify due to lack of information. In the following, we discuss those to which our results are most sensitive.

Our estimates of health benefits, and thus of the degree of internalization, directly depend on the choice of the VSL. Using a value of CHF 8.33 million (2010 francs) that corresponds to the VSL employed by USEPA, we find that Swiss bicyclists internalize about half of the health benefits associated with bicycling, suggesting a large scope for soft measures. If we were to use a VSL of CHF 5.21 million (2010 francs) instead, we would find that people exactly internalize health benefits. On the other hand, including a value for reduction in morbidity risk, and of being healthy in general, would increase exercise-related benefits and thus lead to a decrease in the degree of internalization, as our internal cost estimate is independent of health benefits. Note, finally, that the level of VSL and non-mortality-related benefits do not affect the benefits to inframarginal riders, which constitute the largest source of benefits in our application.

The degree of internalization of health benefits further depends on the method by which we reduce the influence of outliers on our internal cost estimate. Starting the linear extrapolation at a different cutoff will affect the level at which the MC function intersects with the benchmark quantity of bicycling. For example, extrapolating the last 10% based on the slope between the 70th (rather than the 80th) and the 90th percentile lowers the internalized benefits to 0.20 CHF/km and increases net benefits to CHF 71.4 million (result for all cities combined), due to higher pseudoexternalities. However, in the absence of more detailed information about actually chosen routes and their characteristics, we have no way of knowing the "best" cutoff point. What seems clear, however, is that we do not want to base our estimate for the degree of internalization on the stages with the highest internal cost estimate, because they may represent extreme preferences or biased expectations.

Furthermore, the results are sensitive to the specification of equation (3). Using a log-linear specification (where we replace the dependent variable with its natural logarithm) changes the net benefits from reducing accident risk by 90 % from 69.2 to 39.5 million CHF per year, whereas the amount of internalized health benefits is reduced from 0.22 to 0.14 CHF per km (results for all cities combined). Specification tests are ambiguous as to which specification is more appropriate,[16] but a visual inspection of predicted and actual bicycle-km provides support for the linear specification. As is generally the case when theory gives us no indication as to how the variables enter a model, the criteria according to which the "best" specification would have to be chosen are not clear, nor the universe of possible specifications that are tested.

More advanced models of self-selection exist that relax the normality assumption embedded in Heckman's model using semiparametric techniques (e.g. NEWEY, POWELL AND WALKER, 1990), but it is not clear that the results based on a different modeling approach are necessarily more trustworthy than the FIML approach chosen here, given that they depend on further assumptions such as the choice of kernel, bandwidth, and type of method. Note that the parametric assumptions of the Heckman model are especially important in small samples (PUHANI, 2000), whereas in larger samples, FIML performs usually well.

Last, we stress that our estimates are static in nature, and that sustained bicycle-related spending in a city with a steep MC curve may lower the slope over time. Indeed, we find that reducing the

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[16] According to the Wald statistic and the sum of squared residuals, the linear specification performs better; however, the average and the proportional absolute errors are smaller with the log-linear specification.

internal costs of bicycling by increasing road safety not only shifts the MC function downward, but also lowers its slope, such that it would be premature to conclude that bicycle investments should be concentrated in cities that currently have a relatively flat MC function. If the effectiveness of bicycle measures, defined as the increase in bicycle-km per dollar of investment, is S-shaped due to network effects as is commonly assumed, then the value per dollar of investment may in fact be larger in cities with a currently steep MC function. However, the dynamic effects and the effectiveness of bicycle investment at different mode shares are beyond the scope of this study and is left for future research.

6 Conclusions

Our framework for the valuation of bicycle investments adds an economic perspective to a relatively young field of research, which to date has been studied primarily by health and transport scientists. In particular, it expands the valuation beyond simple gross benefits calculations, as provided by WHO’s popular HEAT tool and others. We explicitly consider internal costs to cyclists, which are required to reconcile the contrast between large health benefits and rather low levels of cycling even for short trips. Our framework can be interpreted as an application of standard valuation methods in the spirit of the “rule-of-a-half” to a situation that is nonstandard because the costs of bicycling are entirely nonmonetary in nature.

In addition to net benefits associated with an increase in bicycling in response to some policy intervention, our framework also allows us to compute inframarginal benefits, which are ignored when valuing the expansion of bicycling by means of gross health benefits alone. The higher the level of cycling is, the more relevant inframarginal benefits become relative to the benefits accruing to marginal riders. In our application, we find that the former outweigh the latter.

By monetizing internal costs independently from health benefits related to mortality reductions, we obtain an indication for the degree to which bicyclists internalize health benefits, or more precisely, the sum of health benefits and external effects (for which we do not control as we have no source of variation across cities and time). This is an interesting question in its own right, but it also matters for valuing the benefits of bicycle-related spending, because the non-internalized part of health benefits are "quasi-external" and thus not offset by internal costs. Incomplete internalization further indicates a potential for "soft measures", e.g. in the form of educational campaigns that inform people about the benefits of cycling and lead them to internalize these.

Our framework also serves as a rationale and guidance for future investments in data collection efforts. While the travel survey data available to us are quite rich and considered state of the art, they lack psychological variables, such as attitudes, which limits their capability to predict bicycle behavior. In addition, we identify a main gap in information relevant for internal costs at the level of road network characteristics, namely connectivity and route attributes such as objective and perceived safety and infrastructure types. Besides general progress in research on determinants of cycling, richer data sets of sufficient spatial resolution are needed to advance towards an improved quantitative implementation of our framework.

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