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Public Infrastructure and Productivity: Updating the Canadian Case

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Abstract

This report revisits the public capital hypothesis in Canada using a classical model with updated estimation techniques. Provincial panel data spanning 1998-2020 are leveraged to determine the effect of public infrastructure on business sector output and productivity. Several specifications (levels and first-differences) of the Cobb-Douglas production function are estimated using OLS and FGLS techniques that account for heteroskedasticity, autocorrelation, cross-sectional dependence, and province-specific effects. I find output and productivity elasticities for aggregated public infrastructure to be predominantly insignificant from zero. A detailed disaggregation of public infrastructure by asset type and function also yields largely insignificant results.

Public Infrastructure and Productivity: Updating the Canadian Case

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Executive Summary

This report estimates the impact of public infrastructure on output and productivity in Canada using the aggregated production function framework. Panel data covering the ten provinces during the 1997–2020 period is leveraged. The dataset also includes disaggregated measures of public infrastructure—by asset type and function—allowing us to examine which types of infrastructure are most (and least) productive within the production function framework. Various model specifications and estimation techniques are employed to ensure results are robust.

Beginning with the aggregated analysis, the Cobb-Douglas production function is first estimated in levels through three standard specifications: unconstrained elasticities, constant returns to scale (CRTS) on private inputs, and CRTS on all inputs. To remedy nonstationarity present in the data, I also estimate the model in unconstrained, first-difference form. Both OLS (pooled and fixed effects) and FGLS (random effects) estimation techniques are employed for all specifications.

Under all three returns-to-scale assumptions, output/productivity elasticities with respect to public infrastructure are positive and statistically significant for the pooled OLS estimations (i.e. no fixed effects or solely time fixed effects), ranging from 0.038 to 0.123. Controlling for province-specific effects through fixed effects, a negative and insignificant relationship is found (-0.058 to -0.128). The FGLS coefficients are largely insignificant as well. The change in elasticities seen between the pooled and fixed effects estimations resembles that in previous literature, which has also found fixed effects to reduce the impact of public infrastructure on productivity. The first-difference form, also in line with the literature, yields an insignificant and negative elasticity (-0.138).

The disaggregated analysis is separated into three sections: asset type, asset function, and core vs. non-core. The first two levels of disaggregation generate estimates that largely follow those in the aggregated analysis: many remain statistically insignificant in levels regardless of the estimation technique being used, and essentially all asset types and functions are insignificant in the first-difference specification. In levels, institutional buildings and communication networks have a significant, robust, and positive elasticities. Commercial buildings and transportation machinery and equipment, on the other hand, have a significant, robust, and negative effect on production. The aforementioned infrastructure assets turn insignificant in the first-difference specification with the exception of transportation machinery and equipment.

In terms of asset function, health and housing and community amenities are estimated to have a positive impact on output, while public transit equipment, environmental protection, and public order and safety are deemed negative under the production function framework in levels. When first-differencing, only public transit equipment retains its robust statistical significance.

Finally, I group fuel and energy, transport, housing, environmental protection, and communication asset functions to create a measure of core infrastructure, while the sum of all other functions is considered non-core. Core infrastructure's elasticity is estimated to be insignificant under all estimation techniques, while non-core infrastructure is highly significant and positive in levels. This contradicts much of the literature, which generally finds core infrastructure to be productive. This may be driven by the inclusion of environmental protection and exclusion of health infrastructure from the measure of core infrastructure. The estimate offered by this report suggest that the impact of public infrastructure on output/productivity is largely insignificant from zero. The methodology employed, however, presents a significant caveat that should not be neglected. While the standard production function may be capable of providing rough estimates of the contributions of public infrastructure towards private sector productivity, its aggregated nature, and the extensive set of assumptions that should be satisfied to justify its use, largely prevent its results from having policy implications. In other words, the results presented in this report are "obtained within a very narrow framework" (Garcia-Milà et al., 1996). The widespread statistical insignificance found in this paper only emphasizes the need for micro-oriented, cost-benefit analysis of new infrastructure projects.

Public Infrastructure and Productivity: Updating the Canadian Case[1]

1 Introduction

Canadian infrastructure has seen a rise in attention and over the last few years. In 2016, the Liberal government announced the Investing in Canada Plan (ICP), which committed over $180 billion towards infrastructure over 12 years (Infrastructure Canada, 2018). ICP led to the creation of the Canada Infrastructure Bank a year later, a crown corporation equipped with $35 billion over 11 years and the purpose of investing and attracting private-sector investment for revenue-generating infrastructure projects. Infrastructure Canada examined the challenges and opportunities facing the nation's infrastructure in the 2018 report titled *Investing in Canada: Canada's Long-Term Infrastructure Plan* (Infrastructure Canada, 2018). In 2021, the department initiated an assessment of national infrastructure by engaging with various jurisdictions, groups, and experts (Infrastructure Canada, 2021).

Another development that motivates this paper is the declining labour productivity growth rates in Canada (Greenspon et al., 2021; Sharpe & Ashwell, 2021; Williams, 2021). Just as slowdowns in labour productivity motivated the seminal work of Aschauer (1989a), declining rates in Canada similarly raise questions regarding the role of public infrastructure in stimulating and supporting Canadian productivity.

Finally, with the exception of Jacques-Arvisais and Lapointe (2022), I did not find a paper published in the last decade that specifically contributes to the Canadian literature through econometric analysis. The availability of more recent and disaggregated data, and the fact that marginal benefits derived from various infrastructure assets decrease as their network solidifies, warrant an updated examination of the infrastructure-productivity relationship in Canada.

Empirical investigation of the relationship between public infrastructure and private productivity rose to prominence over three decades ago. Initial studies largely relied on national time-series and aggregated measures of public capital to estimate its effect on production and productivity. These studies often found output elasticities with respect to public capital that are implausibly large (e.g. Aschauer, 1989a, 1989b; Ford & Poret, 1991; Munnell, 1990b). Criticism of these findings naturally

[1]This study was undertaken at the Centre for the Study of Living Standards (CSLS) as part of the Directed Research Program run by the Department of Economics at the University of Ottawa. The research was supervised by CSLS Executive Director Dr. Andrew Sharpe. The author is a mathematics and economics student at the University of Ottawa. Email: msiro087@uottawa.ca

followed, with subsequent papers attributing the large elasticities to several issues (e.g. Aaron, 1990; Gramlich, 1994; Tatom, 1991). First, data at the national level is likely to be nonstationary, meaning standard estimation techniques, namely the production function in levels, are likely to produce results that reflect spurious correlation rather than a direct causal relationship. Furthermore, even if these results reflected causality between infrastructure and productivity, it may not be driven by the former. The simple production function assumes public capital stock is strictly exogenous, such that it is the source of causality, but periods of higher output and, therefore, tax revenues, can lead to increased public investment as well. The production function approach is also prone to various forms of simultaneous and omitted variable bias. The wide range of estimates reported for public capital in the early literature indicates that results were unreliable from the more pragmatic perspective of policy makers.

This study contributes to Infrastructure Canada's national infrastructure assessment by providing an updated econometric analysis of provincial data spanning the 1998–2020 period. It employs the standard Cobb-Douglas production function to retain comparability with the vast literature, while also correcting for some of the issues associated with this classical model. As with many papers following Aschauer (1989a), this study benefits from the use of panel data, which offers greater variation than its time-series counterpart and facilitates the use of various estimation techniques, enabling more exhaustive robustness checks of results. More specifically, I estimate a Cobb-Douglas production function in both levels and differences while accounting for autocorrelation, heteroskedasticity, cross-sectional dependence, as well as fixed and random effects.

Leveraging Statistics Canada's Infrastructure Economic Accounts, which offer disaggregated measures of public infrastructure, this study also reports elasticity estimates for 11 types of infrastructure assets as well as 9 asset functions. This level of disaggregation is unprecedented in the literature employing production functions, and can provide more comprehensive insights into the productivity of various infrastructure assets.

My results overwhelmingly suggest that public infrastructure has little to no effect on business sector output within the production function framework.

Section 2 reviews the literature by region. Section 3 presents the theoretical framework, model specifications, and estimation methods used throughout the study. Section 4 describes the data used. Section 5 presents and discusses the results. Finally, Section 6 concludes.

2 Literature Review

Since the work of Aschauer (1989a), researchers have eagerly undertaken the challenge of solving the public infrastructure-private productivity puzzle. Many forms of data, measures of public capital, model specifications, and econometric techniques have been proposed over the last three decades (see Pereira and Andraz, 2013; Romp and de Haan, 2007, for comprehensive surveys of the literature). Given the methodology and nature of the data used in this paper (see sections 3 and 4), I focus my review of international studies primarily on those leveraging regional panel data and a Cobb-Douglas production function. Since variations in econometric techniques have shown to influence results significantly, this approach maintains focus on the most relevant and comparable results to this study. The limited Canadian literature, however, is surveyed regardless of the methodology employed. Appendix A provides a summary table of the literature employing regional panel data and a Cobb-Douglas production function.

2.1 International

2.1.1 United States

Aschauer (1989a) sparked great debate about the relationship between public infrastructure and production. Employing Cobb-Douglas production for the 1949–1985 period, he concluded that public capital stock (net federal, state, and local capital stocks of nonmilitary equipment and structures) played an important role in explaining the U.S. productivity slowdown in the 1970s. A 1% increase in the ratio of public to private capital stock resulted in a 0.39% increase in output per unit of private capital. This estimate was also robust to different subsamples of time (elasticities range from 0.38% to 0.56%). Furthermore, he found that a 1% increase in public capital stock increased total factor productivity by 0.34-0.39%. Aschauer used capacity utilization rate in manufacturing as a control for business cycle fluctuations.

Later, Aschauer (1989b) investigated the relationship between public investment and productivity growth in G7 countries, as data deficiency prevented capital stock from being used instead. These new measures of public capital and productivity were accompanied by capacity utilization as control, and their elasticities estimated using a production function with OLS. Aschauer found that a 1% increase in public nonmilitary net investment relative to GDP (lagged one year) increases productivity growth (GDP/person employed) by 0.44%, a result that is robust to oil shocks. He also concludes that, keeping tax revenues fixed, governments can raise productivity by "altering the composition of government spending away from public consumption and toward public nonmilitary capital accumulation."

He also provided evidence against the reverse causation argument that is often posed against the use of a production function.

Munnell (1990b) set to confirm Aschauer's (1989a) results using the same Cobb-Douglas framework, albeit with larger emphasis on the various returns-to-scale assumptions that can be made. Moreover, rather than setting output relative to private capital as Aschauer did, Munnell elected to subtract labour from output to establish a measure of labour productivity as the independent variable. Capacity utilization rate in manufacturing is once again used as a control variable. She found that a 1% increase in public nonmilitary capital stock raises private nonfarm business sector output per hour (productivity) by 0.31%-0.37%. She also examines core infrastructure, which includes highways, mass transit, airports, electrical and gas facilities, water supply facilities, and sewers (two-thirds of public capital at the time), while excluding other buildings such as offices, police and fire stations, courthouses, garages, passenger terminals, as well as structures for conservation and development. For this measure of public capital stock, she finds that a 1% increase in the ratio of core infrastructure to labour hours raises productivity by 0.39%. Munnell concluded that insufficient public capital investment at the time may have slowed labour productivity growth by 0.1–0.2 percentage points.

Munnell (1990a) examined the impact of public capital stock on productivity and economic activity at the state and regional levels from 1970 to 1986. Lack of state data, however, necessitated a method to divide national data. She leveraged annual state investment data to obtain a series of state public capital stock and various measures of state activity in different private sectors. Employing a Cobb-Douglas production function and state unemployment rate as a control variable, Munnell estimated an output elasticity for public capital of 0.15%. Separating public capital into components, she also finds that majority of public capital's impact on gross state product comes from highways and water and sewer systems, while other state and local public capital (primarily consisting of buildings such as schools and hospitals) have very little effect. Combining states into four regions, Munnell find positive but varying elasticities for public capital (0.07 for the Northeast, 0.12 for the North Central, 0.36 for the South, and 0.08 for the West).

Expanding on Munnell (1990a), Eisner (1991) used the same state panel to produce different results. Munnell use observation vectors consisting of deviations from the means of public and private capital stock, labour, and output series for all states and years, thereby combining cross-section and time-series variance and covariance. Eisner, however, employs observation vectors of the "differences for each state from the mean of all its own observations"; effectively incorporating state fixed effects. In this model, Eisner finds a small, negative, and insignificant elasticity for public capital, a result that contradicts the significantly positive coefficient reported by Munnell. Under the assumption of constant returns on private inputs, the coefficient returns to positive and significant territory, which Eisner conjectures may be due to public capital proxying for private capital (with which it is correlated). When accounting for time effects instead, elasticity of public capital becomes positive, significant, and similar in magnitude to Munnell and Cook's finding (0.165). In the first-difference regression, Eisner finds statistically insignificant and slightly negative elasticities for private and public capital (-0.32 and -0.007, respectively), as well as a large and highly significant output elasticity for labour (0.831). He therefore concludes that states with more public capital in one year do not produce more during that same year. He rationalizes this conclusion through the possible lagged effect that public infrastructure has on output as well as the fact that many of the benefits derived from public capital are not included in conventional measures of output such as GDP.

Using data for the 48 contiguous states from 1969 to 1983 and a Cobb-Douglas production function, Garcia-Milà and McGuire (1992) investigate the effect of highways (measured as highway capital per square mile) and education (measured as total state and local expenditures for K-12 and post-secondary education) on gross state product. They include time dummies to control for time-specific effects and the business cycle. To account for state-differences, however, they include the population and a measure of the average industrial mix of each state instead of state dummies to preserve the long-run relationship between the factors of production. Garcia-Milà and McGuire find highly significant elasticities for all five factors, with labour featuring an unconventional output elasticity of 0.356, highways estimated at 0.045, and education reporting a large coefficient of 0.165.

Evans and Karras (1994) similarly use a 48-state panel for the 1970–1986 period while controlling for the state unemployment rate. Devoting special attention to the error structure, they adjust for first-order autocorrelation, estimating five specifications: (a) OLS on levels, (b) OLS on levels with time and state fixed effects, (c) OLS on levels with time and state fixed effects and a first-order autoregressive error term, (d) OLS on differences with time fixed effects, and (e) OLS on differences with time fixed effects and a first-order autoregressive error term. When introducing fixed effects in (b), they find that the elasticities of public capital (comprised of highways capital, water and sewers capital, and other capital) and current government services (comprised of educational services, highway services, health and hospital services, police and fire services, sewer and sanitation services) turn from significantly positive (0.096 and 0.045, respectively) to insignificant (-0.048 and 0.044). (c) returns the coefficients to statistical significance while maintaining the same signs from (b) (-0.11 and 0.064). It is worth noting that in (c) labour input is extremely large and significant (0.935) while private capital is small and insignificant (0.002). Specifications involving differences are fairly similar, with (d) and (e) estimating a very large output elasticity for labour, a negative and insignificant elasticity for public capital, and a positive and significant elasticity for government services. Even when disaggregating public capital and government services, or using data exclusively for the manufacturing industry, Evans and Karras do not find any significant and positive effect for public capital on output. The labour and private capital elasticities, which contradict their respective shares of income in all specifications, suggest that the estimates may be biased.

Holtz-Eakin (1994) reconciles the results reported in previous studies by effectively covering conceptual issues and reporting a diverse set of specifications in an effort to correct for them. Using a panel dataset of the 48 contiguous states spanning the 1969–1986 period (no control variable is used), Holtz-Eakin begins with a simple OLS estimation of the Cobb-Douglas production function including time fixed effects. As expected, this estimation yields a significant and large elasticity of 0.203 for public capital. Once state fixed effects are incorporated, the effect remains significant but turns negative (-0.0517). Imposing constant returns on private inputs has negligible effect on this elasticity. Turning to a GLS estimation in which the state effects are treated as random and time fixed effects are retained, Holtz-Eakin reports an insignificant effect of public capital when the function is both unconstrained (0.0077) and under constant returns restriction (0.0212). Finally, he estimates the function in first-difference form while retaining time fixed effects (as well as "long"-difference form). He finds the elasticity of labour to be much larger (0.911), the elasticity of private capital to be much smaller (0.106), and the elasticity of public capital to be negative and not significantly different from zero. Aggregating the state data to the regional level is not found to affect the estimates, "[...] suggesting that the use of regional data does not permit one to capture additional spillovers of any substantial magnitude" (Holtz-Eakin, 1994).

Holtz-Eakin and Schwartz (1995) focus on the spatial nature of public infrastructure by including a measure of "effective" state highway capital in the Cobb-Douglas production function. This measure essentially accounts for the likely spillover effect induced by the stock of highways in neighbouring states. Using state data from 1969 to 1986 and specifications in levels as well as long-difference form (to control for state-specific effects without damaging the long-run relationship between variables), they find spillover productivity from neighbouring highways to be negligible. Holtz-Eakin and Schwartz conclude that "spillovers among states do not appear to be at the heart of recent findings of a large productivity impact from public capital."

Using state-level data from 1970 to 1986, Baltagi and Pinnoi (1995) employ a Cobb-Douglas production function in levels and various differencing forms (unemployment rate is included as control). The pooled OLS estimation, which excludes state fixed effects, reports significant elasticities for both aggregated (0.16) and disaggregated public capital, similarly to Munnell (1990a). Once state-specific effects are implemented, the impact of aggregated public capital becomes small, negative, and insignificant (-0.03). When disaggregated by highways and streets, water and sewer facilities, and other public buildings and structures, elasticities are estimated significantly at 0.08, 0.08, and -0.11, respectively. Treating state effects as random through an FGLS estimation, Baltagi and Pinnoi find little difference in elasticities compared to those in the within estimator. Focusing on the first-difference regression, they find similar elasticities for private inputs to those in previous papers, with an insignificant and low coefficient for private capital and a large, highly significant one for labour. Output elasticity with respect to aggregated public capital, however, remains positive and significant (0.12). When disaggregated, only water and sewer facilities have a significant effect (0.05).

Garcia-Milà et al. (1996) expand on the approach taken by Holtz-Eakin (1994), systematically testing for the most appropriate Cobb-Douglas specification while using disaggregated public capital. The dataset employed spans 1970 to 1983 for the 48 contiguous states. Garcia-Milà et al. begin with an OLS specification involving only time fixed effects, finding significant and positive elasticities for highways as well as water and sewers (0.37 and 0.069, respectively), although other public capital is not significantly different from zero. Upon incorporating state-specific effects, whether they are treated as random through GLS or fixed with OLS, the coefficients on highways and water and sewers are fairly small, positive, and significant while those on other public capital are small, negative, and significant. Finding serial correlation in the data, Garcia-Milà et al. then turn to the first-difference forms of the three specifications reported for levels. They use a Hausman and Taylor as well as a Chow test to determine that, even in first-differences, the third specification with time and state fixed effects is preferred. Regardless, the elasticities for all three types of public capital assets are estimated as slightly negative and insignificant in the three specifications. As in previous studies, first-differencing causes labour to exhibit very high elasticities. While the coefficients for private capital deviate from other studies, Garcia-Milà et al. find that they resemble private capital's accepted income share.

2.1.2 Europe

De la Fuente et al. (1995) analyze data for 17 Spanish regions through three years; 1981, 1986, and 1990. They employ a Cobb-Douglas production function that exhibits constant returns on all factors, accounts for stock of human capital (measured by average schooling of employed workers) and regional land area, and includes time fixed effects. They find a statistically significant elasticity for public capital of 0.21.

Mas et al. (1996) also investigate Spanish data for 17 regions, albeit spanning a much larger period from 1964 to 1991. Employing a time trend and region fixed effects, they report unconstrained and constant returns specifications (both on private and all inputs) that estimate a significant productivity elasticity with respect to public capital of around 0.07. Separating public capital into productive stock (roads, water infrastructures, ports and urban structures) and social stock (health and education), Mas et al. find the former to be significant and positive and the latter to be insignificant and negative. They also test for the spillover effect of productive public capital by including the productive stock of neighbouring regions to each region. This specification yields a higher elasticity for productive public capital, leading the authors to accept the spillover effect hypothesis.

Picci (1999) examines 20 Italian regions from 1970 to 1995. He employs a similar method to Munnell (1990a) for apportioning national data of public investment to each region. In the Cobb-Douglas OLS specification with only time fixed effects, Picci reports a significant output elasticity for public capital of -0.248. This elasticity turns positive (0.358) with the addition of regional fixed effects, a change that contradicts previous literature from the U.S. which has largely found the inclusion of state fixed effects to diminish the magnitude and significance of public capital. Peculiarity is also observed for the private input estimates, where output elasticities of labour and private capital are 1.08 and 0.133, respectively. Under constant returns assumptions, the elasticity for public capital remains virtually the same as in the unconstrained specification. A random effects estimation reports a much lower positive elasticity (0.072), but is rejected by a Hausman test, which favours the fixed effects model. Turning to a first-difference specification that preserves time fixed effects, Picci finds a significant coefficient for public capital that is lower compared to the specifications in levels, but is still much higher than those found by U.S. studies employing first-differences.

Focusing on Germany's manufacturing sector, Stephan (2003) employs a Cobb-Douglas production function and panel data consisting of the 11 West German Bundesländer from 1970 to 1996. After testing for serial correlation, groupwise heteroskedasticity, cross-sectional correlation, and non-stationarity, he estimates various specifications (levels and first-differences) while controlling for capacity utilization. Among these specifications are first-differenced OLS with panel-corrected standard errors (PCSE), and FGLS with PCSE, region fixed effects, and an AR(1) error structure. Stephan reports very large and significant output elasticities for public capital that range from 0.385 to 0.651. Elasticities for labour (0.256–0.498) are estimated to be lower than their income share (0.55).

2.2 Canada

Adding Canada to the literature, Wylie (1996) first employs a translog production function to determine the effect of infrastructure capital stock provided by the "service sector" (represents services such as transportation, telephone systems, electric power systems, trade, finance, insurance and real estate services, schools, universities and hospitals, commercial services, and services of the federal, provincial, and municipal governments) on the Canadian goods-producing sector (defined as manufacturing, agriculture, forestry, fisheries, mines, quarries and oil wells, and construction). Second, he follows Aschauer (1989a) to estimate the effect of infrastructure stock per hour worked on real output per hour worked in the goods sector for the 1946–1991 period. Wylie incorporates a time trend as well as the unemployment rate in his Cobb-Douglas production function which he estimates using OLS. He finds a significant productivity elasticity of 0.517 with respect to total infrastructure stock per hour worked. When limiting infrastructure stock to public infrastructure, its productivity elasticity is stable and significant between 0.407 and 0.436. Both coefficients mentioned are larger than that of direct goods-sector capital stock per hour worked, which ranges between 0.244 and 0.344 depending on the infrastructure variable being analyzed. Wylie concludes that his findings support Aschauer (1989a) and Munnell (1990b).

Khanam (1996) focuses on the effect of highway infrastructure capital and output in the Canadian goods-producing sector (includes agriculture, forestry, fisheries, mines, quarries and oil wells, manufacturing, construction and other utilities) between 1961 and 1994. She begins with a discussion of the primary causes of the diverging results observed in the early literature: "The degree of aggregation, use of different estimation techniques, errors in model specification, use of different functional forms, and errors in variable measurements". Addressing the degree of aggregation, she notes the spurious correlation that can emerge from nonstationarity in national time-series data and leverages both pooled provincial data as well as first-differences to mitigate this issue. To deal with the obstacle of varying functional forms, both Cobb-Douglas and translog production functions are employed to test robustness. Following Holtz-Eakin (1994), she employs various specifications, some with time and province-specific fixed effects, to broaden the estimations. Highway and private capital stocks variables are inputted with one period lag.

Khanam finds statistically significant output elasticities with respect to highway capital stock for the GLS (no time or province effects) and OLS (with time and province effects) specifications of 0.12 and 0.14, respectively. In the first-difference form, only the OLS with no time or province effects specification offers significant output elasticity with respect to highway capital stock (0.17). The marginal product of highway capital stock derived from the Cobb-Douglas production function is similar to that of private capital stock (and thus more "sensible" and "reasonable") with the first-difference, time fixed effect as well as first-difference, time and province fixed effects specifications. Khanam also provides the output elasticities of highway capital stock across provinces, finding, with a few exception, that the elasticities have a positive and diminishing contribution to provincial goods sector output.

Harchaoui and Tarkhani (2003) estimate industry demand and cost functions for the 1961–2000 period, allowing them to decompose multifactor productivity growth, calculate the marginal benefits of public capital for each industry, and determine the effects of public capital on demand for labour, capital and intermediate inputs. The measure of aggregate public capital stock used is a chain Fisher index of engineering construction of the federal, provincial, and municipal administrations. The average cost elasticity with respect to public capital stock for the 37 industries (cover 71% of the Canadian business sector), as determined by the translog cost function, is -0.062. All industries have the expected negative sign, and the most intense users of public capital boast larger magnitudes (e.g. transportation and construction). The average output elasticity with respect to public capital (derived from the cost elasticity) is 0.066, with industries such as transportation and construction once again exhibiting the largest magnitudes. They also find that a $1 increase in the net public capital stock generates approximately 17 cents of cost-saving producer benefits per year.

Paul et al. (2004) employ a translog cost function to investigate the effect of public infrastructure on productivity in 12 Canadian manufacturing industries (cover about two-thirds of total manufacturing sector output) from 1961 to 1995. The stock of public infrastructure capital is measured as end-of-year stock of highways, airports, roads, bridges, marine facilities, pipelines, sewage and water systems. Both public and private capital stock are lagged one period to reflect beginning-of-year stock. They find that for most manufacturing industries the cost elasticities with respect to public capital stock lie between -0.1 and -0.4 and are statistically significant, indicating that public capital reduces costs.

Brox and Fader (2005) also examine the Canadian manufacturing sector for a similar time period (1961–1997), although employing a Constant Elasticity and Substitution-Translog (CES-TL) cost model. The stock of public infrastructure comes from two sources that have been combined. They find a large and statistically significant estimate for manufacturing cost elasticity with respect to public infrastructure stock of -0.476. They note that this finding is larger than the results found by Nadiri and Mamuneas (1994) who use a translog cost function with U.S. data to discover cost elasticities ranging from -0.11 to -0.21. Though not mentioned in the paper, it is also larger than the wider range of cost elasticities reported by Paul et al. (2004) for Canadian manufacturing industries within a very similar period of analysis. Brox and Fader also conclude that public capital is a substitute for private capital and that the former's services enhance the productivity of the latter.

Brox (2006) uses the same CES-TL cost model to investigate public infrastructure in the automotive sector (described as automobile assembly manufacturing industries) for the 1971–2004 period. He finds a significant cost elasticity of -0.677 with respect to public capital stock.

Macdonald (2008) employs a Cobb-Douglas production and cost functions to investigate public capital's role in productivity within Canada's business sector from 1981 to 2005. He leverages provincial panel data with the production function, and industry panel data with the cost function. Macdonald notes the lack of consensus regarding which CRTS assumption is most valid, and so elects to estimate both constant and increasing returns specifications. Only results using constant returns are reported as they fit the data more reasonably. To avoid spurious results caused by trends over time, he uses first-difference form.

Macdonald also recognizes the need to control for fixed effects and contemporaneous shocks; however, he does so differently than Khanam (1996) by employing two system estimators. The first (FGLS1) is a generalized least squares estimator that treats each province as a separate equation; however, the output elasticities with respect to the three inputs are constrained to be equal across provinces. The second estimator (FGLS2) modifies the first to account for residual serial correlation. Furthermore, MacDonald has two specifications for each of the three estimation techniques used (OLS, FGLS1, FGLS2), one with MFP and another where MFP is constrained to zero. This yields interesting results as the productivity growth elasticity with respect to growth in public capital stock is only statistically significant for specifications with MFP = 0, indicating that either the vast majority of the MFP effect can be attributed to public capital, or, much more sensibly, the impact of public capital is difficult to disentangle from overall productivity growth. MacDonald relates his findings to that of Harchaoui and Tarkhani (2003), noting that MFP growth and public capital growth were discovered to be related and that approximately 12% of MFP growth is accounted for by public capital using cost data. Evidently, with the data used in his production function, MacDonald was not able to disentangle the two. When MFP = 0, elasticities were between 0.31 and 0.41. MacDonald concludes that the inability to disentangle MFP and public capital is a data problem rather than an econometric one, and is also present in other panel data studies.

Given the issue with the production function approach, Macdonald turns his attention to a Cobb-Douglas cost function. In this function, Macdonald uses a combination of "roads and vehicles, which allows the impact of public capital to be approximated as proportional to the input share of transportation services." He finds varying cost elasticities for public infrastructure that depend on the specification and weight of the dependent variable. For the business sector, cost elasticities appear to range from -0.08 to -0.15. For the manufacturing sector, the range is -0.14 to -0.27. This range is fairly similar to that found by Nadiri and Mamuneas (1994) for U.S. manufacturing and Paul et al. (2004) for Canadian manufacturing. Macdonald recognizes that "the way public capital is measured here influences the results. Only industries that pay for transportation services, which tend to be goods-producing industries, appear to be making use of public infrastructure. Service industries also make use of public infrastructure, however, they benefit from the density of urban environments and agglomeration effects, which are not captured in transportation costs."

Much more recently, Jacques-Arvisais and Lapointe (2022) examined the relationship between transportation infrastructure, output, and productivity in Canada's business sector from 1997 to 2018. They estimate an unconstrained Cobb-Douglas production function in both levels and differences, including a time trend and the provincial unemployment rate. After testing for heteroskedasticity, serial correlation, and cross-sectional dependence, they settle for the following estimation techniques for the function in levels: (a) OLS with no province fixed effects, (b) OLS with province fixed effects, (c) FGLS, (d) Prais-Winston FGLS, (e) Prais-Winston FGLS with province-specific effects. All five estimate a small, negative, and significant output elasticity for roads infrastructure. Other transportation infrastructure has mixed effects, with (a), (c), and (d) finding a small, positive, and significant coefficients while the rest are insignificant. Marine engineering infrastructure is largely insignificant. These findings are echoed in the first-differenced specification, which turns the small and negative (positive) output elasticity with respect to roads infrastructure (other transportation infrastructure) insignificant. Using an alternative panel covering the 2009–2018 period and featuring more specific categories of transportation infrastructure (roads, railway lines, seaports, and airports), Jacques-Arvisais and Lapointe find mostly insignificant output elasticities in both level and differenced forms, confirming the results from the original dataset.

3 Framework and Estimation Methods

Similarly to the early literature, the analysis performed in this paper is based on a Cobb-Douglas production function that incorporates public infrastructure stock as an independent factor of production:

$$Y = TFP \cdot K^{\alpha_K} L^{\alpha_L} P^{\alpha_P}$$

where Y is value added, TFP is total factor productivity, , K is private capital, L is labour input, and P is public infrastructure. Log-transforming the production function yields

$$\ln(Y) = \ln(TFP) + \alpha_K \ln(K) + \alpha_L \ln(L) + \alpha_P \ln(P)$$

Thus, the following unconstrained production function can be estimated using provincial panel data:

$$\ln(Y_{it}) = \beta + \alpha_K \ln(K_{it}) + \alpha_L \ln(L_{it}) + \alpha_P \ln(P_{it}) + \alpha_{UE} \ln(UE_{it}) + \epsilon_{it}$$

where i indexes province, t indexes time, UE is the provincial unemployment rate added to control for the business cycle, and α_j represents the output elasticity with respect to factor of production j.

Proper treatment of the error term, such that the likelihood of obtaining spurious results is reduced, is thoroughly discussed in the literature (e.g. Evans and Karras, 1994; Holtz-Eakin, 1994). As noted by Beck and Katz (1995), "[panel] data often allow for temporally and spatially correlated errors, as well as for heteroskedasticity." This idea was confirmed specifically for the literature testing the *public capital hypothesis* by Kelejian and Robinson (1997). Therefore, I test for the aforementioned properties.

Autocorrelation: I first apply the test proposed by Wooldridge (2002) for first-order autocorrelation in the error term using the `xtserial` command created by Drukker (2003). The Bias-corrected Born and Breitung (2016) $Q(p)$-test is also run using the `xtqptest` command created by Wursten (2018). Both tests are significant at the 5% level and, therefore, reject the null hypothesis of no serial correlation.

Groupwise heteroskedasticity: Using the `xttest3` command, I find a highly significant modified Wald statistic for both OLS with fixed effects and FGLS estimations, indicating the presence of heteroskedasticity in both. This follows intuition as the provinces vary greatly in size, economic conditions, etc...

Cross-sectional dependence: Given that my panel data consists of $N = 10$ and $T = 23$, I run a Breusch-Pagan LM test using `xttest2` which is applicable for panels with $T > N$ (Baltagi, 2021, p. 412). The null hypothesis of cross-sectional independence is strongly rejected for all tested OLS and FGLS estimations.

Fixed Effects vs. Random Effects: Hausman and cluster-robust overidentification tests are employed using `hausman` and `xtoverid` (Schaffer & Stillman, 2016). Both indicate that a fixed effects specification is superior to one with random effects. I also run `xttest1`, which tests for random province-specific effects, autocorrelation, as well as joint random effects and autocorrelation. The p-values for all tests are well below 0.01, thus, the null hypotheses of no serial correlation and no random province effects are rejected. Similarly to Baltagi and Pinnoi (1995) and Picci (1999), the possibility that province effects are random motivates the use of FGLS estimations along with OLS.

Stationarity: I check for stationarity in the dependent and independent variables using various tests that allow for cross-sectional dependence, among them Hadri (2000) and Breitung and Das (2005). The null hypothesis of Hadri (2000) that all panels are stationary is rejected in favour of the the alternative that at least some of the panels contain unit roots. The null hypothesis that all panels contain unit roots cannot be rejected through Breitung and Das (2005). This confirms the need for estimation of the data in first-difference form as well.

Testing for the above properties has become a dependable practice in the literature employing panel data and Cobb-Douglas production functions (e.g. Jacques-Arvisais and Lapointe, 2022; Stephan, 2003). This development has not only induced the use of estimation techniques that better reflect the data, but also more exhaustive reporting of results through a range of estimation techniques. As discussed below, this study maintains that approach.

For the aggregated public infrastructure analysis in section 5.1, I employ four specifications of the Cobb-Douglas production function: unconstrained elasticities, CRTS on private inputs, CRTS on all inputs, and first-difference form.

Imposing CRTS on private inputs only implies that $\alpha_K + \alpha_L = 1$, generating the following specification:

$$\ln(Y_{it}) - \ln(L_{it}) = \beta + \alpha_K\left[\ln(K_{it}) - \ln(L_{it})\right] + \alpha_P \ln(P_{it}) + \alpha_{UE} \ln(UE_{it}) + \epsilon_{it}$$

Thus, the new dependent variable becomes productivity instead of output (output per hour worked). Under CRTS on all inputs, the constraint on the elasticities is $\alpha_K + \alpha_L + \alpha_P = 1$, resulting in

$$\ln(Y_{it}) - \ln(L_{it}) = \beta + \alpha_K\left[\ln(K_{it}) - \ln(L_{it})\right] + \alpha_P[\ln(P_{it}) - \ln(L_{it})] + \alpha_{UE} \ln(UE_{it}) + \epsilon_{it}$$

The first three specifications are in levels and estimated using the following techniques: (1) OLS with no fixed effects (FE) and Driscoll and Kraay (1998) standard errors (DKSE), (2) OLS with time FE and DKSE, (3) OLS with both time and province FE and DKSE, (4) FGLS with time FE, heteroskedastic and correlated panels, and a common AR(1) coefficient for the error term, (5) FGLS with time FE, heteroskedastic and correlated panels, and panel-specific AR(1) coefficients for the error term, (6) Prais-Winston FGLS with time FE, panel-corrected standard errors (PCSE), and a common AR(1) coefficient for the error term, and (7) Prais-Winston FGLS with time FE, panel-corrected standard errors (PCSE), and panel-specific AR(1) coefficients for the error term.

(1)–(3) are estimated using the `xtscc` command in Stata (Hoechle, 2007). This regression assumes an error structure that is heteroskedastic, autocorrelated up to some lag (in this case the default is 2), and possibly correlated between provinces. DKSE are robust to cross-sectional and temporal dependence as T becomes large. These are all appropriate corrections given the outcomes of the previous tests.

(4)–(5) are estimated using `xtgls` with the `panels(corr)` option as well as `corr(ar1)` or `corr(psar1)`. These options specify an heteroskedastic error structure with cross-sectional correlation and an AR(1) process that is either common or panel-specific. This method is feasible only when T is larger than N, as is the case here, but Beck and Katz (1995) show that the standard errors produced by this method tend to be underestimated.

To mitigate the problem above, (6)–(7) are estimated using `xtpcse`, as recommended by Beck and Katz (1995), and either the `corr(ar1)` or `corr(psar1)` options. Similarly to `xtgls`, this regression assumes a heteroskedastic error structure with cross-sectional correlation and an AR(1) process that is either common or panel-specific. The distinction lies in the Prais-Winston estimation and PCSEs.

Finally, given the results from the unit root tests, I estimate the production function in first-difference form:

$$\Delta \ln(Y) = \beta + \alpha_K \Delta \ln(K_{it}) + \alpha_L \Delta \ln(L_{it}) + \alpha_P \Delta \ln(P_{it}) + \alpha_{UE} \Delta \ln(UE_{it}) + \epsilon_{it}$$

Since first-differencing the variables effectively omits the province FE, this specification is estimated using the following: (1) OLS with DKSE, (2) OLS with DKSE and time FE, (3) OLS with heteroskedastic PCSE, (4) OLS with heteroskedastic PCSE and time FE, (5) FGLS with heteroskedastic and cross-sectionally correlated errors, and (6) FGLS with time FE as well as heteroskedastic and cross-sectionally correlated errors. AR(p) error processes were not added to (1)–(6) as first-differencing drastically mitigates autocorrelation (demonstrated by the AR(1) coefficients being very small when incorporated into the differenced estimations). While estimates for (1)–(2) are expected to be similar to (3)–(4) as both are produced using OLS and standard errors that are robust to similar panel properties, I nevertheless report both to ensure results in first-difference form are insensitive to varying estimation techniques.

4 Data

Panel data is constructed from various Statistics Canada databases. The panel covers the business sector of each province from 1998 to 2020. Statistics Canada defines the business sector as all business establishments belonging to the North American Industry Classification System (NAICS) codes 11–81, with the exception of owner occupied dwellings industry.

Real gross provincial product (chained 2012 dollars) and hours worked are obtained from Statistics Canada's productivity accounts (table: 36-10-0480-01).

Private capital stock (geometric end-year net stock, chained 2012 dollars) is extracted from the Investment and Capital Stock Statistics account within the Canadian System of Macroeconomic Accounts (table: 36-10-0096-01). Since Statistics Canada does not provide business sector estimates for fixed non-residential capital stock, private capital stock is estimated by subtracting the values of the 'non-profit institutions serving households' industry and government sector from the total of all industries. Based on the industries available in the dataset, this adjustment should yield a solid approximation of private capital owned by business establishments belonging to NAICS codes 11–81.

Public infrastructure stock (geometric end-year net stock, constant 2012 dollars) is acquired from the Infrastructure Economic Account within the Canadian System of Macroeconomic Accounts (table: 36-10-0608-01). The data allows for various disaggregations of infrastructure stock, including by purchasing industry, asset type, and asset function. I extract public infrastructure stock by specifying the public sector as the purchasing industry. This sector is comprised of the following categories: federal government (excluding health services and defense), provincial government (excluding health and educational services), municipal (excluding educational services), aboriginal, educational services, hospitals, nursing and residential care facilities, defence services, and government business enterprise. I also acquire public infrastructure stock data disaggregated by asset type and function. The classifications of each, as well as the composition of infrastructure assets by their function, are provided in Appendix B. Since estimates of public infrastructure stock are year-end, I lag them by one period such that each year possesses the monetary value of public infrastructure stock from which benefits can be derived (after accounting for the creation of new stock and the depreciation of used stock in the previous year).

Statistics Canada defines infrastructure as "the physical structures and systems that support the production of goods and services and their delivery to and consumption by governments, businesses and citizens" and notes that it "represents a set of assets that are used by other factors of production (labour and capital) in the production, distribution or consumption of goods and services" (Statistics Canada, 2018). This definition suggests that fixed non-residential capital stock and infrastructure stock (particularly when the latter is specified to be purchased by the public sector while the former belongs to the business sector) are mutually exclusive, thereby mitigating this source of measurement error.

The annual unemployment rate of each province is obtained from the Labour Force Survey (table: 14-10-0020-01).

Canada's three territories are excluded from the analysis for several reasons. First, data for 1997 and 1998 is not available. Second, the Labour Force Survey table from which the unemployment rate is extracted does not provide the rate for the territories. Third, given that Statistics Canada provides estimates in the millions for public infrastructure stock, three public infrastructure assets are reported as zero for the territories in at least some years (oil and gas engineering construction, other machinery and equipment, transportation machinery and equipment). Thus, the logarithm of several territorial observations does not exist. Fourth, the Canadian literature also excludes the territories (e.g. Jacques-Arvisais and Lapointe, 2022; Khanam, 1996); thus, this decision retains comparability. Finally, given the inherent difficulty in measuring public infrastructure, I judge that it is best to avoid the territories' data as it is likely susceptible to even greater measurement error.

Table 1: Descriptive statistics, millions of dollars or hours

Variable	Minimum	Mean	Maximum	Standard Deviation
Real Value Added	2445.9	120689.2	555370.8	140902.8
Labour Hours	80.9	2315.7	10302.3	2793.3
Private Capital	2112	133593.5	603920	149727.1
Public Infrastructure	1012	39907.2	180077	44572.1

5 Results

5.1 Aggregated Public Infrastructure Analysis

5.1.1 Unconstrained Production Function

Table 1 shows the unconstrained production function estimated without public infrastructure as an independent factor of production. The income shares of both private factors, as implied by their output elasticities, are fairly consistent through the seven estimations, with (3) being a notable exception. Kelejian and Robinson (1997) propose that high elasticities for labour input suggest that the variable "may be, at least partially, a proxy for some omitted factors". The average labour share (measured by Statistics Canada as total compensation divided by nominal value added) between 1997 and 2018 is around 58% (Statistics Canada, n.d.-a). Sharpe and Ashwell (2021) also state that the labour share has "steadily [been] around 50–60% in Canada, with the other 40–50% going to capital."

While elasticities for private capital and labour appear to be largely in-line with economic theory, it is also observed that the effect of unemployment on output is estimated to be slightly positive in columns (1)–(3). This peculiarity, however, is negligible. First, (1) and (2) do not account for province-specific effects and, therefore, provide estimates that should not be considered particularly reliable. Second, the coefficients are small and highly insignificant.

Adding public infrastructure to the production function results in some changes to table 1. As can be seen in table 2, elasticities for private capital decrease slightly (but retain their statistical significance) for all but one estimation—(3). This suggests that public infrastructure may be a substitute for private capital, or that the former is simply proxying for the latter. Elasticities for hours worked also decrease slightly with the inclusion of public infrastructure (curiously, the exceptions are (5) and (7), which are the only estimations to employ panel-specific AR(1) processes).

Time and province fixed effects are highly significant in all applicable estimations, indicating their importance. Similarly, the AR(1) coefficients in the error terms for estimations (4)-(7) are very large. For example, the common AR(1) coefficients for (5) and (7) are 0.968 and 0.957, respectively, confirming the presence of autocorrelation and the need to correct for it.

When failing to account for province-specific effects, the output elasticities with respect to public infrastructure are positive and significant at least at the 5% level. Specifically, a one percent increase in public infrastructure increases business sector output by about 0.10–0.12 percent. Once province fixed effects are included, the

Table 2: Unconstrained production function results, levels, public infrastructure omitted

	OLS			FGLS		Prais-Winston FGLS	
Real Value Added	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Private Capital	0.511***	0.509***	0.044	0.353***	0.510***	0.401***	0.424***
	(0.028)	(0.033)	(0.053)	(0.036)	(0.028)	(0.055)	(0.063)
Hours Worked	0.523***	0.528***	0.827***	0.685***	0.499***	0.621***	0.526***
	(0.029)	(0.034)	(0.101)	(0.038)	(0.031)	(0.064)	(0.075)
Unemployment Rate	0.027	0.047	0.010	-0.031**	-0.040***	-0.045**	-0.051**
	(0.032)	(0.037)	(0.036)	(0.013)	(0.011)	(0.020)	(0.020)
Constant	1.088***	0.928***	6.228***	1.666***	1.655***	1.849***	3.243***
	(0.156)	(0.209)	(1.576)	(0.332)	(0.264)	(0.406)	(0.808)
Time FE	—	✓	✓	✓	✓	✓	✓
Province FE	—	—	✓	—	—	—	—
Common AR(1)	N/A	N/A	N/A	✓	—	✓	—
Panel-Specific AR(1)	N/A	N/A	N/A	—	✓	—	✓
R^2	0.994	0.995	—	—	—	1.000	1.000
N	230	230	230	230	230	230	230

Standard errors in parentheses. (In)dependent variables are in logarithmic form.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

elasticity becomes negative and insignificant. When employing random effects through FGLS estimations, the coefficients remain insignificant but turn small and positive. Thus, the output elasticities with respect to public infrastructure estimated here follow a similar development to that found in the literature (e.g. Baltagi & Pinnoi, 1995; Evans & Karras, 1994; Holtz-Eakin, 1994). Overall, the statistically insignificant estimates for public infrastructure in columns (3)–(7) suggest that it has minimal impact on business sector output within the Cobb-Douglas production function framework.

Appendix C provides the same estimations as table 2 while omitting the unemployment rate. Results are robust to the exclusion of unemployment rate as a control variable.

Table 3: Unconstrained production function results, levels, aggregated public infrastructure

	OLS			FGLS		Prais-Winston FGLS	
Real Value Added	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Private	0.481***	0.478***	0.097*	0.323***	0.472***	0.386***	0.411***
Capital	(0.028)	(0.030)	(0.056)	(0.039)	(0.023)	(0.054)	(0.054)
Hours	0.455***	0.438***	0.808***	0.650***	0.534***	0.601***	0.559***
Worked	(0.040)	(0.064)	(0.086)	(0.048)	(0.037)	(0.088)	(0.091)
Public	0.101***	0.123**	-0.115	0.070	0.025	0.038	0.014
Infrastructure	(0.018)	(0.044)	(0.080)	(0.047)	(0.039)	(0.086)	(0.090)
Unemployment	0.018	0.039	0.025	-0.033**	-0.041***	-0.047**	-0.052**
Rate	(0.031)	(0.037)	(0.034)	(0.014)	(0.010)	(0.021)	(0.021)
Constant	0.903***	0.667**	7.976***	1.506***	1.313***	1.755***	2.589***
	(0.185)	(0.313)	(2.316)	(0.375)	(0.230)	(0.438)	(0.735)
Time FE	—	✓	✓	✓	✓	✓	✓
Province FE	—	—	✓	—	—	—	—
Common AR(1)	N/A	N/A	N/A	✓	—	✓	—
Panel-Specific AR(1)	N/A	N/A	N/A	—	✓	—	✓
R^2	0.994	0.995	—	—	—	1.000	1.000
N	230	230	230	230	230	230	230

Standard errors in parentheses. (In)dependent variables are in logarithmic form.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

5.1.2 CRTS Production Function

This section presents regression results under both constant returns on all inputs and constant returns on private inputs assumptions.

Both tables 3 and 4 maintain the narrative that public infrastructure has little to no effect on productivity. The only exceptions to this claim are estimations (4) and (5) in table 3, which produce significant productivity elasticities for public infrastructure (0.044 and 0.025). However, since the elasticities are small, and their significance is not supported by the more conservative Prais-Winston estimations, I do not consider this a significant deviation from the overall message. My findings under CRTS assumptions are similar to Holtz-Eakin (1994) in that they do not change much from the unconstrained form.

Table 4: CRTS on private inputs production function results, levels, aggregated public infrastructure

	OLS			FGLS		Prais-Winston FGLS	
Output per Hour Worked	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Private Capital Per Hour Worked	0.500*** (0.030)	0.499*** (0.035)	0.099 (0.059)	0.338*** (0.036)	0.483*** (0.024)	0.395*** (0.055)	0.438*** (0.065)
Public Infrastructure	0.038*** (0.002)	0.040*** (0.003)	-0.128 (0.086)	0.044*** (0.015)	0.025** (0.011)	0.025 (0.019)	-0.024 (0.035)
Unemployment Rate	0.029 (0.032)	0.050 (0.040)	0.031 (0.034)	-0.033** (0.013)	-0.038*** (0.010)	-0.047** (0.020)	-0.046** (0.020)
Constant	0.946*** (0.164)	0.770*** (0.248)	6.296*** (1.876)	1.483*** (0.352)	1.348*** (0.255)	1.740*** (0.426)	2.703*** (0.853)
Time FE	—	✓	✓	✓	✓	✓	✓
Province FE	—	—	✓	—	—	—	—
Common AR(1)	N/A	N/A	N/A	✓	—	✓	—
Panel-Specific AR(1)	N/A	N/A	N/A	—	✓	—	✓
R^2	0.867	0.877	—	—	—	0.981	0.989
N	230	230	230	230	230	230	230

Standard errors in parentheses. (In)dependent variables are in logarithmic form.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: CRTS on all inputs production function results, levels, aggregated public infrastructure

	OLS			FGLS		Prais-Winston FGLS	
Output per Hour Worked	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Private Capital	0.482***	0.480***	0.063	0.362***	0.482***	0.392***	0.435***
Per Hour Worked	(0.027)	(0.028)	(0.053)	(0.037)	(0.025)	(0.052)	(0.048)
Public Infrastructure	0.087***	0.098**	-0.058	0.003	0.005	0.023	0.032
Per Hour Worked	(0.017)	(0.042)	(0.061)	(0.043)	(0.039)	(0.085)	(0.091)
Unemployment	-0.050	-0.040	0.026	-0.029**	-0.051***	-0.051**	-0.061***
Rate	(0.034)	(0.038)	(0.037)	(0.012)	(0.011)	(0.021)	(0.021)
Constant	1.825***	1.715***	3.605***	2.408***	1.992***	2.288***	2.151***
	(0.183)	(0.267)	(0.148)	(0.140)	(0.113)	(0.247)	(0.242)
Time FE	—	✓	✓	✓	✓	✓	✓
Province FE	—	—	✓	—	—	—	—
Common AR(1)	N/A	N/A	N/A	✓	—	✓	—
Panel-Specific AR(1)	N/A	N/A	N/A	—	✓	—	✓
R^2	0.850	0.858	—	—	—	0.980	0.989
N	230	230	230	230	230	230	230

Standard errors in parentheses. (In)dependent variables are in logarithmic form.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

5.1.3 First-Difference Form

Turning to the first-difference form of the production function, table 5 presents estimates that once again indicate little to no impact of public infrastructure on private output. While all the elasticities for public infrastructure have turned negative, they remain small-to-moderate in magnitude and statistically insignificant from zero. The exception is estimation (5), which does not include time fixed effects and suggests that a one percent increase in public infrastructure decreases output by 0.11 percent. While the vast majority of time fixed effects are insignificant for (2) and (4), they are highly significant in (6), suggesting that the standout negative and significant elasticity reported in (5) may be attributed to the omission of time fixed effects.

These minor changes to the elasticities align with the literature, which has largely found output elasticities with respect to public capital to decrease in magnitude, turn negative, and/or lose their statistical significance once first-differences are used (e.g. Baltagi & Pinnoi, 1995; Evans & Karras, 1994; Garcia-Milà et al., 1996; Holtz-Eakin, 1994). The changes in the elasticities of private inputs, namely private capital becoming small and insignificant while labour input retains its high significance, are also in-line with the literature. Unlike private capital, the unemployment rate demonstrates much more sensible behaviour in the first-difference form, exhibiting a negative and significant coefficient in all estimations. While it may tempting to interpret this as an indication that first-difference form is the more appropriate specification, the literature also notes some of its weaknesses, such as potentially eliminating the long-run relationship between the variables.

Table 6: First-difference production function results, levels, aggregated public infrastructure

	OLS				FGLS	
Real Value Added	(1)	(2)	(3)	(4)	(5)	(6)
Private Capital	0.064 (0.078)	0.074 (0.085)	0.064 (0.097)	0.074 (0.092)	0.074 (0.049)	0.057 (0.053)
Hours Worked	0.388*** (0.072)	0.385*** (0.104)	0.388*** (0.096)	0.385*** (0.122)	0.407*** (0.046)	0.402*** (0.061)
Public Infrastructure	-0.138 (0.081)	-0.069 (0.078)	-0.138 (0.101)	-0.069 (0.111)	-0.108** (0.043)	-0.012 (0.054)
Unemployment Rate	-0.080*** (0.019)	-0.046** (0.017)	-0.080*** (0.020)	-0.046** (0.019)	-0.054*** (0.009)	-0.032*** (0.011)
Constant	0.019*** (0.004)	0.012 (0.014)	0.019*** (0.004)	0.036*** (0.008)	0.018*** (0.002)	0.037*** (0.002)
Time FE	—	✓	—	✓	—	✓
R^2	0.454	0.586	0.454	0.586	—	—
N	220	220	220	220	220	220

Standard errors in parentheses. (In)dependent variables are in logarithmic form and differenced.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

5.2 Disaggregated Public Infrastructure Analysis

The next three subsections summarize the noteworthy findings from my disaggregated analysis; however, I reserve my discussion of the results to the fourth subsection. Under the production function framework, results must already be interpreted with caution (see Section 6 for elaboration), but this theme becomes even more important when attempting to interpret the elasticities for disaggregated measures of public infrastructure.

5.2.1 Public Infrastructure Stock by Asset Type

I begin my analysis of disaggregated public infrastructure with asset types. As a balanced panel is required for some of the estimation techniques employed in this paper, oil and gas engineering construction assets were omitted from the analysis in this subsection because there are many zeroes in the series for Prince Edward Island, Newfoundland and Labrador, and New Brunswick.

Similarly to tables 1 and 2, output elasticities for private capital and labour accurately reflect their factors' respective income share in the FGLS estimations. With regards to output elasticities of public infrastructure assets, institutional buildings, communications networks, and arguably waterworks infrastructure have at least moderately robust, positive estimates, although none are estimated precisely in the OLS estimation with time and province FE. Moreover, the significant elasticities for communications networks and waterworks infrastructure are small, ranging from 0.01 to 0.06. Institutional buildings, which consist of educational institutions and hospitals (among other buildings) showcase more noteworthy elasticities between 0.12 and 0.16. Commercial buildings and transportation machinery and equipment, on the other hand, show robust, negative coefficients between -0.03 and -0.05. It should be noted that the relevant elasticities for commercial buildings tend to only be significant at the 10% level.

Appendix D presents the results for the first-difference specification. Essentially all public infrastructure assets have an effect on business sector output that is insignificant from zero. The only exception is transportation machinery and equipment which possesses a small, negative elasticity that is robust to all estimations.

Table 7: Unconstrained production function results, levels, public infrastructure by asset

	OLS			FGLS		Prais-Winston FGLS	
Real Value Added	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Private Capital	0.502***	0.485***	0.121**	0.411***	0.401***	0.438***	0.421***
	(0.027)	(0.018)	(0.045)	(0.021)	(0.018)	(0.028)	(0.029)
Hours Worked	0.388***	0.386***	0.639***	0.540***	0.516***	0.521***	0.520***
	(0.036)	(0.047)	(0.074)	(0.052)	(0.043)	(0.080)	(0.079)
Commercial Buildings	-0.081***	-0.130***	-0.048*	-0.045**	-0.010	-0.053*	-0.022
	(0.020)	(0.024)	(0.028)	(0.019)	(0.016)	(0.030)	(0.030)
Institutional Buildings	0.364***	0.303***	-0.040	0.158***	0.152***	0.144**	0.124**
	(0.027)	(0.047)	(0.058)	(0.045)	(0.036)	(0.068)	(0.061)
Marine Engineering	0.123***	0.147***	-0.014	0.036*	0.021	0.077***	0.049*
	(0.021)	(0.024)	(0.028)	(0.022)	(0.016)	(0.030)	(0.028)
Transportation Engineering	0.205***	0.119*	0.009	-0.022	-0.024	0.009	-0.025
	(0.048)	(0.069)	(0.109)	(0.032)	(0.024)	(0.052)	(0.050)
Waterworks Infrastructure	0.013	0.049*	-0.006	0.049***	0.062***	0.045*	0.064***
	(0.023)	(0.026)	(0.020)	(0.016)	(0.014)	(0.025)	(0.023)
Sewage Infrastructure	-0.281***	-0.175***	-0.024	-0.057	-0.092***	-0.076	-0.079
	(0.028)	(0.040)	(0.066)	(0.040)	(0.031)	(0.063)	(0.059)
Communications Networks	0.056***	0.062***	0.020	0.022***	0.018***	0.032***	0.023***
	(0.012)	(0.007)	(0.012)	(0.006)	(0.004)	(0.008)	(0.008)
Electric Power	-0.008	-0.025***	-0.026***	-0.010*	-0.007	-0.012	-0.009
	(0.008)	(0.008)	(0.006)	(0.005)	(0.005)	(0.008)	(0.008)
Other Engineering Construction	-0.114***	-0.047	-0.029	0.006	0.019	-0.016	0.001
	(0.037)	(0.035)	(0.022)	(0.018)	(0.012)	(0.026)	(0.023)
Other Machinery and Equipment	0.041***	0.041***	-0.012	0.013**	0.007	0.022***	0.013
	(0.008)	(0.005)	(0.010)	(0.005)	(0.005)	(0.008)	(0.008)
Transportation Mach. and equipment	-0.046***	-0.058***	-0.053***	-0.030***	-0.030***	-0.044***	-0.038***
	(0.010)	(0.008)	(0.009)	(0.009)	(0.006)	(0.013)	(0.012)
Unemployment Rate	-0.062***	-0.056**	-0.013	-0.042**	-0.059***	-0.045*	-0.061***
	(0.022)	(0.026)	(0.034)	(0.016)	(0.012)	(0.023)	(0.022)
Constant	-2.093***	-1.753***	12.697***	0.629*	1.573***	0.180	1.282***
	(0.323)	(0.392)	(3.076)	(0.332)	(0.286)	(0.447)	(0.460)
Time FE	—	✓	✓	✓	✓	✓	✓
Province FE	—	—	✓	—	—	—	—
Common AR(1)	N/A	N/A	N/A	✓	—	✓	—
Panel-Specific AR(1)	N/A	N/A	N/A	—	✓	—	✓
R^2	0.998	0.999	—	—	—	1.000	1.000
N	230	230	230	230	230	230	230

Standard errors in parentheses. (In)dependent variables are in logarithmic form.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

5.2.2 Public Infrastructure Stock by Asset Function

Next, I analyze the impact of public infrastructure by asset function. The output elasticities for private capital are lower than expected, while those for hours worked are higher. These under-and-over-estimations of income shares suggest the results are biased. Moreover, the coefficients for the unemployment rate exhibit very odd behaviour that does not match previous findings. For estimations (1) and (2) the elasticities for unemployment are not only positive, but large and highly significant. Additionally, previous tables have shown that FGLS estimations tend to produce negative and significant coefficients, as would be expected, but in table 7 they are mostly insignificant. Given these factors, the results in table 7 should be interpreted with additional caution.

Health and housing exhibit very robust and positive output elasticities, suggesting these functions drive the positive contributions from public infrastructure to business sector output within the production function framework. On the other hand, public transit, environmental protection, and public order functions are estimated to have a negative effect on output.

Appendix E presents the results for the first-difference specification. Similarly to the analysis by asset type, essentially all infrastructure functions are estimated to have elasticities that are insignificant from zero with only one exception—public transit equipment.

Table 8: Unconstrained production function results, levels, public infrastructure by function

	OLS			FGLS		Prais-Winston FGLS	
Real Value Added	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Private Capital	0.462*** (0.027)	0.455*** (0.018)	0.153*** (0.054)	0.371*** (0.022)	0.353*** (0.017)	0.376*** (0.025)	0.358*** (0.023)
Hours Worked	0.859*** (0.049)	0.882*** (0.067)	0.753*** (0.056)	0.660*** (0.047)	0.732*** (0.045)	0.721*** (0.082)	0.762*** (0.078)
Health	0.240*** (0.016)	0.242*** (0.020)	0.034 (0.035)	0.105*** (0.024)	0.098*** (0.020)	0.128*** (0.038)	0.091*** (0.035)
Education	-0.150*** (0.045)	-0.213*** (0.063)	-0.162** (0.070)	0.035 (0.047)	-0.024 (0.044)	-0.050 (0.070)	-0.067 (0.069)
Fuel and Energy	0.002 (0.005)	-0.009 (0.006)	-0.026*** (0.008)	-0.008 (0.006)	0.001 (0.004)	-0.003 (0.008)	-0.003 (0.007)
Housing and Community Amenities	0.104*** (0.016)	0.140*** (0.026)	0.041** (0.019)	0.057*** (0.018)	0.076*** (0.013)	0.086*** (0.023)	0.097*** (0.021)
Transport	-0.094*** (0.032)	-0.119** (0.055)	0.002 (0.095)	-0.025 (0.025)	-0.027 (0.029)	-0.045 (0.050)	-0.036 (0.057)
Public Transit Equipment	-0.024* (0.012)	-0.021 (0.014)	-0.029*** (0.008)	-0.034*** (0.009)	-0.032*** (0.006)	-0.032*** (0.011)	-0.031*** (0.011)
Environmental Protection	-0.349*** (0.032)	-0.276*** (0.049)	-0.012 (0.064)	-0.095** (0.041)	-0.107*** (0.032)	-0.136** (0.063)	-0.116** (0.054)
Communication	0.025*** (0.008)	0.031*** (0.006)	-0.001 (0.009)	0.014*** (0.005)	0.004 (0.004)	0.018** (0.007)	0.010 (0.007)
Recreation, Culture and Religion	0.013 (0.035)	-0.012 (0.027)	-0.095*** (0.022)	0.012 (0.026)	0.030 (0.020)	0.030 (0.034)	0.040 (0.035)
Public Order and Safety	-0.035* (0.018)	-0.044*** (0.015)	-0.078** (0.028)	-0.041*** (0.013)	-0.081*** (0.009)	-0.060*** (0.015)	-0.090*** (0.014)
Unemployment Rate	0.147*** (0.016)	0.192*** (0.029)	0.040 (0.037)	-0.036** (0.014)	-0.014 (0.013)	0.004 (0.024)	-0.006 (0.023)
Constant	1.027*** (0.324)	0.941*** (0.271)	11.695*** (2.242)	1.279*** (0.256)	1.898*** (0.225)	1.684*** (0.369)	2.098*** (0.401)
Time FE	—	✓	✓	✓	✓	✓	✓
Province FE	—	—	✓	—	—	—	—
Common AR(1)	N/A	N/A	N/A	✓	—	✓	—
Panel-Specific AR(1)	N/A	N/A	N/A	—	✓	—	✓
R^2	0.998	0.998	—	—	—	1.000	1.000
N	230	230	230	230	230	230	230

Standard errors in parentheses. (In)dependent variables are in logarithmic form.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

5.2.3 Core vs. Non-Core Public Infrastructure

Following studies such as Munnell (1990b), Mas et al. (1996), and Picci (1999), I also estimate the elasticities of public infrastructure by core and non-core functions. I define core infrastructure as the sum of stock classified under the following functions: Fuel and energy, transport, housing (as it is comprised of waterworks assets), environmental protection, and communication. All other functions are considered non-core. The results in table 8 are striking. Core infrastructure is estimated to have output elasticities that are insignificant from zero using all estimation techniques, while non-core infrastructure is highly significant and positive. This finding contradicts Picci (1999) and Mas et al. (1996). Non-core infrastructure supposedly being more productive than its core counterpart may be driven by the inclusion of environmental protection in the latter as well as the exclusion of health infrastructure. Health is one of the few functions with a significant and positive effect individually, and environmental protection has a robust, negative effect, as shown in table 7.

Appendix F provides the results for the first-difference specification, in which both core and non-core public infrastructure are reported as having insignificant elasticities. An asset-based definition of core infrastructure was also estimated: the sum of marine engineering, transportation engineering, waterworks, sewage, communications networks, electric power, and oil and gas. As expected, this definition yields similar results to the definition by asset function and is therefore not reported.

5.2.4 Discussion

Several papers have disaggregated public infrastructure by asset type in the past, but never to the extent presented in this section, where as many as 11 infrastructure assets are estimated within the same equation. Majority of assets and functions have been found to be statistically insignificant in levels, while essentially all can be considered insignificant when estimated in first-differences.

Researchers employing disaggregated measures of public capital have offered various explanations for the insignificance or even negative effect exhibited by some types of infrastructure on output within the production function framework. For example, when discussing their insignificant elasticity for public buildings, such as schools and hospitals, Munnell (1990a) states the following:

> The results suggest that the stock of buildings devoted to, say, education may not be the best indicator of the quality of educational services; teachers' salaries, for example, might be a measure. Moreover, even if physical capital were a good measure of service quality, in a highly mobile society the state that provides the educational or health services

Table 9: Unconstrained production function results, levels, core vs. non-core infrastructure, function definition

	OLS			FGLS		Prais-Winston FGLS	
Real Value Added	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Private Capital	0.448***	0.427***	0.067	0.371***	0.467***	0.396***	0.446***
	(0.026)	(0.030)	(0.075)	(0.030)	(0.024)	(0.045)	(0.047)
Hours Worked	0.358***	0.257***	0.854***	0.554***	0.479***	0.511***	0.454***
	(0.038)	(0.077)	(0.098)	(0.045)	(0.038)	(0.082)	(0.083)
Core Public Infrastructure	-0.005	0.006	-0.041	-0.013	-0.034	-0.016	-0.046
	(0.018)	(0.023)	(0.064)	(0.028)	(0.029)	(0.059)	(0.069)
Non-core Public Infrastructure	0.238***	0.357***	-0.095	0.124***	0.130***	0.136*	0.155**
	(0.021)	(0.060)	(0.065)	(0.040)	(0.035)	(0.076)	(0.072)
Unemployment Rate	0.035	0.066	0.029	-0.035***	-0.041***	-0.051**	-0.059***
	(0.031)	(0.043)	(0.035)	(0.011)	(0.010)	(0.021)	(0.020)
Constant	0.764***	0.347	8.124***	1.474***	1.030***	1.558***	1.797***
	(0.184)	(0.338)	(2.266)	(0.236)	(0.239)	(0.310)	(0.507)
Time FE	—	✓	✓	✓	✓	✓	✓
Province FE	—	—	✓	—	—	—	—
Common AR(1)	N/A	N/A	N/A	✓	—	✓	—
Panel-Specific AR(1)	N/A	N/A	N/A	—	✓	—	✓
R^2	0.995	0.995	—	—	—	1.000	1.000
N	230	230	230	230	230	230	230

Standard errors in parentheses. (In)dependent variables are in logarithmic form.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

may not be the one that reaps the benefits.

The claim that monetary measures of public infrastructure assets do not fully reflect said assets' impact on a aggregated productivity is certainly reasonable, and helps explains to at least some degree any counter-intuitive findings derived from the production function approach.

Building on the aforementioned notion, the benefits obtained from many infrastructure assets may also not be accounted for in the measure of value added. For instance, Gramlich (1994) notes that "many of the benefits of highway investment will involve the time saving of private individuals, which will generally not be reflected in national output." He also asserts that the capital stock representing education buildings and hospitals "should not have much short term impact on the supply of aggregate output as it is now measured". Garcia-Milà and McGuire (1992), who focus on the effects of highways and education on productivity, also touch on this issue. They propose that while it is possible that other public capital and services are productive, their impact may not be as direct, meaning estimates of 'secondary' infrastructure assets are unreliable at best, or misleading at worst.

Separating public infrastructure into its core and non-core components is designed to show a more reliable estimate of the effect of infrastructure on productivity. This study, unlike previous ones, finds no evidence that core infrastructure is indeed productive. In fact, my service-oriented measure of non-core infrastructure is found to have a significant and positive effect in levels, though this peculiarity disappears in the first-difference specification.

All in all, while some findings may suggest that some asset types and functions have an insignificant or even negative effect on business sector output, they are likely induced by the nature of the production function framework and the data, which poses a significant challenge towards capturing the true effects. This effectively feeds into my conclusion.

6 Conclusion

This paper evaluates the effect of public infrastructure on Canadian business sector output during the 1998–2020 period. Various specifications of the Cobb-Douglas production function are estimated while correcting for heteroskedasticity, autocorrelation, and cross-sectional dependence. The relationship between public infrastructure and productivity has been found to be predominantly insignificant from zero. There is, however, a significant caveat that must be taken into account when using the Cobb-Douglas production function to estimate the impact of public infrastructure. This caveat, as touched on in the introduction of this paper, has been discussed in several papers employing the same methodology:

> It would be wrong to conclude from this analysis that the large stock of public capital provides no benefits. The regression analysis indicates only that the productivity benefits in excess of direct provision of amenities are negligible. [...] Instead, the main message is that the use of aggregate data do not reveal sufficiently large linkages between public sector capital and private production activities to support the contention that government capital spillovers are the source of economy-wide variations in private productivity. (Holtz-Eakin, 1994)
>
> The conclusion that public capital does not contribute to private output is obtained here within a very narrow framework [...] It is clear

> that this approach does not exhaust all possible methods for examining the linkage between public infrastructure and productivity. [...] we have not demonstrated that public infrastructure is unproductive. Instead, we have found that within the aggregate production function framework, there is no evidence of a positive linkage between public capital and private output. (Garcia-Milà et al., 1996)

> After all, government roads as such do not produce anything, and to include infrastructure or public capital as a separate input in a production function neglects the usually complex links. (Romp & Haan, 2007)

The underlying theme is that while the simple production function may be capable of providing rough estimates of the contributions of public infrastructure towards private sector productivity, its aggregated nature, and the extensive set of assumptions that should be satisfied to justify its use, largely prevent its results from having policy implications. Even under ideal econometric conditions, it can only deliver results convincingly with robust and statistically significant estimates—a requirement that has not been met in this study.

The widespread statistical insignificance found in this paper emphasizes the need for micro-oriented cost-benefit analysis of new infrastructure projects. Spillover effects, province-specific needs, and many other factors must be taken into consideration before making investment decisions. The aggregated framework of the production function, and the data that it entails, mean the model can never fully take these factors into account, regardless of how many econometric tools are deployed to accommodate its use. An alternative approach to the production function that accommodates aggregated data is the VAR model, which does not impose any assumptions on the direction of causality between public infrastructure and value added, and takes lagged values into account. A disadvantage of this methodology, however, is its atheoretical nature making its results difficult to verify and compare.

The availability of recent and disaggregated data warranted an update to the Canadian literature on the public capital hypothesis. Revisiting the standard production function approach allowed the findings of this paper to be compared to literature that extends back over three decades. Ultimately, my findings resembled those in the more recent literature by failing to show a linkage between public infrastructure and private output/productivity.

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A Literature Review Summary

Table A1: Summary of the literature employing regional panel data and a Cobb-Douglas production function

				Public Capital Elasticities			
Paper	Region	Period	Measure of Public Capital	OLS (No FE)†	OLS (FE)	GLS	First-Difference
Munnell (1990a)	US, 48 states	1970–1986	Aggregated	0.06*–0.15*	—	—	—
			Highways & streets	0.06*			
			Water & sewers	0.12*			
			Other	0.01			
Eisner (1991)	Munnell (1990a)		Aggregated	-0.026–0.165*	—	—	-0.007–0.305*
			Highways & streets	0.064*–0.077*			
			Water & sewers	0.079*–0.116*			
			Other	-0.115*–0.011			
Garcia-Milà and McGuire (1992)	US, 48 states	1969–1983	Highways	—	0.044–0.045*	—	—
			Education		0.072*–0.165*		
Evans and Karras (1994)	US, 48 states	1970–1986	Aggregated capital	0.096*	-0.110*–-0.048		-0.063–-0.029
			Highway capital				-0.062
			Water and sewer capital				0.011
			Other capital				-0.061*
			Aggregated services	0.045*	0.044–0.064*		0.035*–0.064*
			Educational services				0.057*
			Highway services				0.03
			Health & hospital services				0.009
			Police & fire services				-0.007
			Sewer & sanitation services				0.004
Holtz-Eakin (1994)	US, 48 states	1969–1986	Aggregated government capital	0.203*	-0.056*–-0.052*	0.008*–0.021*	-0.102
Baltagi and Pinnoi (1995)	US, 48 states	1970–1986	Aggregated	-0.03–0.39*	—	0.004	0.12*
			Highways & streets	0.06*–0.16*		0.06*	0.07
			Water & sewers	0.08*–0.19*		0.08*	0.05*
			Other	-0.11*–0.09		-0.098*	0.01

* Indicates statistical significance at the 5% level.

† Includes specifications with only time or region fixed effects.

Paper	Region	Period	Measure of Public Capital	Public Capital Elasticities			
				OLS (No FE)†	OLS (FE)	GLS	First-Difference
Garcia-Milà et al. (1996)	US, 48 states	1970–1983	Highways	0.37*	0.127*	0.12*	-0.058–-0.007
			Water & sewers	0.069*	0.064*	0.043*	-0.029–-0.002
			Other	-0.01	-0.071*	-0.048*	-0.056–-0.022
De la Fuente et al. (1995)	Spain, 17 regions	1981, 1986, 1990	Aggregated	—	0.21*	—	—
Mas et al. (1996)	Spain, 17 regions	1964–1991	Aggregated	—	0.065*–0.071*	—	—
			"Productive"		0.083*–0.063*		
			"Social"		-0.025–-0.021		
Picci (1999)	Italy, 20 regions	1970–1995	Aggregated	-0.248*	0.358*	0.072*	0.184*
			Core		0.501*		
			Non-core		-0.052*		
Stephan (2003)	Germany, 11 regions	1970–1996	Aggregated	—	0.651*	0.385*–0.547*	
Khanam (1996)	Canada, 10 provinces	1961–1994	Highways	0.1	0.14	0.12	0.09–0.17*
Macdonald (2008)	Canada, 10 provinces	1981–2005	Aggregated	—	—	—	-0.06–0.02
Jacques-Arvisais and Lapointe (2022)	Canada, 10 provinces	1997–2018	Roads	-0.201*	-0.082	-0.064–-0.086	-0.074–-0.027
			Other transport	0.101*	-0.003	0.04–0.053*	0.027–0.032
			Marine	-0.025*	-0.025	-0.044–0.02	-0.039–-0.008

* Indicates statistical significance at the 5% level.

† Includes specifications with only time or region fixed effects.

B Infrastructure Asset Types and Functions

Table B1: Classifications of Infrastructure Asset Types

Commercial Buildings	• Sports facilities with spectator capacity • Indoor recreational facilities • Student residences • Airports and other passenger terminal • Communications building
Institutional buildings	• Schools, colleges, universities and other educational buildings • Hospitals • Nursing homes, homes for the aged • Religious centres and memorial sites • Museums • Historical sites • Libraries • Public security facilities
Marine engineering infrastructure	• Seaports • Marinas and harbours • Canals and waterways • Other marine infrastructure
Transportation engineering infrastructure	• Highway and road structures and networks • Bridges • Tunnels • Railway lines • Runways
Waterworks infrastructure	• Water filtration plants • Other water infrastructure
Sewage infrastructure	• Sewage treatment plants • Other sewage infrastructure
Communications networks	• Cables and lines (except optical fibre) • Optical fibre cables • Transmission support structures • Other communication construction infrastructure
Electric power infrastructure	• Wind and solar power plants • Steam production plants • Nuclear production plants • Hydraulic production plants • Power transmission networks • Power distribution networks • Other electric power construction
Oil and gas engineering construction	• Pipelines

Other engineering construction	• Waste disposal facilities • Outdoor recreational facilities • Pollution abatement and control
Other machinery and equipment	• Turbines, turbine generators, and turbine generator sets • Nuclear reactor steam supply systems • Water treatment equipment • Power and distribution transformers
Transportation machinery and equipment	• Buses • Locomotives, railway rolling stock, and rapid transit equipment

Source: Statistics Canada, n.d.-b

Table B2: Classifications of Infrastructure Asset Functions

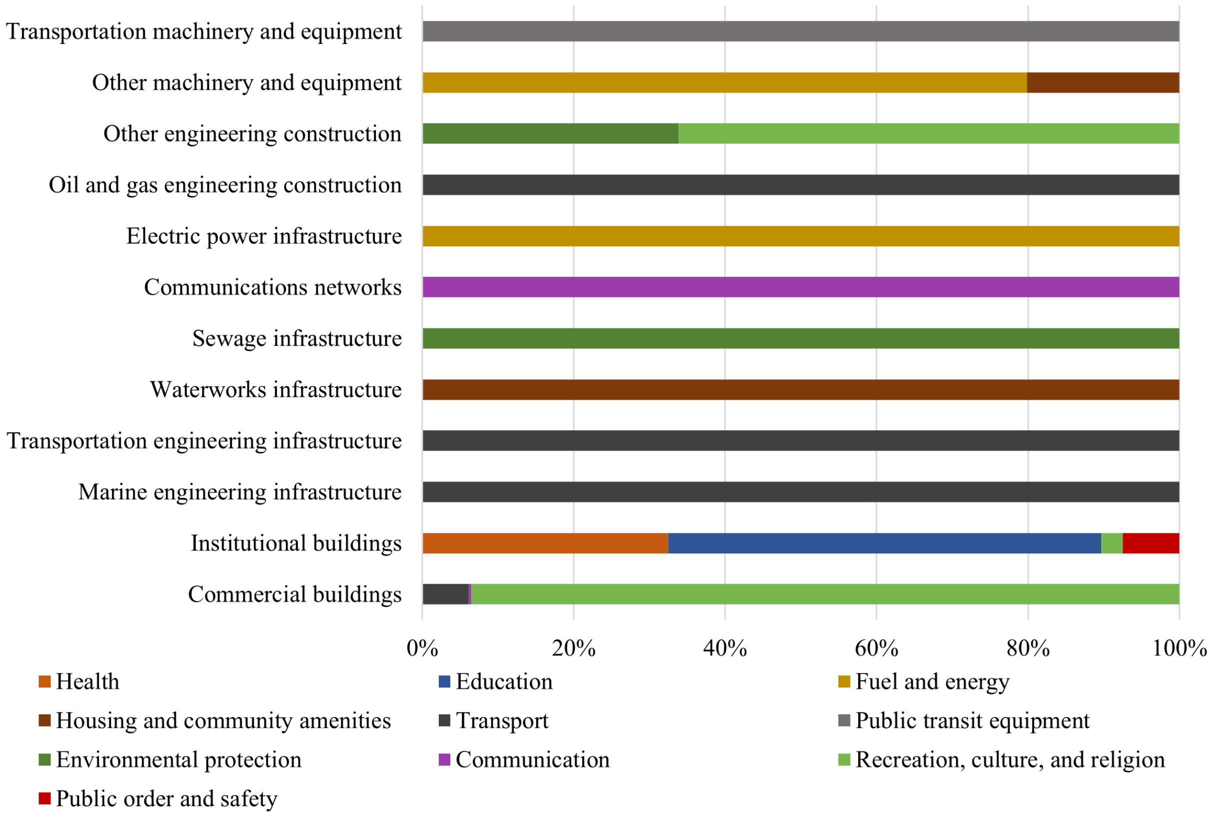
Health	• Medical products, appliances and equipment • Outpatient services • Hospital services • Public health services • R&D health • Health n.e.c.
Education	• Pre-primary and primary education • Secondary education • Post-secondary non-tertiary education • Tertiary education • Education not definable by level • Subsidiary services to education • R&D education • Education n.e.c
Fuel and energy	• N/A
Housing and community amenities	• Housing development • Community development • Water supply • Street lighting • R&D housing and community amenities • Housing and community amenities n.e.c.
Transport	• N/A
Public transit equipment	• N/A

Environmental protection	• Waste management • Waste water management • Pollution abatement • Protection of biodiversity and landscape • R&D environmental protection • Environmental protection n.e.c
Communication	• N/A
Recreation, culture, and religion	• Recreational and sporting services • Cultural services • Broadcasting and publishing services • Religious and other community services • R&D recreation, culture and religion • Recreation, culture and religion n.e.c.
Public order and safety	• Police services • Fire-protection services • Law courts • Prisons • R&D public order and safety • Public order and safety n.e.c.

n.e.c.: "not elsewhere classified"

Source: OECD, 2021

Figure B1: Composition of infrastructure assets by their functions



C Aggregated Specification Without Unemployment Rate

Table C1: Unconstrained production function results, levels, unemployment rate omitted

	OLS			FGLS		Prais-Winston FGLS	
Real Value Added	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Private Capital	0.478***	0.473***	0.102*	0.314***	0.444***	0.372***	0.397***
	(0.026)	(0.025)	(0.051)	(0.038)	(0.026)	(0.060)	(0.059)
Hours Worked	0.452***	0.433***	0.791***	0.679***	0.555***	0.641***	0.598***
	(0.041)	(0.066)	(0.076)	(0.042)	(0.035)	(0.086)	(0.087)
Public Infrastructure	0.103***	0.128**	-0.104	0.054	0.028	0.016	-0.012
	(0.020)	(0.047)	(0.077)	(0.044)	(0.037)	(0.085)	(0.088)
Constant	0.990***	0.859***	7.989***	1.410***	1.407***	1.669***	2.668***
	(0.085)	(0.136)	(2.317)	(0.400)	(0.266)	(0.499)	(0.818)
Time FE	—	✓	✓	✓	✓	✓	✓
Province FE	—	—	✓	—	—	—	—
Common AR(1)	N/A	N/A	N/A	✓	—	✓	—
Panel-Specific AR(1)	N/A	N/A	N/A	—	✓	—	✓
R^2	0.994	0.995	—	—	—	0.999	1.000
N	230	230	230	230	230	230	230

Standard errors in parentheses. (In)dependent variables are in logarithmic form.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

D Public Infrastructure by Asset Type, First-Difference Form

Table D1: First-difference production function results, public infrastructure by asset type

	OLS				FGLS	
Real Value Added	(1)	(2)	(3)	(4)	(5)	(6)
Private Capital	0.054	0.048	0.054	0.048	0.076	0.053
	(0.089)	(0.093)	(0.109)	(0.102)	(0.052)	(0.060)
Hours Worked	0.407***	0.401***	0.407***	0.401***	0.384***	0.391***
	(0.063)	(0.111)	(0.092)	(0.122)	(0.045)	(0.069)
Commercial Buildings	0.011	0.018	0.011	0.018	0.007	-0.008
	(0.039)	(0.034)	(0.031)	(0.030)	(0.016)	(0.019)
Institutional Buildings	-0.093	-0.144	-0.093	-0.144	-0.063	-0.075
	(0.105)	(0.101)	(0.097)	(0.092)	(0.045)	(0.054)
Marine Engineering	0.013	0.048	0.013	0.048	0.007	-0.005
	(0.037)	(0.051)	(0.032)	(0.032)	(0.016)	(0.027)
Transportation Engineering	-0.059	0.023	-0.059	0.023	-0.021	-0.007
	(0.038)	(0.062)	(0.050)	(0.056)	(0.024)	(0.035)
Waterworks Infrastructure	-0.004	-0.007	-0.004	-0.007	0.012	0.031*
	(0.035)	(0.037)	(0.024)	(0.026)	(0.015)	(0.018)
Sewage Infrastructure	0.011	0.041	0.011	0.041	-0.031	-0.017
	(0.088)	(0.104)	(0.069)	(0.063)	(0.034)	(0.040)
Communications Networks	0.010	0.009	0.010	0.009	0.008*	0.007
	(0.011)	(0.010)	(0.008)	(0.008)	(0.004)	(0.005)
Electric Power	-0.010**	-0.012***	-0.010	-0.012	-0.010**	-0.012**
	(0.005)	(0.004)	(0.008)	(0.008)	(0.004)	(0.006)
Other Engineering Construction	-0.016	-0.011	-0.016	-0.011	-0.016	0.000
	(0.025)	(0.021)	(0.023)	(0.022)	(0.011)	(0.015)
Other Machinery and Equipment	-0.009	-0.005	-0.009	-0.005	-0.008	-0.005
	(0.011)	(0.009)	(0.014)	(0.012)	(0.007)	(0.008)
Transportation Mach. and Equipment	-0.043**	-0.027**	-0.043***	-0.027**	-0.032***	-0.022***
	(0.017)	(0.011)	(0.013)	(0.012)	(0.006)	(0.007)
Unemployment Rate	-0.074***	-0.051***	-0.074***	-0.051***	-0.058***	-0.050***
	(0.018)	(0.015)	(0.018)	(0.018)	(0.010)	(0.012)
Constant	0.025***	0.040***	0.025***	0.040***	0.020***	0.039***
	(0.005)	(0.006)	(0.004)	(0.009)	(0.002)	(0.003)
Time FE	—	✓	—	✓	—	✓
R^2	0.498	0.612	0.498	0.612	—	—
N	220	220	220	220	220	220

Standard errors in parentheses. (In)dependent variables are in logarithmic form and differenced.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

E Public Infrastructure by Asset Function, First-Difference Form

Table E1: First-difference production function results, public infrastructure by function

	OLS				FGLS	
Real Value Added	(1)	(2)	(3)	(4)	(5)	(6)
Private Capital	0.047 (0.081)	0.051 (0.094)	0.047 (0.103)	0.051 (0.097)	0.042 (0.053)	0.066 (0.060)
Hours Worked	0.413*** (0.062)	0.419*** (0.108)	0.413*** (0.092)	0.419*** (0.122)	0.403*** (0.048)	0.383*** (0.066)
Health	-0.003 (0.060)	-0.027 (0.054)	-0.003 (0.049)	-0.027 (0.044)	-0.006 (0.022)	-0.016 (0.028)
Education	-0.086 (0.054)	-0.107 (0.064)	-0.086 (0.089)	-0.107 (0.080)	-0.067 (0.042)	-0.081* (0.047)
Fuel and Energy	-0.011** (0.005)	-0.013*** (0.005)	-0.011 (0.009)	-0.013 (0.008)	-0.007 (0.005)	-0.010* (0.006)
Housing and Community Amenities	-0.010 (0.030)	0.006 (0.030)	-0.010 (0.023)	0.006 (0.026)	0.021 (0.015)	0.030* (0.018)
Transport	-0.075 (0.045)	0.011 (0.061)	-0.075 (0.051)	0.011 (0.057)	-0.038 (0.026)	0.002 (0.035)
Public Transit Equipment	-0.041** (0.018)	-0.026* (0.013)	-0.041*** (0.012)	-0.026** (0.012)	-0.029*** (0.006)	-0.023*** (0.007)
Environmental Protection	0.019 (0.080)	0.037 (0.100)	0.019 (0.067)	0.037 (0.061)	-0.019 (0.036)	-0.001 (0.044)
Communication	0.005 (0.013)	0.005 (0.011)	0.005 (0.009)	0.005 (0.009)	0.002 (0.004)	0.004 (0.005)
Recreation, Culture and Religion	0.009 (0.039)	0.011 (0.036)	0.009 (0.034)	0.011 (0.034)	-0.011 (0.019)	-0.007 (0.023)
Public Order and Safety	-0.047 (0.031)	-0.078** (0.034)	-0.047 (0.031)	-0.078** (0.032)	-0.013 (0.016)	-0.027 (0.018)
Unemployment Rate	-0.071*** (0.019)	-0.046*** (0.015)	-0.071*** (0.018)	-0.046** (0.019)	-0.053*** (0.010)	-0.038*** (0.012)
Constant	0.025*** (0.005)	0.042*** (0.006)	0.025*** (0.004)	0.042*** (0.009)	0.020*** (0.002)	0.039*** (0.003)
Time FE	—	✓	—	✓	—	✓
R^2	0.499	0.616	0.499	0.616	—	—
N	220	220	220	220	220	220

Standard errors in parentheses. (In)dependent variables are in logarithmic form and differenced.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

F Core Infrastructure, First-Difference Form

Table F1: First-difference production function results, public infrastructure by function

	OLS				FGLS	
Real Value Added	(1)	(2)	(3)	(4)	(5)	(6)
Private Capital	0.054	0.056	0.054	0.056	0.065	0.048
	(0.083)	(0.089)	(0.099)	(0.093)	(0.049)	(0.053)
Hours Worked	0.397***	0.394***	0.397***	0.394***	0.409***	0.405***
	(0.070)	(0.106)	(0.096)	(0.121)	(0.047)	(0.061)
Core Public Infrastructure	-0.071	-0.016	-0.071	-0.016	-0.060**	0.001
	(0.061)	(0.057)	(0.074)	(0.077)	(0.030)	(0.037)
Non-Core Public Infrastructure	-0.111	-0.105	-0.111	-0.105	-0.066	-0.057
	(0.104)	(0.102)	(0.101)	(0.094)	(0.044)	(0.052)
Unemployment Rate	-0.079***	-0.045**	-0.079***	-0.045**	-0.053***	-0.033***
	(0.019)	(0.017)	(0.020)	(0.019)	(0.010)	(0.011)
Constant	0.020***	0.037***	0.020***	0.037***	0.018***	0.038***
	(0.004)	(0.004)	(0.004)	(0.008)	(0.002)	(0.002)
Time FE	—	✓	—	✓	—	✓
R^2	0.455	0.588	0.455	0.588	—	—
N	220	220	220	220	220	220

Standard errors in parentheses. (In)dependent variables are in logarithmic form and differenced.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$