OPTMIZING TRANSPORTATION INFRASTRUCTURE INVESTMENT USING COMPUTABLE GENERAL EQUILIBRIUM MODELS

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Introduction and literature review

Computable General Equilibrium (CGE) models are increasingly used for economy-wide evaluations of transportation projects and policies. Their popularity stems from numerous benefits that these models offer compared to earlier methods used in economic analyses such as Cost Benefit Analysis (CBA), Input-Output (IO) models, and Partial Equilibrium (PE) models. For instance, in the CGE context, the distribution of impacts, the linkages between markets, and the presence of externalities can be examined. These models are also behaviorally-based, making them theoretically attractive. Traceability of the results is another benefit these models offer (Tavvasszy et al., 2002; Mayeres et al., 2005; Robson and Dixit, 2015; Robson and Dixit, 2016; Kawakami et al., 2004; Kim, 1998).

The applications of CGE models include, but are not limited to, evaluating economic impacts of transportation network changes, infrastructure investment, land-use and economic interaction, trade agreements, border crossing analysis, disaster recovery, road pricing, etc. (Robson and Dixit, 2016; Bröcker, 2004; Bröcker et al., 2010; Oosterhaven et al., 2001; Kim and Hewings, 2009; Conrad and Heng, 2002; Mayeres and Proost, 2001; Bröcker et al., 1998; Tscharaktschiew and Hirte, 2012; Seung and Kraybill, 2001; Seung and Kraybill, 2001; Anas and Kim, 1996; Anas and Xu, 1999; Horridge, 1994; Higgs, 1988; Nguyen and Wigle, 2011; Ueda et al, 2001; Mayeres and Proost, 2004; Van Dender, 2003).

Our literature review reveals that most applications of CGE models in transportation fall into comparative analysis, where scenarios before and after transportation projects or policies are compared. However, the potentials of these models go beyond just comparative analysis. In this paper, a framework is proposed that introduces the concept of optimization into the CGE context. This framework is particularly aimed at optimizing transportation infrastructure investment over space and time. The proposed framework offers an empirically-based conversion of infrastructure investment (i.e., in $) into transportation network attributes (e.g., capacity). The proposed methodology is described in the next section, followed by a formulation of a simple non-trivial model. Then, concluding remarks and current and future research directions are presented.

Framework

A CGE model represents the economy while a transport model represents the transportation network. The CGE model consists of a set of equations representing the behavior of each agent in the economy (firms, consumers, government agencies, etc.). Taking consumers as an example, the consumers decide on their consumption level of commodities to maximize their welfare (measured by utility) subject to their budget constraints. Firms, on the other hand, decide on the level of their inputs of production factors (e.g., capital, labor, and intermediate commodities) to maximize their profit subject to their budget constraints. In a simple setting, firms produce commodities that are transported to the consumers across all regions. Similarly, the consumers (households) commute to work in addition to making shopping and recreational trips. Government, on the other hand, levies taxes on firms and households to finance public goods such as infrastructure. The transportation model, at its simplest, consist of the typical four step transportation modelling components: trip generation, trip distribution, modal split, and traffic assignment. For more details on this, refer to (McNally, 2007).

What differentiates CGE models from Input-Output (IO) models is the constraint on the supply side, meaning that the demand for a commodity cannot exceed the amount supplied by firms. Similarly, the labor required for production cannot exceed the labor supplied by the households. In simple terms, CGE models can be thought of as a set of supply and demand curves that are solved simultaneously.

The relationship between the economic and transportation systems can be captured by an equilibrium approach, where the bilateral linkage between the two imposes continuous translation of changes in one to the other. Prior literature has typically focused on either spatial or temporal economic impacts of a policy or project. Taking infrastructure investment as an example, infusion of money into improving infrastructure takes place in stages, which are temporal shocks to the system. Also, depending on the location of the improvement, it has a spatial dimension as well. The infusion of money into infrastructure affects the economy by attracting construction related industries in the short run, while in the long run, it causes fundamental behavioral changes, such as locational change of firms and households. This spatial and temporal interaction of the two components is usually not taken into account simultaneously.

For the purpose of optimizing infrastructure investments, a reformulation of a CGE model is required, from a system of simultaneous equations, to a constrained optimization model. Alternatively, all possible infrastructure investments in time and space could be enumerated and evaluated. What differentiates our framework from what has been done previously is twofold: first, the framework proposes simultaneous optimization of spatial and temporal dimensions of infrastructure investments. Second, unlike other studies that represent infrastructure investment solely by a reduction in transportation costs, this framework offers an empirically-based approach to directly link these infrastructure investments to government expenditure in the CGE model. The infrastructure investments require corresponding revenue sources (e.g., taxes) for funding. Taking the study of Imdad and Westin, (1998) as an example, transportation investment is represented as a reduction in transport costs without any linkage to the amount of investment in the CGE model. This may lead to unrealistic results in terms of the effects of infrastructure investment, since the presumed reduction in transport costs is not measured against the cost of the corresponding infrastructure investment. To address this limitation in the application of the CGE approach, the proposed framework offers a direct conversion of the investment (dollar value) to changes in transport network attributes such as capacity.

Figure 1 shows a schematic representation of a fully integrated transport-CGE model. There are two channels through which the CGE model impacts the transport model. First, it provides the transport model with transport demands. These transport demands directly affect the generation and distribution steps of the transport model as they provides Origin-Destination (OD) level transport demands. Second, the infrastructure investments made by the government in the CGE model are translated into changes in transportation network attributes, which lead to reductions in transport costs. Ideally, once the transportation costs are updated, the transport model must reach a new internal equilibrium where the updated cost is fed into the four steps. However, if computational complexity is of concern, this internal equilibrium state can be skipped and just one iteration of the four steps suffices. The resulting travel costs are fed back into the CGE model, where the commuting and movement of goods are impacted by the updated transport costs. The CGE model must then also reach a new internal equilibrium. The two models interact until the entire system reaches an equilibrium (i.e., transport demands and costs stop changing). Once an equilibrium is reached, the model outputs are used to extract certain measures such as competitiveness, consumer welfare, etc. These measures are often used as the basis for comparison between tested scenarios (i.e., between the base case and the policy replacement scenario).

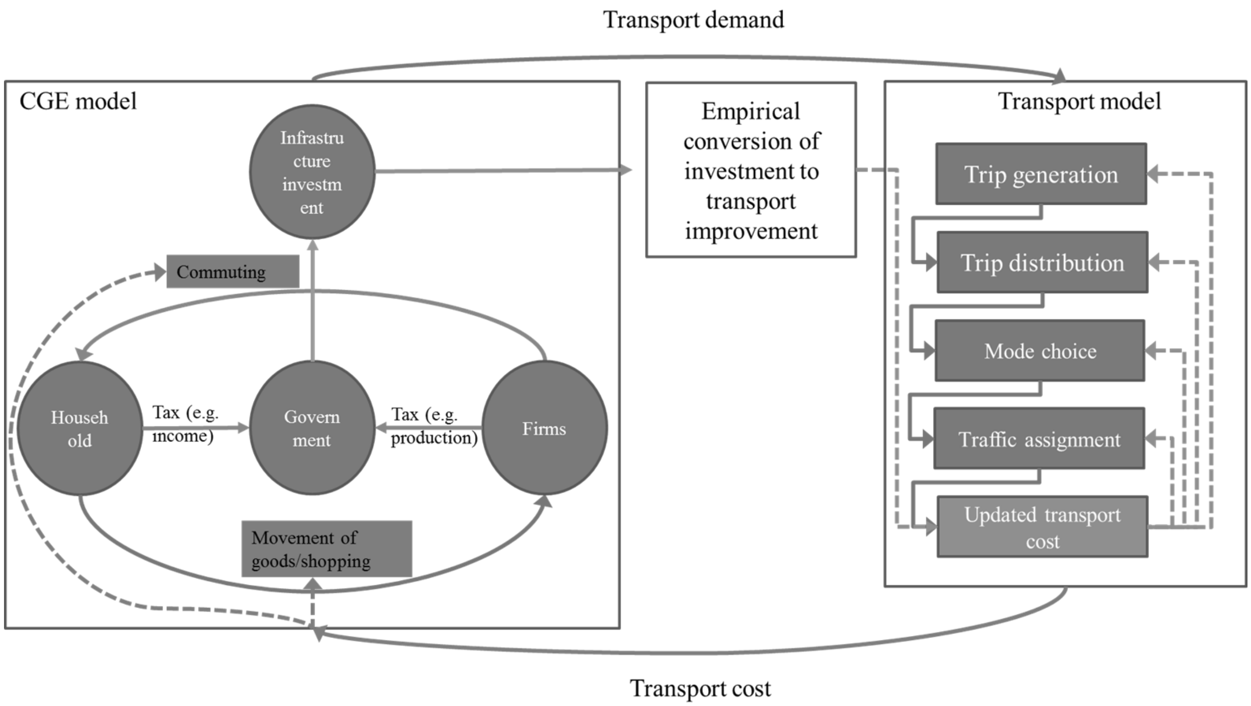

Figure 1: Flowchart of the proposed framework

The system presented above can mathematically be represented as a set of equations that are solved simultaneously. To introduce the concept of spatial and temporal optimization, assume that the transport network has $L=\{L_1,L_2,\ldots, L_l\}$ links connecting the regions in the model. If $B_L=\{b_1,b_2,\ldots\}$ represents the set of all possible investment on link L, and $T=\{T_1,T_2,\ldots, T_t\}$ represents the time periods through which investment can be made, then, various subsets of $\{S_{lbt} \mid l \in L,\ b \in B_L,\ t \in T\}$ must be evaluated to determine a set of optimal investments over space and time. For illustrative purposes, the next section of the paper formulates a simple non-trivial model.

Simple non-trivial model formulation

Although the proposed framework has both spatial and temporal dimensions, a formulation for a simple non-trivial case of spatial optimization of investments is presented. The formulation of the model consists of households' behavior, firms' behavior, and market clearing equilibrium conditions. The model is schematically illustrated in Figure 2, where arrows represent the flows of commodities and factors.

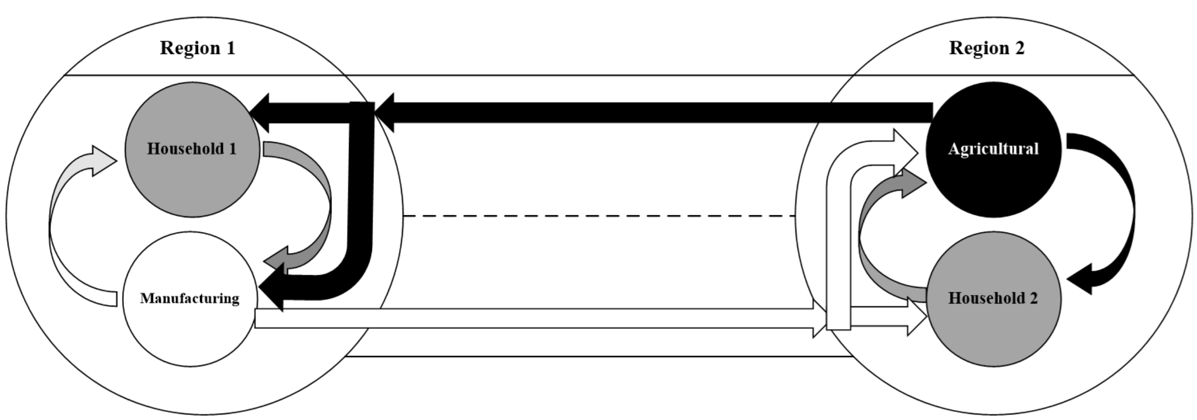

Figure 2: Schematic illustration of the model

Households' behavior

There is one household in each region. Each owns a fixed endowment of labor which is sold to the regional industry (grey arrows in Figure 2). This implies the assumption of immobility of labor across regions. The income, which is earned through selling labor endowment, is spent on purchasing manufacturing and agricultural commodities, which are represented by white and black arrows in Figure 2, respectively. The demand for commodities is determined by the utility-maximizing behavior of households in each region, which is modeled by use of the Cobb-Douglas functional form.

(1) $U_1 = d_1({X_{mnf,1}}^{\alpha_1})({X_{agr,1}}^{ß_1})$, $\alpha_1 + ß_1 = 1$

(2) $U_2 = d_2({X_{mnf,2}}^{\alpha_2})({X_{agr,2}}^{ß_2})$, $\alpha_2 + ß_2 = 1$

where α_i and $ß_i$ are the share parameters of manufacturing and agricultural commodities in the household *i*'s utility function, respectively, d_r is the scale parameter for utility function of the household in region *r*, and $X_{ind,r}$ represents the demand for commodity (ind)(manufacturing and agricultural) by the household in region *r*. Constant returns to scale implies $\alpha_i + ß_i = 1$.

An underlying assumption is the full employment of the regional labor supply which means the wage varies to ensure an equilibrium of demand and supply for the labor market. The budget constraint is therefore formulated such that income, which comes from selling the labor endowment to regional firms, equals the spending on both the manufacturing and agricultural commodities, and the levied tax to finance transportation infrastructure.

(3) $BC1\colon P_{L1}\overline{L}_1 = P_{mnf,1}X_{mnf,1} + P_{agr,1}X_{agr,1} + T_1$

(4) $BC2\colon P_{L2}\overline{L}_2 = P_{mnf,2}X_{mnf,2} + P_{agr,2}X_{agr,2} + T_2$

where P_{Lr} is the price of labor in region *r* (or wage of labor in region *r*), $\overline{L}_r$ is the labor endowment of the household in region *r*, $P_{ind,r}$ is the price of commodity (ind) in region *r*, and T_r is the levied tax on the household in region *r* to finance the infrastructure investment. The left side of the Equation 3 is the income for household 1, while the right side of the equation is the expenditures of household 1. The household's optimization problem is formulated as maximizing the household's utility (e.g., Equation 1) subject to its budget constraint (e.g., Equation 3). Solving the household's optimization problem using Lagrange multipliers leads to the following commodity demand functions:

(5) $X_{mnf,1} = \frac{P_{L1}\overline{L}_1 - T_1}{P_{mnf,1}(1+\frac{ß_1}{\alpha_1})}$

(6) $X_{agr,1} = \frac{P_{L1}\overline{L}_1 - T_1}{P_{agr,1}\left(1+\frac{\alpha_1}{ß_1}\right)}$

(7) $X_{mnf,2} = \frac{P_{L2}\overline{L}_2 - T_2}{P_{mnf,2}(1+\frac{ß_2}{\alpha_2})}$

(8) $X_{agr,2} = \frac{P_{L2}\overline{L}_2 - T_2}{P_{agr,2}\left(1+\frac{\alpha_2}{ß_2}\right)}$

Taking Equation 5 as an example, the demand for the manufacturing commodity by the household in region one increases with the household's income (nominator) and decreases with an increase in the price of manufacturing products in region 1 (in the denominator). This is consistent with the economic concept that an increase in the price of a normal good causes a reduction in its demand. Ceteris paribus, the increase in income causes an increase in the consumption of a normal good, which is reflected in the above formulation as well.

Firms' behavior

It is assumed that region 1 specializes in manufacturing while region 2 specializes in agriculture. The firms employ the regional labor supply; they also take the product of the other industry as an intermediate input to their production. The firms make profit by selling their final output to the households and firms in all the regions. The optimization problem describing the firms' behavior then becomes choosing the demand for inputs (labor and intermediate commodity) to their production that maximize their profits (Equation 9 and 11) subject to their production functions (Equation 10 and 12).

(9) $\pi_1 = P_{mnf,1}Z_1 - P_{agr,1}x^f_{agr,1} - P_{L,1}L^f_1$

(10) $Z_1 = b_1(L^f_1)^{\Upsilon_1}(x^f_{agr,1})^{\lambda_1}, \Upsilon_1 + \lambda_1 = 1$

(11) $\pi_2 = P_{agr,2}Z_{agr,2} - P_{mnf,2}x^f_{mnf,2} - P_{L,2}L^f_2$

(12) $Z_2 = b_2(L^f_2)^{\Upsilon_2}(x^f_{mnf,2})^{\lambda_2}, \Upsilon_2 + \lambda_2 = 1$

where π_{ind} is the profit function of industry (ind), Z_{ind} is the total production level of commodity (ind), $x^f_{ind,r}$ is the demand for commodity (ind) required in the production of commodities in region r, and L^f_{ind}, is the labor input to the production of commodity (ind). λ_{ind} and Υ_{ind} are the production share parameters of the input factors for production function of industry (ind), and b_{ind} is the scale parameter of production technology of industry (ind). The first term on the right side of Equation 9 is the revenue of firm 1 that comes from selling manufacturing products, while the other two terms proceeding are the expenditures spent on labor and agricultural commodities. Equation 10, on the other hand, limits the production of manufacturing commodity given the labor and agricultural inputs. Assuming constant return to scale, $\Upsilon_i + \lambda_i = 1$. Lagrange multipliers can again be used to solve the optimization problem of the firms, which leads to the following demand functions:

(13) $L^f_1 = \frac{P_{mnf,1}\Upsilon_1 Z_1}{P_{L,1}}$s

(14) $x^f_{agr,1} = \frac{P_{mnf,1}\lambda_1 Z_1}{P_{agr,1}}$

(15) $L^f_2 = \frac{P_{agr,2}\Upsilon_2 Z_2}{P_{L,2}}$

(16) $x^f_{mnf,2} = \frac{P_{agr,2}\lambda_2 Z_2}{P_{mnf,2}}$

Taking Equation 13 into consideration, the demand for labor by the manufacturing industry increases as the firm's output increases and decreases with an increase in the labor wage in that region, which once again corresponds to underlying microeconomic assumptions.

Market clearing condition

As mentioned before, what differentiates CGE models from IO models is the clearing of markets which means that the demand and supply for all the factors and commodities in the model must equate. The following equations are to ensure market clearing conditions in the labor and commodities markets:

(17) $L^f_1 = \overline{L}_1$

(18) $L^f_2 = \overline{L}_2$

(19) $Z_2 = X_{agr,2} + (X_{agr,1} * t_{21} + x^f_{agr,1} * t_{21})$
(20) $Z_1 = X_{mnf,1} + (X_{mnf,2} * t_{12} + x^f_{mnf,2} * t_{12})$

t_{ij} is the transport factor for moving commodities from region *i* to region *j* with a value of greater than one. For representation of transportation, the iceberg approach is employed, which is inspired by the notion that iceberg melts as it moves (Samuelson, 1952). Thus, the transport cost is represented as a reduction in the amount of the manufactured commodity delivered to the destination region. Equation 20, as an example, states that the production for manufacturing product must be equal to the local demand, $X_{mnf,1}$, and the demands of the household and firms in region 2, $X_{mnf,2} * t_{12} + x^f_{mnf,2} * t_{12}$ respectively. t_{12} is included to take into account the transport cost as explained below.

Based on this notion, a relationship between the prices of the transported commodity and the transport factor can be developed. If *V* is the volume to arrive at the destination region, then $t_{ij}V$ must be produced in the region of origin as it is assumed that $(t_{ij} - 1)V$ vanishes due to transport activity. If P_1 and P_2 represent the prices in region 1 and 2, and V_1 and V_2 represent the corresponding volumes, where V_1 is to be transported from region 1 to region 2, then by use of the value conservation law, P_2=$t_{12}P_1$ holds true. Hence, the following equations apply:

(21) $P_{mnf,2} = P_{mnf,1}t_{12}$
(22) $P_{agr,1} = P_{agr,2}t_{21}$

The infrastructure is assumed to be financed through taxing the households, T_1 and T_2. To close the model, assuming the exogenous level of investment *B*, and that households share the transport investment expense equally, the following equation applies:

(23) $T_1 = T_2 = \frac{B}{2}$

Welfare measure

The objective in our case study is to determine the optimal level of investment in road infrastructure that leads to the maximum possible level of welfare for households' welfare. Hichk's Equivalent Variation (*EV*) measure of welfare is used in this model. If an economic shock causes a change in household's utility and market prices, *EV* is the amount of income that has to be paid to the household at the new utility after the economic shock to keep the prices same as before the economic shock. EV has been frequently used as the comparison measure in many studies. For CD utility function, the following formulation for *EV* is extracted (Bröcker et al., 2010):

(24) $EV_1 = P^a_{L,1}\bar{L}_1 \left[\left(\frac{P^b_{mnf,1}}{P^a_{mnf,1}} \right)^{\alpha_1} * \left(\frac{P^b_{agr,1}}{P^a_{agr,1}} \right)^{ß_1} \right] - P^b_{L,1}\bar{L}_1$

(25) $EV_2 = P^a_{L,2}\bar{L}_2 \left[\left(\frac{P^b_{mnf,2}}{P^a_{mnf,2}} \right)^{\alpha_2} * \left(\frac{P^b_{agr,2}}{P^a_{agr,2}} \right)^{ß_2} \right] - P^b_{L,2}\bar{L}_2$

The objective of the optimization could take this form of maximizing $EV_1 + EV_2$. With this measure as the objective function, one must evaluate the welfare measure for all possible values of *B* to determine the optimal level of infrastructure investment. As *B* increases from an optimal level, taxes will increase more than transportation improvements benefit prices. As *B* decreases from an optimal level, prices will increase more than the taxes saved.

Converting investment to network change

It is assumed that the investment on each road, increases its capacity. If C^0 is the capacity of a constructed road for which the construction cost is represented by $COST^0$, assuming that the ratio of capacity to construction cost remains constant over time for that specific road, the following formula can be applied to calculate the capacity after investment B is made:

$$C^1 = B * \frac{C^0}{COST^0}$$

For this specific case we assume that the investment is equally distributed between the two roads and that both have the same capacity to construction cost ratio. The following formula applies:

(26) $$C^{12} = C^{21} = 0.5(B * \frac{C^0}{COST^0})$$

Transport factor calculation

The state-of-practice in the use of iceberg theory has been to assume a distance dependent transport factor. The distance consideration has the obvious limitation of not considering congestion. Another obvious drawback of this configuration is that not all the investment leads to a reduction in distance. Due to these limitations, we propose the use of travel time dependent transport factor, which takes into account congestions and bottlenecks in a transport network.

First, a specific volume-delay function (Bureau of Public Roads (BPR) function) is used to determine the travel time (Horowitz, 1991). Let's assume that tt^0 is the free flow travel time, and t^1 is the travel time on the link. If V is the traffic volume commuting on the link and C is the capacity of that link, then the travel time, tt^1 can be calculated using the following formula:

$$tt^1 = tt^0 \left(1 + \zeta \left(\frac{V}{C}\right)^{\xi}\right)$$

where ζ and ξ are the parameters that depend on the type and speed of the road. Default values are 0.15 and 4 for ζ and ξ respectively. C is the capacity at Level of Service (LOS) C (Horowitz, 1991).

In our model, the transported commodity between the two regions are $X_{mnf,2} + x^f_{mnf,2}$ from region 1 to 2 and $X_{agr,1} + x^f_{agr,1}$from region 2 to 1. Assuming that each unit of manufacturing and agricultural commodities require ρ and $\acute{\rho}$ transport trips, and that there is no return trip associated with each trip, then the travel times for road 12 and road 21 are as follow:

(27) $$tt^1_{12} = tt^0_{12} \left(1 + \zeta_{12} \left(\frac{\rho(X_{mnf,2} + x^f_{mnf,2})}{C_{12}}\right)^{\xi_{12}}\right)$$

(28) $$tt^1_{21} = tt^0_{21} \left(1 + \zeta_{21} \left(\frac{\acute{\rho}(X_{agr,1} + x^f_{agr,1})}{C_{21}}\right)^{\xi_{21}}\right)$$

(Bröcker, 2004) mentions that the travel cost does not proportionally change with the distance. Here, we adopt the same concept for travel time and apply the same simple formulation used by (Bröcker, 2004):

$$t_{ij} = \tau(tt_{ij})^{\nu} + 1$$

τ and ν are the scale and proportionality parameters that must be calibrated. Sample data including travel cost and the corresponding travel time can be used to calibrate these parameters. Following formulas apply:

(29) $\quad t_{12} = \tau_{12}(tt_{12})^{\nu_{12}} + 1$
(30) $\quad t_{21} = \tau_{21}(tt_{21})^{\nu_{21}} + 1$

Equations 5-8, 13-16, and 17-20 form the CGE modelling equations that can be solved using commercial software packages, such as GAMS. The remaining equations are required for optimization of the integrated transport-CGE system. A Social Accounting Matrix (SAM) that summarizes the transactions between the production activities and factors is required for calibration of modelling parameters.

Concluding remarks and future avenues

Computable General Equilibrium (CGE) models have been widely used for economic evaluation of transportation policies and projects. Our literature review has revealed that these models have typically suffered two drawbacks. First, the state-of-practice has usually been in the comparative analysis context, where the economic impacts of scenarios before and after a policy implementation are investigated. Second, in the infrastructure investment application of these models, infrastructure investment is translated as a reduction in transport costs, but not linked to government expenditure. In this study, a framework is developed to address these limitations. To address the first limitation, the proposed framework introduces optimization into the CGE framework by determining the optimal investments over time and space. To address the second limitation, the proposed methodology formulates a direct empirical-based conversion of investment ($) from the CGE model into change in transportation network attributes (e.g., capacity). Compared to other modelling practices, this formulation not only offers a more realistic representation, but also from a modelling perspective, it provides a more reliable evaluation of a potential policy or project. For illustrative purposes, a formulation for a simple non-trivial model was presented.

The proposed framework could be used to optimize the level of investment in infrastructure given an objective function such as maximizing competitiveness, consumer welfare, etc. The objective function can go beyond just welfare or competitiveness; it could focus on exports to another country, or profit maximization of a government agency. An application of the proposed framework currently undertaken by the researchers of this study, is to determine the optimal level of infrastructure to maximize Canada’s global competitiveness. This requires expanding on the model in several ways other than just the scale of the model (multiregional and multi-sectoral). First, is to use more flexible functional form such as Constant Elasticity of Substitution (CES) rather than CD. Second, is formulating the transport cost using a more realistic approach, as a marginal industry, rather than iceberg approach which has been justifiably criticized in the literature on several grounds. Finally, the current model represent monopolistic market structure while in reality imperfect competition of various degrees may exist. Inclusion of these details compromises a more accurate representation of the economic environment with more computational complexity and data demands.

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Appendix 1: Parameters and variables

In this section we present the definition of the variable and parameters used in the model. Table 1 presents the endogenous variables of the CGE model (i.e., determined by the CGE model). Table 2 presents the model's parameters and exogenous variables of the CGE model (i.e., specified outside of the CGE model). Parameters are determined through calibration processes while variables are determined as shocks to the model. Note that the definition of exogenous/endogenous is dependent on the system under investigation. As an example, if the system is the integrated CGE-transport model, then the travel times are considered as endogenous while they are exogenous if the CGE model is considered as the system.

Table 1: Endogenous variables of the CGE model

Variables	Description
U_r	Utility of the representative household in region r
$X_{ind,r}$	Consumption of commodity of industry (ind) by household in region r
$P_{L,r}$	Price or wage of labor in region r
$P_{ind,r}$	Price of commodity (ind) in region r
Z_{ind}	Total production of commodity (ind), since each region produces specifically one product, Z_1 corresponds to manufacturing and Z_2 corresponds to agricultural
π_{ind}	Profit function of industry ind
$x^f_{ind,r}$	Intermediate commodity (ind) required by firm in region r
L^f_{ind}	Labor factor required for production by firm (ind), L^f_1 is the labor required for production of manufacturing product, L^f_2 corresponds to that of agricultural.
t_{ij}	Transport factor for moving products from region i to region j
EV_r	Equivalent variation (EV) Hick's measure of welfare for household in region r
$P^b_{ind,r}$	Price of commodity (ind) in region r before policy implementation
$P^a_{ind,r}$	Price of commodity (ind) in region r after policy implementation
$P^b_{L,r}$	Price or wage of labor in region r before policy implementation
$P^a_{L,r}$	Price or wage of labor in region r after policy implementation
C^{ij}	Capacity of the link connecting region i to j

Table 2: Model parameters and exogenous variables of the CGE model

Parameters	Description
α_r	Share parameter of manufacturing in utility function of household in region r
$ß_r$	Share parameter of agricultural in utility function of household in region r
$\overline{L}_r$	Endowment of labor by the household in region r
b_r	Scale parameter of production function of firm in region r
Υ_{ind}	Labor share parameter of production function of industry ind
λ_{ind}	Share parameter of intermediate commodity for production of industry ind
d_r	Scale parameter of household's utility function in region r
C^0	Initial capacity
$COST^0$	Initial construction cost
ζ_{ij}, ξ_{ij}	Volume-delay function parameters for link ij
τ_{ij}, ν_{ij}	Transport cost scale and proportionality parameters

ρ and $\acute{\rho}$	Trips per unit of commodity, manufacturing and agricultural respectively
B	Budget borrowed to invest in infrastructure
tt_{ij}^{0}	Free flow travel time of link ij
tt_{ij}^{1}	travel time of link ij
T_i	Levied tax to finance transport infrastructure