4 On the evaluation of large projects in closed and open economies

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4.1 Introduction

There has been some controversy how to design a cost–benefit analysis of projects so large that they cause significant price changes in other sectors of the economy. Such projects include high-speed rails, new airports and ports, and tax reforms. The favored approach 'collapses' all price effects into the primary market. As pointed out by Bullock (1993), it is easy to get lost when trying to provide a proof of the approach. He also asserts that previous authors have considered a closed economy and demonstrates that the proof fails if there are traded goods.

The purpose of this paper is to provide a simple derivation of a "short-cut" that collapses the evaluation of a megaproject to a single market. Bullock's open-economy result is reconsidered, and it is shown that the short-cut indeed holds under flexible exchange rates. As a by-product, the paper also demonstrates how to account for distortionary taxation, that is, the deadweight loss of taxation.

In addition, another approach, involving line integrals, is developed. It allocates gains and losses to different stakeholders. It contradicts claims that double counting results if gains and/or losses outside the primary market are accounted for. For example, it is often claimed that adding property values to time savings in the evaluation of, say, a new high-speed rail causes a kind of double counting. However, if properly designed the evaluation avoids the double-counting problem and provides some insights with respect to the distributional impacts of a large project.

An advantage of using CBA techniques to evaluate large projects is that they need no detailed and restrictive assumptions about utility and production functions. Rather, the project under scrutinization can often be modelled in detail. This contrasts with computable general equilibrium (CGE) techniques, which draw on more standardized sectors. A drawback of CBA is the problem of capturing distortions 'elsewhere' in the economy. However, it should be mentioned that there are attempts to use cost–benefit techniques to evaluate Big projects. The most noteworthy example is probably provided by Florio (2019) who suggests the use of CBA to evaluate Big Science like large particle accelerators, outer space probes, and genomics platforms.

The rest of the paper is structured as follows. Section 4.2 outlines the basic model. In Section 4.3 this model is used to derive a large-project evaluation rule that allocates benefits and costs to different agents. Section 4.4 turns to an approach which collapses all effects but distortions into a single market. It is demonstrated that the rule of half can be applied in a way that significantly simplifies the evaluation. Section 4.5 extends the rule to an open economy. Section 4.6 provides a sketch of a CBA of a high-speed rail, HSR. A few conclusions and an Appendix are added. The Appendix also provides a numerical general equilibrium model which sheds additional light on the results stated in the main part of the paper and could be interpreted as an extremely simple variation or embryo of a CGE.

4.2 The Basic Model

The focus in this paper is on a representative household. In a capitalist economy, this household, owns all firms, supplies labor, pays taxes, and consider all prices as exogenous. (It would just add clutter to have, say, H > 1 identical households). The household is assumed to be equipped with well-behaved ('textbook') preferences. The well-behaved direct utility function is denoted $u = u(x, \Gamma - L)$, where x denotes a vector of commodities, Γ denotes the time endowment, and L denotes the supply of homogeneous labor. Therefore, the indirect utility function is also well-behaved and serves as the social welfare function in this economy.

However, instead of using this function to derive project evaluation rules, the augmented expenditure function is employed. This function is defined as follows:

$$E(p,w,m,V^0) = e(p,w,V^0) - m, \tag{1}$$

where p denotes a 1×n vector of consumer relative prices, w denotes the wage rate, $e(.)$ denotes the 'pure' expenditure function, m denotes a lump-sum income, and V^0 denotes the initial level of utility. The lump-sum income, consisting of the sum of profit incomes plus a lump-sum surplus or deficit from the government, is exogenous from the household's point of view but is endogenous from the point of view of the economy. Assuming there is a representative firm in each sector of the economy, the sum of profit income is denoted $\pi(q,w)$, where q denotes producer prices. In a multi-household context, this approach, drawing on the concept of compensated equilibrium, avoids the

Boadway-paradox according to which those gaining from a non-marginal redistribution can always compensate those who lose, even if the economy is taken from one (Marshallian) first-best general equilibrium allocation to another one. Refer to Boadway (1974).

The government earns income from taxation of commodities and runs a firm producing the first commodity. This firm is used to generate cost–benefit rules, while all other governmental activities are suppressed. Commodity taxes are ad valorem and could be interpreted as a value-added tax, VAT, accompanied by extra taxes on some commodities, such as energy, and subsidies to some commodities, such as agricultural products. Any public sector surplus or deficit, denoted T, is returned to or paid by the household in a lump-sum fashion.

4.3 The General Project Evaluation Rule

The focus of this paper is on large projects. How large is a large project? The typical project addressed in many manuals is implicitly infinitesimally small. This assumption imply that any resulting price adjustments can be ignored, at least if markets are perfect. Nevertheless, a typical feature of transport sector projects is that they are assumed to be non-marginal, hence generating changes in consumer and producer surpluses, not only in the market under evaluation but often also in the markets for substitute modes. In addition, changing property values are interpreted as representing capitalization of primary changes in travel times and so on. This suggests that not only direct travel costs/prices change more than marginally. Therefore, it seems legitimate to derive cost–benefit rules that can handle price changes also in secondary and other markets.

Consider now a large change in the government's provision of the first-sector commodity. This causes (Hicksian) general equilibrium relative producer prices to change from (q^0, w^0) to (q^1, w^1). The associated compensating variation, denoted CV, is defined as follows:

$$CV = m^1 - m^0 + e(p^0, w^0, V^0) - e(p^1, w^1, V^0). \qquad (2)$$

This sign convention implies that CV is positive if the project causes lump-sum income to increase or expenditure $e(.)$ to fall. Equation (2) provides a simple and straightforward cost–benefit rule. However, the expenditure function is not directly observable, implying that we must find other ways to estimate CV.

One approach is to 'disaggregate' equation (2) in the following way:

$$\begin{aligned} CV = {} & \sum_{i=1}^{n}[\pi^i(q^1,w^1)-\pi^i(q^0,w^0)]+t\cdot[q^{D1}\cdot x(p^1,w^1,V^0)-q^{D0}\cdot x(p^0,w^0,V^0)]- \\ & \int_c [x(.)dp+L(.)dw]+[q_1^1\cdot g_1^1-C(q^1,w^1,g_1^1)]-[q_1^0\cdot g_1^0-C(q^0,w^0,g_1^0)], \end{aligned} \tag{3}$$

where t denotes a tax vector, q^D denotes a diagonal matrix of producer prices,[1] x denotes (Hicksian) demand for commodities, L denotes supply of labor, a subscript c refers to the path taken in evaluating the line integral in the second line of the equation, g_1 denotes the supply of the public sector firm behind the considered change, and $C(.)$ denotes its conditional cost function. This approach can compactly be summarized as follows.

1. Use the profit functions to estimate the sum of changes in private sector producer surpluses.

2. Based on the compensated (Hicksian) demand functions for taxed commodities, estimate the change in tax revenue.

3. Add changes in compensated consumer surpluses and labor producer surplus, as developed in what follows.

4. Add the change in producer surplus of the public sector firm, covered within the two final square brackets in equation (3), using its conditional cost function to estimate costs.

The line integral in equation (3) deserves a comment. There is, in principle, an infinite number of paths that are permissible, provided the expenditure function is well-behaved. They all result in one and the same total change in compensated consumer surplus. However, they generate different individual surpluses, depending on where in the evaluation chain a market appears. One path is to evaluate the area to the left of the sector 1 compensated demand curve between initial and final levels of p_1, holding all other prices, including the wage, at their initial levels. Next, holding $p_1 = p_1^1$, evaluate the change in the compensated consumer surplus in sector 2, holding the remaining prices at their initial levels. Then, holding the two first prices at

[1] Let t be a 1×n vector, q^D be a n×n diagonal matrix with producer prices in the main diagonal and zeros elsewhere, and x a n×1 vector (and any sign indicating transposed vectors is suppressed). Then their product reduces to tax revenue.

their final levels, evaluate the sector 3 surplus, and so on. Finally, given $p = p^1$, evaluate the compensated labor producer surplus change as w is changed from w^0 to w^1; this kind of evaluation is illustrated graphically in Figure 2 in Section 4.6, which is devoted to an outline of a CBA of a HSR. Reversing the order of integration will change individual surpluses, in general, but results in the same total compensating variation. Recall that commodity 1 now is evaluated conditional on all other prices being held at their final rather than at their initial levels causing the compensated demand curve to have a different position and slope, in general. Informative analyses are provided by Hoehn and Randall (1989) and Carson et al. (1998) how the magnitude of an individual surplus is affected by where in the evaluation sequence it is evaluated.

It is important to underscore that one can 'disaggregate' the total surplus in the way illuminated by equation (3), and that the same rule applies if a private-sector project is considered. In a multi-household economy this approach provides a simple distributional analysis where gains and losses are allocated to different stakeholders. Sometimes, the literature gives the impression that the approach outlined here implies double counting of benefits and/or costs, but as long as the conditions for path independency are satisfied, the approach results in one and the same CV independently of the route or path taken. For example, a transport investment could result in both lower travel costs and affect property values. Then these effects could be accounted for in the way suggested by equation (3) without causing a double-counting problem. This is further illuminated in Section 4.6, where a HSR is evaluated.

The reader could also 'convert' changes in profits to producer surplus measures measured as areas to the left of supply and demand curves between initial and final producer prices. Then, evaluate the conditional cost functions as line integrals, just as done above for e(.). This could be a wise strategy if the investigator wants to illuminate how different markets are affected by the project. A useful simplification in empirical applications is provided by separable production functions, such as Cobb-Douglas, where the different cost items are additive, that is, only depends on the own factor price and the scale of operations.

4.4 A Short-Cut

There is another approach to CBA, discussed by Just et al. (1982) and further developed by Bullock (1993), who (among other things) addresses inconsistencies in Just et al. (1982, Appendix D); Just et al. (2004) addresses the concerns raised by Bullock (1993). However, here we provide a slightly different proof. Suppose that we can solve the general equilibrium producer prices as functions of the exogenous production g_1 of the public sector firm (suppressing other parameters of the problem, for example tax rates). Then, $q_i^* = f^i(g_1)$ for i = 1,…, n-1, arbitrarily using commodity n as numéraire (with producer price equal to unity and consumer price equal to 1 + t_n) , and w^* = $h(g_1)$, where an asterisk refers to an equilibrium level.

Consider the market for commodity i. Assume for notational simplicity that the commodity is not used as an input in production. Regardless of this last assumption, the direct effect of a small, induced price adjustment vanishes from the evaluation of the project:

$$[x_i^s(q^*, w^*) - x_i(p^*, w^*)]dq_i^* = 0, \tag{4}$$

where $p_i^* = (1+t_i)\cdot q_i^*$, and the price change is "driven" by a change in g_1. The simple reason why the net effect equals zero is that supply x_i^s equals demand x_i in equilibrium, and in equation (4) they appear with opposite signs. Next, consider a discrete or large change in g_1. Provided prices continue to clear markets throughout the change, the equality of the two terms within square brackets in equation (4) will hold. Tax revenue is also affected, and this effect is accounted for below.

Summing across markets, and integrating with respect to g_1, the cost–benefit rule reduces to:[2]

$$CV = \int_{g_1^0}^{g_1^1} [q_1^*(g_1) - C_{g_1}^g(q^*(g_1), w^*(g_1), g_1)]dg_1 + TW, \tag{5}$$

where $q^*(g_1) = [f^1(g_1), \ldots, f^{n-1}(g_1), 1]$, $C_{g_1}^g(.)$ denotes a marginal cost, and TW is a short-cut for the total of sector-specific tax wedges. Because the TW-term is a bit involved it is developed in the Appendix. It may come as a surprise that the project is

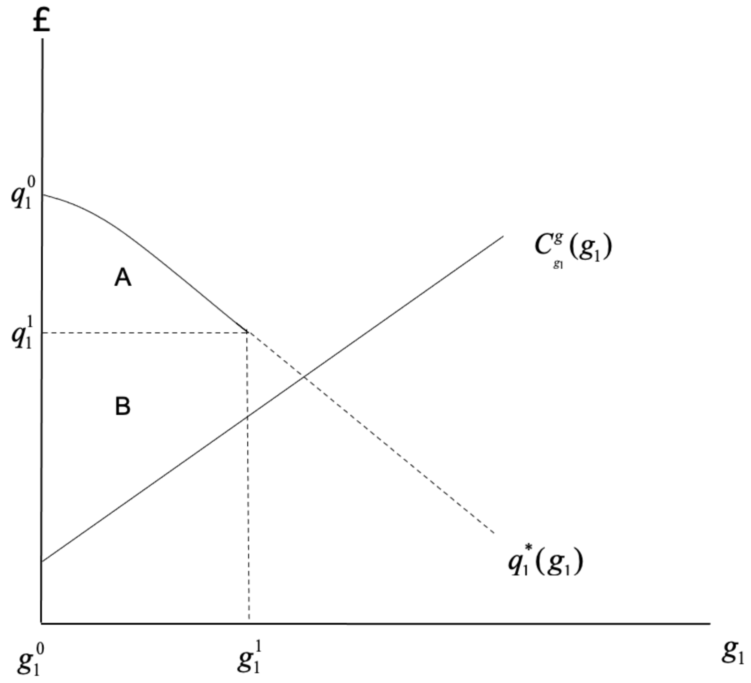
[2] In the Appendix it is shown how a short-cut for changes in tax rates to finance the project could be added to equation (5).

evaluated at producer prices. However, the impact on tax revenue is contained in the *TW*-term. In the special case where the net change in demand for the commodity under evaluation equals the change in g_1, one could deduct $t_1 \cdot q_1^* dx_1 = t_1 \cdot q_1^* dg_1$ from the (marginal) tax wedge term and multiply q_1^* by $(1 + t_1)$ in equation (5), that is, value the project at consumer price, and replace *TW* by the remaining parts of *TW*. However, in general one would expect the net change in demand to differ from the change in g_1, unless the public sector firm has a monopoly, as in Section 4.6, where a CBA of a HSR is outlined.

A graphical illustration of the integral in equation (5) is provided by Figure 1. The benefits are evaluated as an area under the equilibrium price path and the increase in costs as an area under the marginal cost curve. The difference between benefits and costs is captured by area A plus area B. (An optimally designed project would be such that the equilibrium price equals marginal cost, at least if $TW = 0$, while $TW \neq 0$ suggest that we are in a second-best world.)

Figure 1

Benefits and costs captured in the market for commodity 1.



In the absence of distortions, equation (5) illustrates results derived by, among others, Bullock (1993), Just et al. (1982, 2004), and in a more graphical fashion by Bailey (1954) and Mohring (1993).[3] However, note that *CV* in equation (5) equals *CV* in equations (2)-(3). They just draw on different ways of evaluating the change in going from g_1^0 to g_1^1; equation (3) draws on a line integral plus discrete changes, while equation (5) involves a line integral expressed as a definite integral. This equality provides an important and useful insight for practical evaluations. Recall warnings that one risk double-counting of benefits and/or costs if one does not proceed as in equation (5). To illustrate, suppose the first market in equation (3) is a travel market under evaluation, the second market is the market for a competing transport mode, and the third market is the property market. If no other markets are significantly affected, then area A + B plus *TW* corresponds to the *sum* of the terms in equation (3) over the three

[3] Further references are Brännlund and Kriström (1996) and Johansson and de Rus (2018).

markets. Recall that the curve in Figure 1 is an *equilibrium path*, not the (initial or final or some intermediate) demand curve for the considered transport mode. To further illustrate, suppose the supply of properties is completely inelastic. Then, according to equation (3) a property price increase simply represents a redistribution. Whether the gain to property owners corresponds to an area in the figure is out of the scope of the paper to investigate. Nevertheless, noteworthy is that some infrastructure investment, for example new highways, possibly mostly move development around a region such that infrastructure-induced development is close to a zero-sum game (Ewing, 2008).

A neat approximation of area A + B is provided by the rule of half:

$$CV \approx \frac{1}{2}(q_1^0 + q_1^1)\Delta g_1 - C_{g_1}(g_1^0)\Delta g_1 + TW, \tag{6}$$

where $\Delta g_1 = g_1^1 - g_1^0$ (and the marginal cost estimate possibly is replaced by a more exact estimate). Thus, the approximation is based on a straight line between the initial and final price-quantity configurations in the figure. A kind of upper bound for the benefits is obtained by shifting the price curve upwards by the tax on the commodity, i.e., by valuing benefits at the consumer price (but to avoid double counting the added effect should be deducted from the *TW*-term). If the initial and final price quantity combinations, that is, g_1^0 and g_1^1 are available (and the difference between Marshallian and Hicksian equilibria is negligible), it is a straightforward exercise to approximate area A + B in Figure 1.

Nevertheless, a caveat is in order. The pre-project demand curve for the commodity might be quite different from the equilibrium path for q_1. Hence, an ex-ante evaluation of equation (5) based on the initial demand curve would result in a biased estimate, in general. Thus, equation (5) must be applied with great caution. The same holds true when using survey techniques, such as contingent valuation and discrete choice experiments, to estimate the WTP ex ante for a project. In terms of Figure 1, the estimated WTP, holding all other prices at their initial prices, could be quite different from the area under the equilibrium path. This is worth observing in empirical evaluations. The same caveat applies for ex post evaluations, where estimates are based on *final*, rather than initial, equilibrium prices.[4]

Equation (5) provides no simple quick fix, not even in an otherwise perfect economy. In fact, if only the initial (final or with the project) demand curve for the examined commodity is available, equation (3) might provide a safer evaluation route; recall that the line integral permits a path such that the considered commodity is placed at the beginning (the end) of the evaluation sequence, that is, evaluated at initial (final) prices, as illustrated below equation (3). In theory at least, this provides an exact evaluation route.

4.5 The Short-Cut in an Open Economy

Bullock (1993) points at an important shortcoming of equation (5). The equation only holds if all commodities are nontraded. In an open economy facing a fixed exchange rate, as is the case also for many countries within currency areas, one would expect Bullock's claim to hold. The large project will add to or deduct from a country's current account. Thus, like distortive taxes, a current account-effect is not covered by areas under the equilibrium path in equation (5); the equality in equation (7) below does not hold under a fixed exchange regime.

However, over the longer run one cannot rule out that trade flows adjust to achieve balance in the current account. With respect to multinational projects, the question also arises whether they should be assessed at the national or at a larger level. This important question relating to who "stands" in an evaluation is not addressed here.

In any case, matters are different under flexible exchange rates. Suppose for notational simplicity that just two commodities are traded, and that there are no intermediate uses of these commodities. There is a domestic excess supply of one commodity, that is, net export, while there is domestic excess demand for the other commodity, that is, net import. Because the exchange rate is flexible, the following holds:

[4] A simple numerical illustration based on CES preferences for three commodities overestimates the “true” area under the q_1^* -curve by 15 percent if based on the initial demand function for the considered commodity. The ex post curve, estimable once a project is running, underestimates the true area by around 6 percent, a quite decent outcome.

$$\varepsilon \cdot [q_1^w \cdot (g_1 + x_1^s - x_1) + \cdot q_2^w (x_2^s - x_2)] = 0, \tag{7}$$

where ε denotes the exchange rate, and a superscript w refers to a world market price in foreign currency. Equation (7) provides the current account expressed in domestic currency. When prices adjust, the current account in foreign currency multiplied by $d\varepsilon$ replaces the equilibrium conditions (4) for the traded goods. Hence, if the considered large change in g_1 impacts on net export, the exchange rate will adjust to clear the current account. Solving the exchange rate (simultaneously with other prices and wages) as a function of g_1 provides an equilibrium path for ε holding the current account in balance as g_1 is adjusted. Therefore, equation (5) is still valid (but the *TW*-term might be affected, depending on how traded goods are taxed).

However, if the project, here g_1, is so large that it impacts on a world market price, that is, affects the country's terms of trade, matters are different. In terms of equation (4), the change in the world market price is not multiplied by an equilibrium condition, but typically by an excess demand or an excess supply. This impact is not covered by equations (5)-(6).[5] Nevertheless, the approximation in equation (6) provides a cheap, cost-effective first-aid kit that is useful for obtaining a rough assessment of the social profitability even of complex megaprojects. Although a market good has been used here to illustrate the approach, it is equally applicable if the project provides a public good or is aimed at reducing emissions of damaging climate gases, for example.

4.6 A Sketch of an Evaluation of a New HSR

This section provides an illustration of the two approaches outlined in Sections 4.3 and 4.4 by outlining a CBA of a hypothetical high-speed rail. A HSR consists of infrastructure and rolling stock that allows the movement of passenger trains capable of speeds above at least 200-250 km per hour (according to the definition applied by the EU). This technology competes with road and air transport over distances of 400-600 km, and in which it is usually the main mode of transport. For short trips, the private vehicle has a comparative advantage, and for long distance travel, air becomes the ultimate transport mode.

[5] Such effects are covered by equation (3) and could be added to equations (5)-(6), at least in theory. Suppose, for simplicity, that the considered firm has virtually no impact on ε and is a (not necessarily profit-maximizing) monopolist. Then the consumer surplus gains made by foreigners when q_1^w falls as g_1 is increased, converted to domestic currency, should be deducted from equation (5).

A rigorous economic appraisal would compare several relevant "do something" alternatives with the base case, as discussed in de Rus (2011). These alternatives include upgrading the conventional infrastructure, management measures, road, and airport pricing or even the construction of new road and airport capacity. However, for the limited purposes of this section it is sufficient to restrict attention to two transport modes, the new or planned HSR and an existing transport mode. For this reason, the demand functions for the first two commodities are modified to read:

$$x_i(.) = x_i[(1+t_1)\cdot q_1 + tc_1 \cdot w, (1+t_2)\cdot q_2 + tc_2 \cdot w, p_3, \ldots, p_n, w, V^0], \qquad (8)$$

where $i = 1, 2$, q_i denotes the pre-tax monetary cost (pre-tax fare), tc_i denotes the time a trip by transportation mode i requires, and, for simplicity, time is valued at the ruling market wage; refer to de Rus (2011) for discussion of typical approaches used in the practical evaluation of projects. Adding $tc{\cdot}w$ to the fare paid by a traveler, one obtains the generalized travel cost, denoted $p_i^G = (1+t_i)\cdot q_i + tc_i \cdot w$. We interpret x_1 as high-speed rail demand, while x_2 denotes demand for a substitute transportation mode (such as a 'conventional' train, car, bus or aircraft). By assumption, $tc_1 < tc_2$, and both commodities are non-essential in the sense that one can survive without consuming them. Demand for a non-essential commodity equals zero if its price becomes sufficiently high.

The easiest way to provide an overview of a CBA of a new HSR is by using the indirect utility function of a representative individual. The CV for the project is implicitly defined by the following equation:

$$V[(1+t_1)\cdot q_1^1 + tc_1 \cdot w^1, p_2^{G1}, p_3^1, \ldots, p_n^1, w^1, m^1 - CV] = V[0, p_2^{G0}, p_3^0, \ldots, p_n^0, w^0, m^0], \qquad (9)$$

where a superscript 1 (0) denotes general equilibrium prices and incomes with (without) the considered HSR. This approach illuminates that CV is a function of the time cost. The higher tc_1 (and w^1), ceteris paribus, the lower is the WTP. Similarly, the higher the fare, the lower is CV. Moreover, the agent need not consider the modes equivalent from a quality perspective (comfort, noise, and so on). Her preferences are reflected in the slopes and positions of the demand functions and hence in the magnitude of CV. Finally, general equilibrium induced adjustments in other prices and incomes affect the WTP; climate and other environmental impacts will be addressed below. Unfortunately, utility functions are not observable. Therefore, we return to our monetary approaches.

4.6.1 The Demand Side Approach

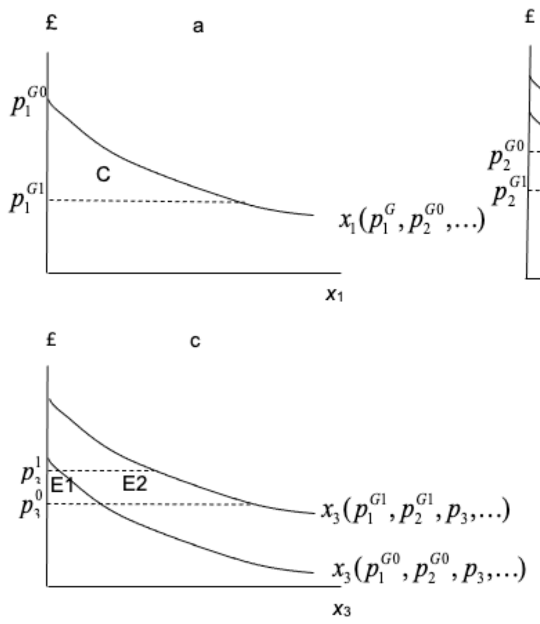
The only variable cost item in equation (8) is the pre-tax fare, although, from a general equilibrium perspective, also w is endogenous. The high-speed rail demand curve is pictured in Panel a of Figure 2.[6] Given the time cost of a trip (and preferences), there is a fare such that the generalized travel cost becomes so high that demand equals zero. This choke price is denoted $p_1^{G0}(=(1+t_1)\cdot q_1^0+tc_1\cdot w^0)$ in Figure 2 and mimics the pre-HSR situation. Although fixed, the time cost affects the position of the demand curve. The lower the time cost, the farther to the north-east is the demand curve situated. This feature is obvious from equation (8). If the generalized travel cost faced by HSR travelers equals p_1^{G1}, they earn a Hicksian consumer surplus (or a compensating variation) equal to area C in Figure 2. This assumes that this market is the first in the evaluation chain, implying that all other prices are kept constant at their initial levels. In a multi-household society where preferences differ across travelers, and each traveler undertakes one trip, they are ranked according to WTP. The marginal traveler is willing to pay no more than p_1^{G1} in terms of the generalized travel cost or $(1+t_1)\cdot q_1^1$ in terms of the fare.

Turning to the second market, pictured in Panel b of Figure 2, due to the reduction of p_1^G the demand curve for x_2 is assumed to shift to the left. Overall, there is a reduction in the equilibrium generalized travel cost p_2^G, and the gain in Hicksian consumer surplus equals area D in Figure 2. Finally, there is a third affected market where the introduction of the new transport mode causes the equilibrium price to increase. It could be a local housing market that is facing an increase in demand due to the HSR. In any case, the change in Hicksian consumer surplus is evaluated conditional on the first two prices being held at their final levels, that is, $p_i^G=p_i^{G1}$ and $p_2^G=p_2^{G1}$. The resulting loss of Hicksian consumer surplus is captured by area E = E1 + E2 in Panel c of Figure 2.

[6] Alternatively, one could draw the demand curve with the fare $(1+t_1)\cdot q_1$ on the vertical axis. This is equivalent to a parallel downward shift of the demand curve by $tc_1\cdot w^0$.

Figure 2

Panel a: HSR market; Panel b: Market for another transportation mode; Panel c: A third affected market.



As clarified in the discussion of line integrals in connection to equation (3), the considered evaluation sequence is one out of many possible paths. For example, we could evaluate the change in the third market given that the other prices are held at their initial levels, then evaluate the second market given p_3^1 and p_1^{G0}, and so on. This will affect the magnitudes of the individual Hicksian surpluses but leave the total surplus, that is, area C + D + E in Figure 2, unchanged.

To arrive at a complete evaluation, one would have to add possible changes in Hicksian consumer surpluses in other markets, any producer surplus change in the labor market, changes in profit incomes, tax revenue, and the profit of the public sector firm assumed to construct and operate the HSR; see points 1-2 and 4 following equation (3). It should be noted that if one replaces the (perfect competition) profit functions in equations (3) by profit expressions, the approach is compatible with imperfect competition, for example, monopolies, oligopolies and monopsonies. That clarification justifies the absence of supply curves in Figure 2. Climate issues will be addressed below.

4.6.2 The Short-Cut Approach

Turning to the short-cut approach, the supply of the first commodity is still denoted g_1. The pre-tax or producer fare q_1 adjusts to maintain equilibrium between demand and provision (ceteris paribus) throughout the shift from $g_1 = g_1^0 = 0$ to $g_1 = g_1^1$. Therefore, the approach stated in equation (5) is applicable also for the evaluation of the HSR. It might come as a surprise that the time cost does not explicitly enter the evaluation. However, the equilibrium fare q_1^* is a function of tc_1 and tc_2 (while w is endogenous and evaluated along its equilibrium path as g_1 adjusts). Hence, in terms of Figure 1, the slope and position of the equilibrium price path depends on the magnitude of the time parameters. A reduction (increase) of tc_1 (tc_2) would cause an upward shift in the equilibrium path.[7] One could also value the HSR at end-user fares by shifting $t_1 \cdot q_1 dg_1$ from TW to the integral in equation (5); recall that the public sector firm is the sole supplier so its supply equals demand in equilibrium.

[7] See the Appendix for the evaluation of a change in the travel time of an *existing* HSR.

Because the two evaluation approaches considered in this section provide two different and permitted paths for the evaluation of the considered project, they result in the same overall *CV*. A third way, drawing on the (unobservable) indirect utility function, is provided by equation (9). A simple numerical general equilibrium model illustrating the equivalence of the three approaches has been posted on ResearchGate (Johansson 2021) and is added to the appendix. This model also suggests that a CGE can be used to undertake general equilibrium CBA.

4.6.3 The CBA

Drawing on equation (3) in de Rus (2011) the cost–benefit analysis of the HSR can compactly be summarized as follows:

$$\begin{gathered} CV^{PV} = \int_{\tau=\tau^0}^{\tau^E} CV(\tau)\cdot e^{-(r_\tau-\gamma_\tau)}d\tau - I + SV(\tau^E) = \\ \int_{\tau=\tau^0}^{\tau^E}\Big[\int_0^{g_{1\tau}^1}[q_{1\tau}^*(g_{1\tau}) - C(q_\tau^*(g_{1\tau}), w_\tau^*(g_{1\tau}), g_{1\tau})]dg_{1\tau} + TW_\tau\Big]\cdot e^{-(r_\tau-\gamma_\tau)}d\tau - I + SV(\tau^E), \end{gathered} \tag{10}$$

where CV^{PV} denotes the total present value WTP for the HSR, τ^0 denotes the date when the railway becomes operational, τ^E denotes the time horizon, r_τ denotes the time τ real discount rate, γ_τ denotes time τ growth of benefits and costs, I denotes the present value at time zero of the investment cost, and $SV(.)$ denotes any present value at time zero of remaining infrastructure and rolling stock at the time operations cease. Any distortions other than taxes are ignored as are any annual fixed maintenance and operating costs, that is, annual costs that are independent of the magnitude of $g_{1\tau}^1$. The discount rate would typically be assumed to be constant over time or decreasing (hyperbolic discounting). The formulation in equation (10) admits discussion of the optimal timing of the investment. For example, initially demand could be so low that annual benefits do not cover annual costs. If so, it is socially profitable to delay the investment until this condition is met.

A remaining issue relates to emissions of climate gases (ignoring here other emissions that harm living organisms). Even if the steel, concrete, and so on, needed for the construction of the rail and the electricity needed during the phases of construction and operation are covered by the European Union's system for emission trading (EU ETS), the HSR could have an impact on global emissions. After the 2018 reform of the system, the supply of permits is *endogenous*, implying that a project causing emissions of greenhouse gases might increase, leave unchanged, or even reduce total emissions; refer to Johansson (2020) for details and further references. On the other hand, if there is a tax on climate gases reflecting the global marginal damage caused by additional emissions, there is no need to adjust the CBA. Refer to Jorge-Calderón and Johansson (2017) for details. However, even in such an ideal case, there is a caveat. The substitute transport mode(s) need not be covered by the same policy instruments. For example, aircraft emit water vapor at high altitudes, creating condensation trails contributing to climate change. These impacts are not covered by EU ETS. In addition, parts of the equipment needed for the considered transport modes may be imported from countries lacking effective policy instruments.

4.6.4 Lessons from the HSR-Example

An import lesson from this exercise for applied studies is that the ex-ante demand curve for x_1 in Figure 2 cannot be given an interpretation as an equilibrium path, that is, $q_1^*(.)$ in general. Recall that such an interpretation ignores the induced adjustments in the rest of the economy. The exception occurs in the unlikely event that the HSR leaves prices in all other markets unaffected. Then, the $q_1^*(.)-$curve can be interpreted as the inverse demand curve for x_1. A possible catcher in the rye when several prices adjust is as follows. Suppose that we have somehow estimated the general equilibrium with the HSR. Then the fare-quantity combinations (q_1^1, x_1^1) and $(q_1^0, 0)$ can be used to provide a linear approximation of area A+B in Figure 1. This is an application of the rule of half stated in equation (6). However, if the $q_1^*(.)-$curve is non-linear, the rule might provide a poor answer. For example, in the simple numerical general equilibrium model in the Appendix, the rule of half overestimate *CV* by 25–30 percent.

A second lesson is that solving for the generalized travel cost instead of the fare and integrating p_1^{G*} over g_1 is possible but roundabout. To arrive at the desired result, one must evaluate the time cost along its equilibrium path and deduct the resulting amount from the integral of p_1^{G*}. This claim is supported by the numerical general equilibrium model in the Appendix. The same result applies in a partial equilibrium context where the time cost is assumed to be constant.

Another lesson is that one can disaggregate benefits and costs as suggested by Figure 2 and in more detail by equation (3). However, it is important to realize that there are strict mathematical rules for such a distributional analysis. One cannot simply base the analysis on initial or estimated final demand and supply curves. The evaluation must be based on the concept of a line integral. This approach is easily extended to account for market power. The short-cut approach, on the other hand, is more challenging from a technical point of view, at least if there is market power in secondary markets; the supply by the firm in the primary market is exogenous in the current paper. Hence, the firm can be modelled as acting as a monopolist at one extreme or as if there was perfect competition at the other.

Finally, it has been assumed that any surplus (deficit) caused by the HSR is returned to (collected from) households in a lump-sum fashion. This is the standard assumption employed in CBA. However, in the Appendix we have extended the short-cut approach to CBA to the perhaps more realistic case where an ad valorem tax is increased to finance any deficit partially or fully.

4.7 Conclusions

The purpose of this paper has been to derive cost–benefit rules for large projects. Two different but consistent general equilibrium approaches have been used. One approach disaggregates benefits and costs across different markets. The approach draws on strict mathematical rules. What one must evaluate is a line integral. This means that there are many different paths to choose among. All result in one and the same total outcome. This approach functions even when there are distortions such as taxes and market power.

The other approach aims at capturing the effects of even a megaproject in the market for the transport mode under investigation. This works nicely if all markets are perfect. It becomes more involved if there are distortions like taxes and market power or if the project has a noticeable impact on world market prices. Still, applying the rule of half, it points at a simple tool for a rough evaluation of a large transport project. The obvious but costly alternative would be to use a computable general equilibrium model.

We have also extended the approach to an open economy showing that it works under flexible exchange rates. However, if the project is so large that it affects world market prices in foreign currency, a term reflecting the change must be added. The reason is that foreigners have no standing in the typical CBA. An exception is provided by analysis at an international level, for example, the European Union or, in the case of climate change where, typically, a global perspective is applied.

Another extension is provided by using a distortive tax to finance the project. This is of relevance for many large-scale transport investments undertaken by national governments; lump-sum taxation need not be available. The paper also provides a sketch of a CBA of a high-speed rail. Among other things, it points at the danger of using the ex-ante demand function for travels as a proxy for the equilibrium fare path. Such an approach could result in a seriously biased estimate of the WTP for trips. The paper also points at a possible simple catcher in the rye. Given an estimate of the fare-demand combination, the rule of half can be used to obtain a rough estimate of the WTP for a new HSR.

The analysis in the current paper is based on the concept of the compensating variation holding agents at their initial or pre-project levels of utility. It would be possible to instead base the analysis on the equivalent variation, where agents are held at their final or with-project utility levels (as is typically the case in computable general equilibrium models). Mäler (1985) has suggested that the choice of compensated money measures should in some cases be influenced by distributional considerations, provided society prefers a more even to a more uneven income (or welfare) distribution. Suppose that initially, before a reasonably small project is undertaken, society is indifferent to small changes in income distribution. Then equivalent variation, which is based on pre-project conditions (prices, incomes, and so on), is the relevant measure. On the other hand, if it is judged that income distribution with the project is such that small changes in income distribution would not affect social welfare, then the CBA of the project should be based on the compensating variation measure; this measure is defined in terms of final levels of incomes, and so on. The reader is referred to Mäler (1985) for further details.

Nevertheless, in a real-world evaluation, a more detailed distributional analysis than the one suggested above might be required. A first step in such an analysis is to distribute benefits and costs across stakeholders. This provides the decision-maker with basic information of the considered project's/policy's distributional impact. Some influential international manuals on project evaluation, such as the ones by the EU and the (Green Book of the) UK, also recommend the use of specific social welfare functions, where the social welfare weight attributed to a special (possibly regional) group depends on the group's income per capita or per (standardized) household. The reader is referred to Johansson and Kriström (2016, Section 7.5) for a discussion of how these manuals handle distributional issues, and to European Commission (2014) and HM Treasury (2020) for further details.

Appendix

The tax wedge term *TW* in equation (5) corresponds to a definite integral with integrand equal to:

$$MTW = \sum_i [\sum_{j \neq n} t_i \cdot q_i^*(.) \frac{\partial x_i(p^*, w^*, V^0) \cdot (1+t_j)}{\partial q_j}] + \sum_i t_i \cdot q_i^*(.) \frac{\partial x_i(p^*, w^*, V^0)}{\partial w} = \sum_i t_i \cdot q_i^*(.) \frac{\partial x_i^*(g_1, V^0)}{\partial g_1}, \tag{A.1}$$

where *MTW* denotes the marginal tax wedge evaluated at general equilibrium prices, and all constants (tax rates and so on) except initial utility are suppressed in the second line. Thus, integrate the sum with respect to g_1 from g_1^0 to g_1^1 along the optimal price paths, which are functions of g_1, noting that one can exploit the fact that $dq_i^* = (\partial f^i(g_1) / \partial g_1) dg_1$ and $dw^* = \partial h(g_1) / \partial g_1) dg_1$. The result of this definite integral is denoted *TW* in equation (5).

Finally, consider the possibility that the project is partially financed by an increase in an ad valorem tax, for example, the one on x_i. One could view the tax rate as a function of the size of the considered project: $\alpha_i \cdot g_1^j = t_i^j$, where α_i is a constant such that $\alpha_i \cdot g_1^j = t_i^j$ for $j = 0, 1$. This produces a new set of general equilibrium prices as functions of g_1. Straightforward but tedious calculations reveal that, in addition to the integral of (A.1), one must add the following definite integral to equation (5):

$$\int_{g_1^0}^{g_1^1}[\alpha_i \cdot g_1 \cdot q_i^*(.)\frac{\partial x_i(q_1^*(.)(1+t_1),\ldots,q_i^*(.)(1+\alpha_i \cdot g_1),\ldots)}{\partial t_i}+ \\ \sum_{j\neq i} t_j \cdot q_j^*(.)\frac{\partial x_j(.)}{\partial t_i}]\cdot q_i^*(.)\alpha_i dg_1, \tag{A.2}$$

where $\partial x_i(.)/\partial t_i$ denotes a substitution effect, $\partial x_j(.)/\partial t_i$ a cross-substitution effect, and the integrands can be (seemingly) simplified in the same way as is done in the second line of equation (A.1). The first term accounts for the change of "value" of the tax wedge in the market facing the tax increase (most easily seen by replacing the ad valorem tax by a unit tax, causing q_i^* to vanish from the expression). The second term accounts for the change in the value of the cross-substitution terms.

As equation (A.2) reveals, there are parallel expressions involving cross-substitution effects in the remaining markets. The magnitude of the terms in equation (5) are also affected because the equilibrium paths for prices are changed when they are functions of both g_1 and the new parameter $\alpha_i \cdot g_1$. It seems difficult to account for this type of tax funding of a project without access to a CGE model or a simulation model. However, in principle, (A.2) can be transformed to a 'non-marginal' cost of public funds which is easier to estimate.

To assess the value of a change in the travel time of a trip with an *existing* HSR, let us consider the Lagrange function for the expenditure minimization problem:

$$\mathcal{L}(.) = p \cdot x - w \cdot L + \lambda \cdot [V^0 - U(x, \Gamma - L - tc \cdot x)], \tag{A.3}$$

where $p = [(1 + t_1)\cdot q_1,\ldots, (1 + t_n)\cdot 1]$, λ denotes a Lagrange multiplier, and in the main text tc equals zero except for x_1 and x_2. Taking the partial derivative of $\mathcal{L}()$ with respect to tc_1 yields $\lambda \cdot U_\ell \cdot x_1$, where a subscript ℓ refers to leisure time. In optimum, $\lambda \cdot U_\ell = w$. Hence, $\partial e(.)/\partial tc_1 = w\cdot x_1(.)$. Integrating $-w^*(tc_1)\cdot x_1(.)$ between initial and final travel times, holding g_1 constant (or replaced by a supply function), yields the general equilibrium adjustment in Hicksian consumer surplus associated with a change in the travel time tc_1. Note that $q_1,\ldots, q_{n-1}$ and w are now functions of tc_1 and hence adjust as tc_1 changes such that equilibrium is maintained throughout in all markets. The numerical illustrations in the Appendix consider a simultaneous change in capacity and travel time of an existing HSR, where travel time is affected by, say, bottlenecks or traffic jams.

The rest of this Appendix provides a numerical illustration of many, but not all, results presented in the section on a high-speed rail. A simple Stone-Geary type of quasi-linear utility function is postulated because transportation is hardly an essential commodity (in contrast to, for example, air to breath). A trip is assumed to require *tc* time units, and there are just two modes of transportation. The first mode is initially not available, but it is evaluated using cost–benefit techniques.

The direct utility function is as follows:

$$U = \delta \cdot \ln(x_1 + 1) + \ln(x_2 + 1) + \ln(\Gamma - \delta \cdot tc_1 \cdot x_1 - tc_2 \cdot x_2 - L) + x_3 \qquad \text{(A.4)}$$

where $\delta = 1$ if provision of the first commodity is strictly positive and $\delta = 0$ otherwise, and x_3 denotes the numéraire. Demand functions are defined as follows:

$$\begin{aligned} x_i(.) &= \frac{1 - q_i - tc_i \cdot w}{q_i + tc_i \cdot w} \qquad i = 1,2 \\ x_3(.) &= \delta \cdot T + \pi_2 + w \cdot L - \delta \cdot q_1 \cdot x_1 - q_2 \cdot x_2 \end{aligned} \qquad \text{(A.5)}$$

where $T = q_1 \cdot g_1 - w \cdot (g_1)^2$, and $\pi_2 = (q_2)^2/(4 \cdot w)$. Thus, the first commodity is provided by the government. Any ad valorem taxes are suppressed here. Note that travel time is valued at the wage rate.

Supply of labor is defined as follows:[8]

$$L(.) = \Gamma + \delta \cdot tc_1 + tc_2 - \frac{1}{w} - \delta \cdot \frac{tc_1}{q_1 + tc_1 \cdot w} - \frac{tc_2}{q_2 + tc_2 \cdot w} \qquad \text{(A.6)}$$

Note that the functions in equations (A.5)-(A.6) will look the same if the analysis is based on the expenditure function; recall that preferences are quasi-linear.

Equilibrium conditions for the two transport markets and the labor market are used in the numerical exercise:

[8] Evaluated at the equilibrium prices for $g_1 = 2$, it holds that $\partial L(.)/\partial tc_i < 0$.

$$\begin{aligned}
&\frac{1-q_1-tc_1\cdot w}{q_1+tc_1\cdot w}=\delta\cdot g_1\\
&\frac{1-q_2-tc_2\cdot w}{q_2+tc_2\cdot w}=\frac{q_2}{2\cdot w}\\
&\Gamma+tc_1+tc_2-\frac{1}{w}-\frac{tc_1}{q_1+tc_1\cdot w}-\frac{tc_2}{q_2+tc_2\cdot w}=\delta\cdot(g_1)^2+\frac{(q_2)^2}{4\cdot w^2}
\end{aligned} \tag{A.7}$$

These can be solved to obtain $q_i^*=q_i^*(g_1)$ and $w^*=w^*(g_1)$; the functions and their graphs for the first market and the labor market are shown at the end of the paper (holding tc_1 = 1/10). Obviously, these equilibrium paths are functions of tc_1 and tc_2, in addition to g_1. However, the functions are reported for tc_2 = 4/10.

Consider now a shift of g_1 from $g_1^0=0$ to $g_1^1=2$ with tc_1 = 1/10, tc_2 = 4/10, and Γ=24. The general equilibrium price vector changes from $[q_1^0\approx 0.9943, q_2^0\approx 0.273, w^0\approx 0.057]$ to $[q_1^1\approx 0.326, q_2^1\approx 0.293, w^1\approx 0.069]$.[9] Thus, the increased demand for labor increases the equilibrium wage rate. In turn, this causes the equilibrium (ticket) price of the second commodity to increase. The initial market prices (q_1^0, w^0) are such that demand for trips on the high-speed rail equals zero.

The indirect utility function can be used to assess the social profitability in a quite simple way and is here used as a kind of consistency check. The compensating variation is implicitly defined by the following equation:

$$\ln(x_1^1+1)+\ln(x_2^1+1)+\ln(\Gamma-tc_1\cdot x_1^1-tc_2\cdot x_2^1-L^1)+x_3^1-CV=U^0 \tag{A.8}$$

where a superscript 1 (0) refers to the final (initial) equilibrium levels, and initial utility is $U^0\approx 4.073$. One finds that $CV\approx 0.834$.

Next, proceed sequentially as in equation (3) in the main paper to obtain:

[9] All *CV*-estimates reported below are based on approximations of prices to (up to) 16 decimals. Thus, using the approximate prices stated here need not exactly replicate the reported results.

$$CV = -\int_{q_1^0}^{q_1^1} \frac{1-q_1-tc_1\cdot w^0}{q_1+tc_1\cdot w^0}dq_1 - \int_{q_2^0}^{q_2^1} \frac{1-q_2-tc_2\cdot w^0}{q_2+tc_2\cdot w^0}dq_2 +$$
$$\int_{w^0}^{w^1}\left[\Gamma + tc_1 + tc_2 - \frac{1}{w} - \frac{tc_1}{q_1+tc_1\cdot w} - \frac{tc_2}{q_2+tc_2\cdot w}\right]dw + \Delta T + \Delta\pi^2 \approx$$
$$0.434 - 0.045 + 0.083 + 0.376 - 0.014 = 0.834$$

(A.9)

Note that one could as well integrate over generalized travel costs $x_i = (1-p_i^G)/p_i^G$, where $p_i^G = q_i + tc_i \cdot w$, as is done in the main paper, and obtain the same result.

Finally, use the equilibrium paths for q_1 and w as in equation (5) in the main paper to obtain:

$$CV = \int_{g_1^0}^{g_1^1}[q_1^*(g_1) - w^*(g_1)\cdot 2\cdot g_1]dg_1 \approx 1.086 - 0.252 = 0.834 \quad \text{(A.10)}$$

The (disgusting!) functions $q_1^*(.)$ and $w^*(.)$ are shown at the end of this paper, but their graphs, also shown, are smooth. If we instead had solved market equilibria using the generalized travel cost, we would simply have obtained the inverse demand function for x_1, i.e., $p_1^G = 1/(1+x_1)$. Then one must evaluate the time cost along the path for the wage rate and deduct the resulting amount to arrive at the desired result (1.0986 – 0.0122 – 0.252 ≈ 0.834).

The rule of half does not perform excellently in this case:

$$CV \approx \frac{1}{2}\cdot(q_1^1+q_1^0)\cdot x_1^1 - w^0\cdot(g_1)^2 \approx \frac{1}{2}\cdot(0.326+0.994)\cdot 2 - 0.0575\cdot 4 = 1.09 \quad \text{(A.11)}$$

where $x_1^1 = g_1^1 = 2$ in equilibrium. The fit improves slightly to around 1.044 if the final equilibrium wage rate is used. This poor performance is obvious from inspection of the non-linear graph of the q_1^* - function shown below.

The exercise undertaken in this paper demonstrates that one can use different approaches to assess the social profitability of an investment. It should also be noted that we do not explicitly have to estimate the value of the gain in travel time when the HSR is introduced. However, CV decreases (increases) as tc_1 (tc_2) increases. Nevertheless, such an approach does not reflect the social value of a reduction in travel time. To see why, differentiate the indirect utility function or the expenditure function with respect to tc_1 to obtain:

$$dV(.) = -de(.) = dCV^{tc_1}(tc_1, \bar{g}_1) = -w \cdot x_1(.)dtc_1 = -w \cdot \left(\frac{1 - q_1 - tc_1 \cdot w}{q_1 + tc_1 \cdot w} \right) dtc_1 \quad \text{(A.12)}$$

Thus, utility (expenditure) decreases (increases) as the travel time marginally increases. To evaluate a discrete change, use equation (A.7) to solve q_1, q_2, and w as functions of tc_1 for fixed g_1, i.e., $g_1 = \bar{g}_1$, and integrate (A.12) between initial and final levels of tc_1. Alternatively, replace a fixed g_1 in equation (A.7) by a supply function for the HSR. Note that one must solve (A.7) also for q_2 although it does not appear in (A.12). This is so because in the general equilibrium CBA of the change in travel time, q_1, q_2 and w adjust to maintain balance between supply and demand in markets; holding q_2 constant would result in a disequilibrium in the market for the second commodity (and q_1 and w would not follow their general equilibrium paths).

Let us also briefly consider a joint change in capacity and travel time for an existing HSR, where travelers are delayed due to more traffic causing traffic jams or bottlenecks are eliminated reducing travel times. A first variation is to add the integrated right-hand side expression in equation (A.12) to equation (A.9), recalling that one must decide where to place the integral in the evaluation chain because (A.9) is still a line integral (and the equilibrium prices will be different when both g_1 and tc_1 change).

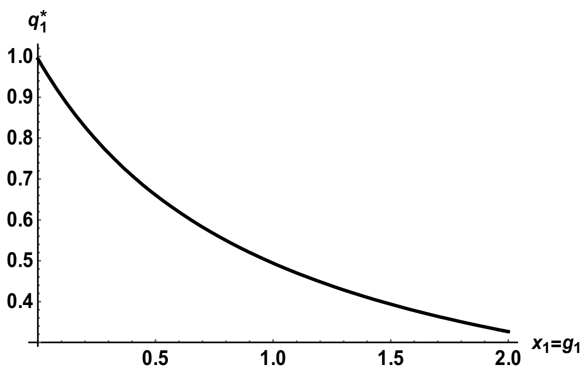
A second variation is to evaluate equation (A.10), holding tc_1 at its initial level. Next holding g_1 at its final level, evaluate equation (A.12) for the discrete change in travel time. Thus, we now evaluate a line integral. Hence, we could reverse the order of integration and arrive at the same overall compensating variation. Thus, the short-cut approach becomes a line integral in this more complex case.

A third variation assumes that the travel time is a function of capacity. Suppose that $tc_1 = 3/10 - (1/10) \cdot g_1$, i.e., $dtc_1 = -(1/10)dg_1$. Then the following expression is added to the integrand in equation (N.7):

$$-w \cdot \left(\frac{1 - q_1 - tc_1 \cdot w}{q_1 + tc_1 \cdot w} \right) \cdot \left(-\frac{1}{10}\right) \quad \text{(A.13)}$$

where $tc_1 = 3/10 - (1/10)\cdot g_1$. Suppose that g_1 increases from $g_1 = 1$ to $g_1 = 2$, while the travel time reduces from 2/10 to 1/10. The initial general equilibrium price vector equals $[q_1^0 \approx 0.488, q_2^0 \approx 0.2784, w^0 \approx 0.060]$ while the final one is the same as previously. Then $CV \approx 0.2118$, $CV^{\Delta g} \approx 0.1979$ if evaluated conditional on $tc_1 = 2/10$, and $CV^{\Delta tc} \approx 0.0139$ if evaluated conditional on $g_1 = 2$. These results are obtained by using the equilibrium paths for prices stated at the end of the paper. It is left to the reader to verify that the indirect utility function generates $CV \approx 0.2118$.

$$
\begin{aligned}
&q_1^*(.) = \frac{1}{4}\Bigg(\frac{4}{1+g_1} - 5tc_1 + \frac{60tc_1}{-117+5g_1(g_1+tc_1)} + \frac{30tc_1}{-601+25g_1(g_1+tc_1)} + \\
&30tc_1\sqrt{-\frac{(121-5g_1(g_1+tc_1))^2(-1819+75g_1(g_1+tc_1))}{(601-25g_1(g_1+tc_1))^2(117-5g_1(g_1+tc_1))^2}} + \\
&tc_1\surd\Bigg(25+300\Bigg(\frac{1}{601-25g_1(g_1+tc_1)} - \frac{2}{-117+5g_1(g_1+tc_1)} - \\
&\sqrt{-\frac{(121-5g_1(g_1+tc_1))^2(-1819+75g_1(g_1+tc_1))}{(601-25g_1(g_1+tc_1))^2(117-5g_1(g_1+tc_1))^2}}\Bigg) + \\
&400\left(\begin{aligned}&\frac{2}{-117+5g_1(g_1+tc_1)} + \frac{1}{-601+25g_1(g_1+tc_1)} + \\ &\sqrt{-\frac{(121-5g_1(g_1+tc_1))^2(-1819+75g_1(g_1+tc_1))}{(601-25g_1(g_1+tc_1))^2(117-5g_1(g_1+tc_1))^2}}\end{aligned}\right)^2\Bigg)\Bigg)
\end{aligned}
$$



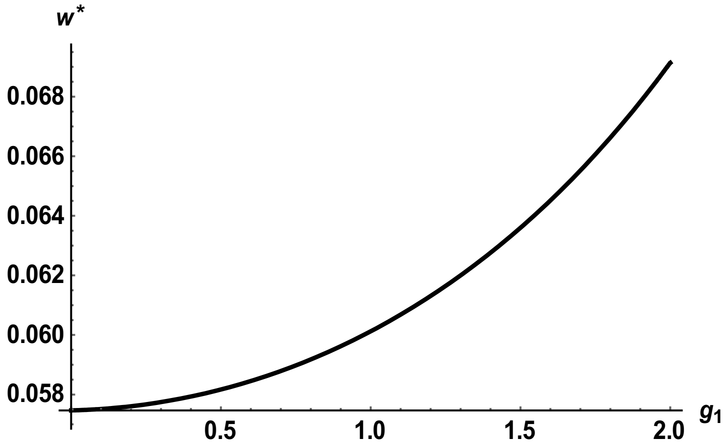
$$w^{*}(.)=\frac{5}{4}(1-\frac{12}{-117+5g_1\left(g_1+tc\ \right)}-\frac{6}{-601+25g_1\left(g_1+tc_1\right)}-$$

$$6\sqrt{-\frac{\left(121-5g_1\left(g_1+tc_1\right)\right)^2\left(-1819+75g_1\left(g_1+tc_1\right)\right)}{\left(601-25g_1\left(g_1+tc_1\right)\right)^2\left(117-5g_1\left(g_1+tc_1\right)\right)^2}}-$$

$$\frac{1}{5}\surd(25+300(\frac{1}{601-25g_1\left(g_1+tc_1\right)}-\frac{2}{-117+5g_1\left(g_1+tc_1\right)}-$$

$$\sqrt{-\frac{\left(121-5g_1\left(g_1+tc_1\right)\right)^2\left(-1819+75g_1\left(g_1+tc_1\right)\right)}{\left(601-25g_1\left(g_1+tc_1\right)\right)^2\left(117-5g_1\left(g_1+tc_1\right)\right)^2}})+$$

$$400\left(\begin{array}{c}\frac{2}{-117+5g_1\left(g_1+tc_1\right)}+\frac{1}{-601+25g_1\left(g_1+tc_1\right)}+\\ \sqrt{-\frac{\left(121-5g_1\left(g_1+tc_1\right)\right)^2\left(-1819+75g_1\left(g_1+tc_1\right)\right)}{\left(601-25g_1\left(g_1+tc_1\right)\right)^2\left(117-5g_1\left(g_1+tc_1\right)\right)^2}}\end{array}\right)^2))$$



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