

The role of distance decay in estimating wider economic benefits from agglomeration

Mark Harvey

Bureau of Infrastructure, Transport and Regional Economics, GPO Box 594, Canberra, ACT

Email for correspondence: mark.harvey@infrastructure.gov.au

Abstract

Agglomeration benefits are usually the largest category of wider economic benefits of transport projects. They are estimated by applying productivity elasticities to forecast changes in effective densities. These productivity elasticities are obtained by regression analysis to fit production functions that include effective density as an accessibility measure. In most cases, the functional form and parameter values for the distance decay curve in the effective density specification are simply assumed. This paper discusses how different decay curve assumptions affect productivity elasticity and agglomeration benefit estimates. It is shown that an agglomeration benefit is comprised of a large number of terms, each affected in multiple ways by the decay curve. Numerical simulations for hypothetical cities and projects are employed to further investigate the effects. Generally, a faster rate of distance decay leads to lower productivity elasticity and lower agglomeration benefit estimates. It is recommended that the decay curve functional form and parameters be estimated from productivity data when estimating productivity elasticities rather than imposed by assumption.

1 Introduction

Wider economic benefits (WEBs) are improvements in economic welfare arising from market imperfections (prices of goods and services differing from costs to society as a whole), that are not captured in traditional cost–benefit analysis (CBA). Of the types of WEBs commonly estimated, benefits from agglomeration economies are usually the largest. In a comparison of CBA results for seven urban transport projects, Douglas and O’Keefe (2016) reported agglomeration WEBs ranging between 5% and 40% of conventional benefits.

This paper focusses solely on agglomeration WEBs, abbreviated to “WB1” as in UK DfT (2007). It examines aspects of the detailed mechanics of WB1 estimation in ways not done to date in the literature.

WB1 arises from productivity increases of businesses given better access to other businesses and to workers as a result of a transport improvement. For WB1 purposes, accessibility for a firm is measured by “effective density” (ED), which is the sum of employment in zones weighted by a distance decay factor given by a smooth downward sloping curve. WB1 is estimated by applying an agglomeration or productivity elasticity to the forecast changes in EDs caused by a transport project. A productivity elasticity is the percentage increase in productivity in a zone from a one

percent increase in ED for the zone. With only a few exceptions, the literature is focussed on estimating these elasticities without considering the form and parameters of the distance decay curve that underlies the ED measure. Misspecification of the decay curve could add or subtract large amounts to project benefits and affect investment decisions worth billions of dollars. It is therefore important to understand this potential weakness in the current methodology and efforts be made to address it.

Section 2 is a short literature review concentrating on productivity and distance decay elasticity estimates. Section 3 derives mathematical relationships between the productivity and decay curve elasticities and WB1 estimates. It is shown that a WB1 estimate is a sum of a large number of terms, each affected by the decay curve in multiple ways. Due to the large amount of data and complex interactions that combine to make an estimate of a productivity elasticity or the WB1 for a project, simulation modelling was considered the only way to proceed further. Section 4 introduces the simulation describing how data was artificially generated for hypothetical cities with different layouts and eight alternative decay curves. Section 5 addresses the question of how changing the decay curve affects productivity elasticity estimates by comparing results of regressions of the productivity index for zones in each hypothetical city against EDs obtained using the alternative decay curves. Then, hypothetical transport projects are used to test the effects of the different decay curves on the size of WB1 estimates for travel time savings (static WB1) in section 6 and for employment density increases (dynamic WB1) in section 7. Sections 8 and 9 build on the discussion to address alternative transport impedance measures and the relationships between ED, the gravity model and trip numbers.

2 Agglomeration economies and distance decay

Higher employment densities and better transport access for businesses and employees create external economies in form of higher productivity. Duranton and Puga (2004) categorise the sources of agglomeration economics into sharing (greater specialisation, sharing indivisible goods and facilities, sharing risks), matching (workers better matched to job requirements) and learning (knowledge generation, diffusion and accumulation). Venables (2007) presents a model showing how a transport improvement that encourages more workers to commute to the city centre with a consequent improvement in productivity from agglomeration, causes an economic benefit on top of the benefits for existing and generated trips estimated by a conventional CBA. The size of these benefits depends in part on the productivity elasticity.

The methodology used study the impact of agglomeration on productivity is regression analysis of production functions that include an agglomeration measure as a Hicks-neutral shifter (Rosenthal and Strange 2004, Graham 2007a, p. 328),

$$Y = g(A) \cdot F(L, K, I) \quad (1)$$

where Y is a firm's value added in a locality, $g(A)$ is the influence of agglomeration as a function of the agglomeration measure, and $F(L, K)$ is a function of labour and capital. The term "Hicks neutral" means that the shifter does not affect the balance between labour and capital. Ideally, estimation is undertaken using data at the level of individual plants (including splitting up multiple-location firms) but data availability and confidentiality restrictions may prevent this (Rosenthal and Strange 2004). The advantages of such plant-level data are that they better represent the optimising behaviour assumed in economic theory, provide greater data variability and can

reduce some biases from unobserved heterogeneity (Melo et al 2009a, p. 335). There are challenging endogeneity issues to address in regression of spatial productivity data (see for example, Graham and Van Dender 2011), but these are outside the scope of the present paper.

In studies aimed at deriving productivity elasticities specifically for the purpose of WB1 estimation, it is usual to undertake separate regressions for different industries or groups of industries. For example, Maré and Graham (2009) estimated productivity elasticities for New Zealand at the one-digit-level. Their estimates ranged from 0.032 for agriculture, forestry and fishing to 0.087 for finance and insurance and are now recommended in the NZ Economic Evaluation Manual (NZTA 2018). Graham (2007a, p. 320) presents a table of productivity elasticities for manufacturing from “prominent studies” ranging from 0.01 to 0.2. His own weighted average elasticity for manufacturing was 0.077. Service industries tend to have the highest elasticities with Graham (2007a) obtaining a weighted average elasticity of 0.197. The most recent survey of elasticities, covering 47 international empirical studies, reported an unweighted mean of 0.046 (Graham and Gibbons forthcoming). There was considerable variation — a range of –0.800 to 0.827 related to the sector, country and research method.

Early studies of the agglomeration–productivity relationship used total population or employment in the area (state, region or city) in which the business was located as the agglomeration measure (see Melo et al 2009a, p. 335 for examples from the 1970s and 1980s). Ciccone and Hall (1996) introduced employment density, which has the advantage of being insensitive to differences in land area sizes. The disadvantage of such approaches is that agglomeration is measured only within the boundaries of the geographic units used (Melo et al 2009a, p. 335). To allow for agglomeration effects from outside the area or zone in which a firm is located and which decay with distance from the firm, one approach is to aggregate employment into concentric bands around each business location (Rosenthal and Strange (2003 and 2008), Rice et al (2006), Di Addario and Patacchini (2008), Graham et al (2009), Melo and Graham (2009b) and Melo et al (2017)). Employment in each band is included in the production function with a regression coefficient estimated for each band.

The ED approach to measuring agglomeration, which takes account of distance decay, was developed specifically for the purpose of estimating the productivity benefits of agglomeration from transport infrastructure projects. Research commissioned by the UK Department for Transport in the early 2000s defined the ED measure and quantified the relationship between ED and productivity (Worsley 2011, p. 15). Since then, a number of studies estimating productivity elasticities from EDs have been undertaken with the intent that the elasticities be used to quantify agglomeration benefits from transport projects (for example, Graham (2007a and b), Maré and Graham (2009), Le Nechet (2012), and Hensher et al (2012)).

Typically, in such studies, the functional form and parameter value of the decay curve are set by assumption. Graham (2007a and b), Maré and Graham (2009), Graham and Van Dender (2011), Le Nechet (2012), and Hensher et al (2012) all use inverse curves with elasticities of –1.0 to estimate productivity elasticities. The one exception in the literature where the decay curve parameters were estimated from productivity data for use in estimating WB1 is Graham et al (2009).

Graham et al (2009) reviewed the literature relating to distance decay from several different fields including trade, gravity and locational models. Distance decay

elasticities found in the literature range from -0.5 to -3.0 with most around -1.0 . Graham et al (pp. 14-15) concluded that the elasticity of flows of goods and people with respect to distance is of the order of -1.0 . They go on to state that there is no definitive answer to the question of the most appropriate functional form, but there is no evidence that the simple inverse distance function underperforms in this context relative to more complex measures.

A major difficulty in fitting a decay curve from data at the same time as estimating a productivity elasticity is that the production function is *multiplicative* (or a sum of logs), while the ED is the *sum* of a large number of terms. Estimation requires non-linear regression, whereby an optimisation procedure is employed to find parameter values that minimise the sum of squared residuals, as in Graham et al (2009). To reduce the number of terms in the non-linear regression to a manageable level, Graham et al adopted the concentric band approach, mentioned above. They estimated the decay curve elasticities for industry groups shown in table 1, which are the values currently recommended in the UK CBA guidance (UK DfT 2018, p. 24).

From table 1, agglomeration benefits are highest for business services, but the productivity impacts for business services, as well for as for consumer services, decay more rapidly than for manufacturing.

Table 1: Productivity and decay curve elasticities from Graham et al (2009) and UK Transport Analysis Guidance

Industry group	Productivity elasticity	Decay curve elasticity
Manufacturing	0.021	-1.097
Construction	0.034	-1.562
Consumer services	0.024	-1.818
Business services	0.083	-1.746
Economy (weighted average)	0.043	-1.655

In a study of three US manufacturing industries, Drucker and Feser (2012) found that decay curve elasticities of -0.1 provided the best fit of the data for the less spatially concentrated rubber and plastics and metalworking machinery industries and -1 for the more spatially concentrated measuring and controlling devices industry.

3 Mathematical relationships between elasticities and agglomeration WEBs estimates

This section examines the mathematical relationship between the productivity and decay curve elasticities and WB1 estimates. The expressions derived are used later in the paper to help explain the simulation results.

The ED or “access to economic mass” measure incorporates both the scale and proximity of economic activity (Graham 2007a, p. 327). ED is defined as the sum of surrounding economic mass weighted by transport impedance between the firm and each unit of economic mass. For a firm at point (x_0, y_0) between X^- and X^+ in the east-west direction and Y^- and Y^+ in the north-south direction

$$ED_{x_0 y_0} = \int_{X^-}^{X^+} \int_{Y^-}^{Y^+} M(x, y) \cdot f(x, y, x_0, y_0) dy dx \quad (2)$$

where $M(x, y)$ is economic mass as a function of location and $f(x, y, x_0, y_0)$ is the decay factor (or weight) between the firm and every location on the plane.

For practical application, the area is divided into discrete zones. The ED for a firm in zone i is calculated as

$$ED_i = \sum_{j=1}^n M_j \cdot f(g_{ij}) \quad (3)$$

where n is the number of zones, M_j is economic mass in zone j , and $f(g_{ij})$ is the decay curve, which gives the decay factor as a function of the transport impedance, g , between zone i and zone j .¹

The decay factor declines as impedance rises, hence $f'(g) < 0$. Economic mass is usually measured by employment, though gross value added and population are alternatives (Graham and Gibbons forthcoming).² Impedance can be measured by straight-line distance, actual distance, in-vehicle time, generalised time or generalised cost. There are arguments for and against straight-line distance over generalised time or generalised cost (Graham (2007b), UK DfT (2007)). While straight-line distance EDs are an option for productivity elasticity estimation, a time or cost measure must be used to estimate WB1 from changes in transport impedance. Impedances for car and public transport between the same origin–destination pair have to be combined via a logsum formula or a weighted average using trip numbers as weights.³ Section 8 further discusses alternative impedance measures.

In CBAs of transport projects, the proportional improvement in productivity for a zone is obtained by applying a productivity elasticity to the proportional change in ED for the zone between the base case and the project case. WB1 for zone i is obtained by multiplying this proportional change by total gross value added (GVA) in the zone.⁴ The formula used in CBAs is

$$WB1_i = \left[\left(\frac{ED_{iPC}}{ED_{iBC}} \right)^\eta - 1 \right] GVA_i \quad (4)$$

where

- ED_{iPC} and ED_{iBC} are the EDs for zone i in the project case and the base case respectively
- η is the productivity elasticity, $\eta = \frac{d \log GVA}{d \log ED}$, and
- GVA_i is gross value added in zone i in the base case.

¹ Graham and Gibbons (forthcoming) use “mean effective density” in which equation 3 is divided by n , the number of zones. This does not change the relativities between EDs for different zones, which is all that matters.

² Use of employment as the measure of economic mass captures business-to-business interactions, which are likely to be more important for learning and sharing as sources of agglomeration economies. Population as the measure of economic mass is likely to be more important for better matching of employees to businesses as a source of agglomeration economy. Ideally, a regression analysis would include EDs calculated in both ways, but the different ED measures are likely to be too highly correlated to produce meaningful results.

³ It would be desirable to include impedances for walking and cycling but city transport models, at present, rarely feature active travel modes.

⁴ GVA is the contribution of labour and capital to the production process. It equals the value of output minus the value of intermediate goods and equals GDP net of taxes and subsidies. UK DfT (2018) recommends GDP.

The total WB1 for the project is found by adding together the WB1 values for all zones and industries.

A transport project can alter EDs through changes in transport impedance referred to as “static” agglomeration economies, and changes in economic mass referred to as “dynamic” agglomeration economies.⁵

The next section shows how the decay curve affects the productivity elasticity estimate. The decay curve also affects WB1 via the estimated changes in EDs between the base and project cases. We now derive alternative formulas for WB1, valid for small changes, to explain how. These formulas are based on the elasticity of WB1 in a single zone i , $WB1_i$, from a small change in impedance or mass for a single zone j . Graham and Gibbons (forthcoming) also derive the results in this section but express them less simply.

Considering dynamic agglomeration economies first, because the derivation is simpler, from equation 3, the elasticity of ED_i with respect to M_j is

$$\frac{\partial ED_i}{\partial M_j} \frac{M_j}{ED_i} = \frac{M_j \cdot f(g_{ij})}{\sum_{j=1}^n M_j \cdot f(g_{ij})} = s_{ij} = \frac{\partial \log ED_i}{\partial \log M_j} \quad (5)$$

where s_{ij} is the share of $M_j \cdot f(g_{ij})$ in ED_i .

The elasticity of $WB1_i$ with respect to M_j is then

$$\frac{d \log WB1_i}{d \log ED_i} \frac{\partial \log ED_i}{\partial \log M_j} = \frac{\partial \log WB1_i}{\partial \log M_j} = \eta s_{ij} \quad (6)$$

Thus the increase in WB1 for zone i from a small percentage change in mass in zone j , $\% \Delta M_j$, is approximately $\eta s_{ij} \cdot \% \Delta M_j / 100 \cdot GVA_i$. It is approximate because the share values in the expression (s_{ij}) are held constant at their base case levels, while the change in mass changes the share values, the more so the larger the mass change.

Adding up all the WB1 benefits for all zones, j , to obtain $WB1_i$, then summing these for all zones, i ,

$$\text{Dynamic WB1} \approx \sum_{i=1}^n \left(\sum_{j=1}^n \eta s_{ij} \cdot \frac{\% \Delta M_j}{100} \cdot GVA_i \right) \quad (7)$$

Turning now to static agglomeration economies, the elasticity of ED_i with respect to impedance, g_{ij} , is

$$\frac{\partial ED_i}{\partial g_{ij}} \frac{g_{ij}}{ED_i} = M_j \frac{df(g_{ij})}{dg_{ij}} \frac{g_{ij}}{ED_i} = \frac{M_j \cdot f(g_{ij})}{ED_i} \frac{df(g_{ij})}{dg_{ij}} \frac{g_{ij}}{f(g_{ij})} = s_{ij} \varepsilon_{ij} = \frac{\partial \log ED_i}{\partial \log g_{ij}} \quad (8)$$

where $\varepsilon_{ij} = \frac{df(g_{ij})}{dg_{ij}} \frac{g_{ij}}{f(g_{ij})}$ is the elasticity of the decay factor with respect to impedance between zones i and j .

The elasticity of $WB1_i$ with respect to g_{ij} is then

$$\frac{d \log WB1_i}{d \log ED_i} \frac{\partial \log ED_i}{\partial \log g_{ij}} = \frac{\partial \log WB1_i}{\partial \log g_{ij}} = \eta s_{ij} \varepsilon_{ij} \quad (9)$$

⁵ UK DfT (2018, p. 7) uses the term, “dynamic” agglomeration economies to refer to the combined effects of the static changes (changes in generalised costs), employment effects from land-use change, and any subsequent changes in generalised costs caused by the land-use changes. To examine the effects of mass changes in isolation, we use the term “dynamic” throughout this paper to refer to changes in economic mass with impedance held constant.

Note that $\varepsilon_{ij} < 0$ because a *saving* in travel time (a negative value) raises the decay factor and hence leads to an increase in WB1.

The increase in WB1 for zone i from a small change in transport impedance between zone i and zone j is approximately $\eta s_{ij} \varepsilon_{ij} \cdot \% \Delta g_{ij} / 100 \cdot GVA_i$, where $\% \Delta g_{ij}$ is the percentage change in impedance between zone i and zone j .

Adding up all the $WB1_i$ changes for all zones

$$\text{Static WB1} \approx \sum_{i=1}^n \left(\sum_{j=1}^n \eta s_{ij} \varepsilon_{ij} \cdot \frac{\% \Delta g_{ij}}{100} \cdot GVA_i \right) \quad (10)$$

Equations 7 and 10 show that a WB1 estimate is a sum of a large number of small amounts representing potential opportunities for interactions that could contribute to productivity. There are potentially n -squared terms, but many will be zero, having no change in impedance or mass. Higher productivity elasticities give rise to higher WB1 estimates, other things held equal. The presence of the share values, s_{ij} , in the equations imply that transport improvements will have greater WB1 impacts when they improve connectivity between larger and closer places (Graham and Gibbons forthcoming).

The decay curve affects dynamic and static agglomeration benefit estimates via both channels of the productivity elasticity value, η , and the share values, s_{ij} . For static WB1, there is a third channel of the decay curve elasticity, ε_{ij} . Changes in impedance act on ED through movement along the decay curve. As Graham et al (2009), observe, a reduction in impedance between two zones is equivalent to employment shifting closer together.⁶

4 Simulation model

The formulas derived in the previous section are not by themselves able to explain the effects of different decay curves on WB1 estimates. The combined effect of the different channels through which a decay curve affects WB1 is not obvious, especially given the huge number of terms covering the whole range of distances between zones. Numerical simulation using artificial data for hypothetical cities therefore was used to further investigate how different decay curves affect productivity elasticity and WB1 estimates. The artificial ED and productivity data were created from an assumed base productivity elasticity and decay curve, which represent the actual model determining the productivity impacts of agglomeration throughout the city. Results obtained using the base decay curve are compared with the results obtained using alternative decay curves. The methodology aims to show what occurs when an analyst unwittingly assumes a decay curve that is different from actual curve that underlies the data.

Exponential and inverse decay curves are special cases of the Tanner function used in gravity models, $DF = e^{\beta g} \cdot g^{\alpha}$, where DF is decay factor. The elasticity of decay factor with respect to impedance is $\varepsilon = \beta g + \alpha$. The values of α and β must be set to ensure $\varepsilon \leq 0$ over the entire range of values of g to avoid having an improvement in

⁶ The increase in ED_i from the m_j units of mass in zone j relocating to a slightly closer zone k is $-m_j \frac{\partial ED_i}{\partial m_j} + m_j \frac{\partial ED_i}{\partial m_k} = -m_j f(g_{ij}) + m_j f(g_{ik})$. The increase in ED_i from a unit reduction in impedance between zones i and j is $\frac{\partial ED_i}{\partial g_{ij}} = m_j f'(g_{ij})$, which is practically identical to the relocation of mass closer by one unit of impedance, $-f(g_{ij}) + f(g_{ik}) \approx f'(g_{ij})$, where $g_{ij} - g_{ik} = 1$.

transport impedance between two zones cause an agglomeration disbenefit. Hence, a positive α value can only coexist with a negative β value. The inverse decay curve has a zero β value and a constant elasticity of α along all points of the curve. The negative exponential decay curve has a zero α value and increasing elasticity in absolute terms along the curve.

For the numerical simulations, trip time was chosen as the impedance measure and eight decay curves with the following coefficient values, written as (β, α) , were tested:

- Five inverse curves: $(0, -0.5)$, $(0, -1)$, $(0, -1.5)$, $(0, -2.0)$, $(0, -2.5)$
- One curve with declining elasticity in absolute terms: $(0.02, -3)$ with the decay factor constrained to zero above 150 minutes when the elasticity becomes positive
- Two negative exponential curves: $(-0.02, 0)$ and $(-0.05, 0)$.

Figures 1 and 2 show plots of the curves and the elasticity values respectively.

Figure 1: Decay curves tested

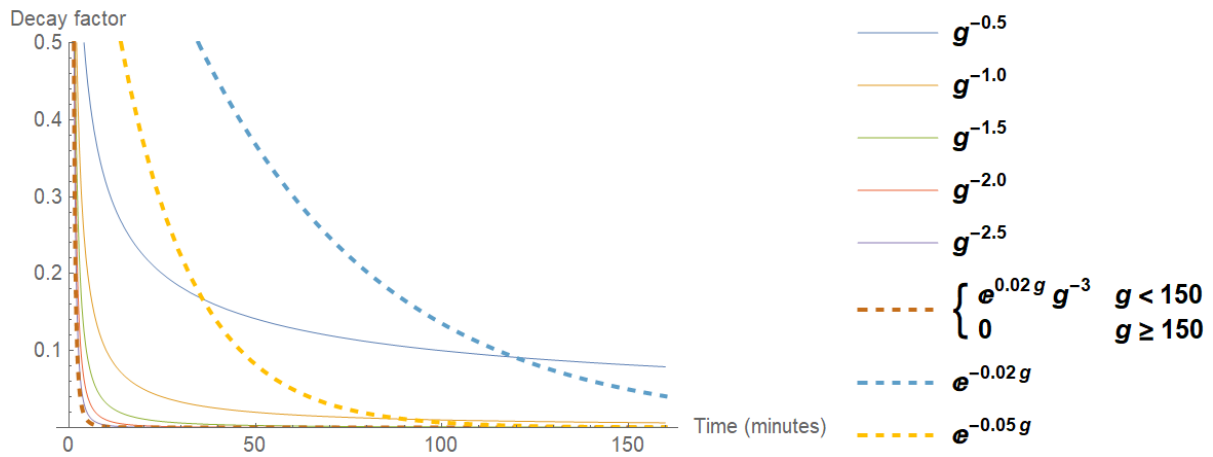
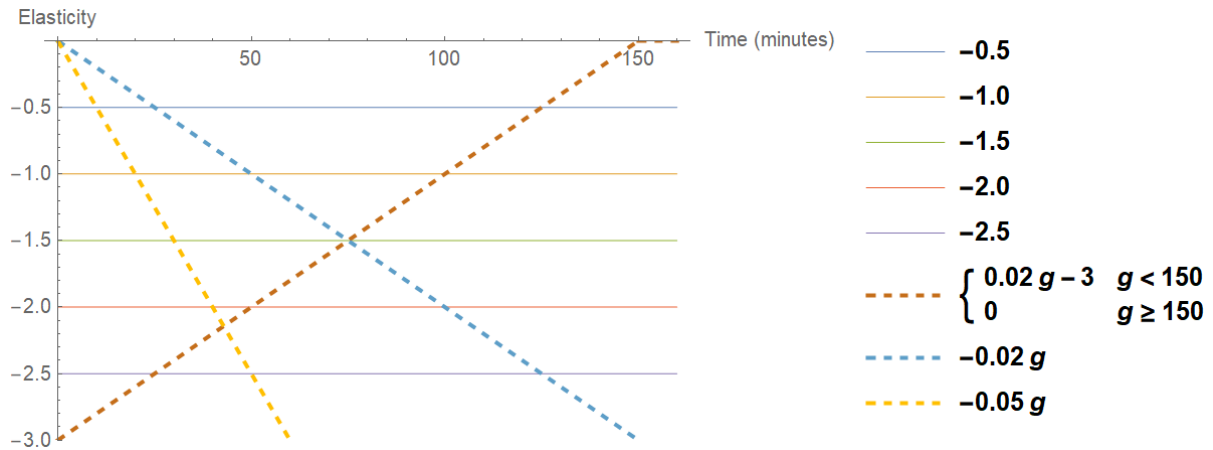


Figure 2: Elasticities of decay factor with respect to time for decay curves tested



The simulations were undertaken for a hypothetical city with zones on a square grid centred on the origin $(0, 0)$ and extending 10 zones north, south, east and west. Each zone is a square of four minutes by four minutes (the “zone size”). Hence the four corner zones have coordinates: north-east $(40, 40)$, north-west $(-40, 40)$, south-east $(40, -40)$ and south-west $(-40, -40)$. For city A, the economic mass declines with the

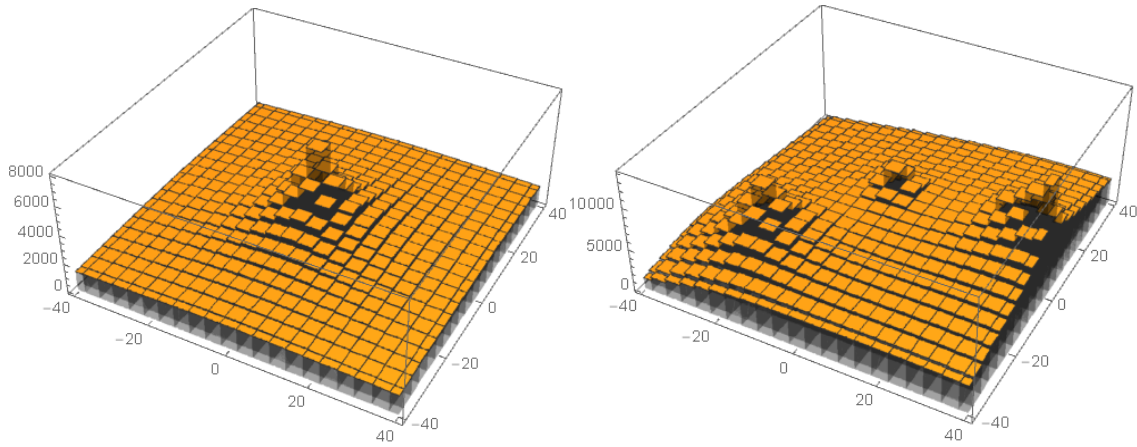
square root of Euclidean distance (Pythagoras' theorem) from the centre. Within-zone distances (the distance between each coordinate and itself) were set at half the zone size, which represents intra-zonal travel and avoids division by zero. Hence,

$$\text{Distance from centre } (0,0) \text{ and point } (x,y) = \text{Max}(\text{Zone size}/2, \sqrt{x^2 + y^2}) \quad \text{and} \\ \text{Mass} = 10000 / \sqrt{\text{Distance from centre}}$$

where *Zone size* is 4 and the 10 000 figure is an arbitrary constant.

Hypothetical city B features an irregular spread of economic mass with its main mass at point (39, 0), as could occur in a city with its CBD close to the coast, two other business districts, and there is a small linear slope away from the main CBD. Figure 3 shows the layout of cities A and B with the masses as block heights. Hypothetical city C (not shown) has the same set of masses as city A but randomly distributed across the 441 zones.

Figure 3: Economic masses for hypothetical cities A and B



For the purposes of calculating effective densities and WB1, times between zones were measured using Manhattan distances, defined as the sum of horizontal and vertical distances between points on grid. Thus the cities' streets are assumed to form a perfect square grid pattern with no diagonals whatsoever. The Manhattan distance between two points (x_1, y_1) and (x_2, y_2) is $|x_1 - x_2| + |y_1 - y_2|$. The Manhattan distance from one corner of the square city to the opposite corner is 160 minutes.

To explore the effects of the shorter trip lengths in a smaller city, the simulations were also undertaken for hypothetical city A with its length and breadth halved. The zone size was reduced from 4 to 2 minutes travel time. The half-size city occupies a quarter of the area with corners at $(-20, -20)$, $(-20, 20)$, $(20, -20)$ and $(20, 20)$. Economic masses were reset at $\text{Mass} = 10000 / \sqrt{2} \times \text{Distance from centre}$ (multiplication by two reverses the halving of the distances) to keep total mass in the city the same.

The inverse decay curve with an elasticity of -1.5 , $DF = g^{-1.5}$, was made the base against which the other decay curves are compared, being mid-range for the inverse curves and close to the economy weighted average value in table 1. In all cases, the productivity elasticity was assumed to be 0.1. The productivity shifter for each zone i is then

$$ED_i^{0.1} = \left(\sum_{j=1}^n M_j g_{ij}^{-1.5} \right)^{0.1} \quad (11)$$

where g is the Manhattan distance in minutes between zones i and j . Given these assumptions, a set of artificial productivity values was created for the 441 zones for each of the four cities.

5 Decay curve effect on productivity elasticity estimate

This section discusses the simulated estimation of productivity elasticities by regression analysis of the artificially generated zone productivities against EDs using the different decay curves and for the different cities. It explains why faster decay rates lead to lower productivity elasticity estimates and conversely, and also, why city size does not matter for inverse decay curves, but does for other decay curves.

Table 2 shows the results of regressions of the log productivities derived from equation 11 for the 441 zones against log EDs calculated using the alternative decay curves for the four hypothetical cities. The first five results columns show inverse decay curves. Naturally, the base decay curve for the productivity data, $DF = g^{-1.5}$, yields a productivity elasticity estimate of 0.1 and a correlation coefficient of 1.0 for all hypothetical cities. For all cities, productivity elasticity falls as α becomes more strongly negative. The falling elasticity curve, $DF = e^{0.02g-3}$, which represents a relatively high decay rate, produces the lowest productivity elasticity estimates. Of the rising elasticity curves, $DF = e^{-0.02g}$ results in higher productivity elasticities than the more rapidly decaying $DF = e^{-0.05g}$.

A determinant of differences in productivity elasticities is the variation in EDs across zones produced by the different decay curves. For the same productivity values, regression against a set of EDs with higher variation produces a lower elasticity estimate.⁷ Table 2 shows the coefficients of variation for the EDs for the different curves and elasticities illustrating the inverse relationship between variability in EDs and productivity elasticity estimates.

Halving city size has no effect on productivity elasticity estimates for inverse decay curves.⁸ The reason is that inverse decay curves are homogeneous of degree α , that is

$$\sum_{j=1}^n M_j \cdot (k g)^\alpha = k^\alpha \sum_{j=1}^n M_j \cdot g^\alpha \quad (12)$$

Multiplying all impedances by a factor of k , multiplies all EDs by a constant, k^α with no change in relative ED values. ED's obtained from decay curves with non-zero β coefficients lack this property so the shorter trip lengths in the half-size city change ED relativities. An implication is that productivity elasticities derived using non-constant elasticity decay curves for a given city should not be transferred to other cities of greatly different sizes.

⁷ Graham and Gibbons (forthcoming) also show that as decay curve elasticity falls in absolute terms, the variation in EDs across zones is reduced. They did not discuss the implications for productivity elasticity and WB1 estimates. Graham (2007b) noted the relationship between variation in EDs and productivity elasticities.

⁸ The author has confirmed that this statement applies to City B scaled down to half size as well as to City A.

Table 2: Productivity elasticity estimates with different decay curves

Decay curve type	Inverse curves — constant elasticity					Falling elasticity	Exponential curves — rising elasticity	
Decay curve β	0	0	0	0	0	0.02	-0.02	-0.05
Decay curve α	-0.5	-1	-1.5	-2	-2.5	-3	0	0
City A regular								
Correlation	0.994	0.998	1.000	0.997	0.986	0.976	0.983	0.988
Elasticity	0.268	0.137	0.100	0.090	0.089	0.092*	0.157	0.086
CV for EDs (%)	9.7	19.0	26.6	31.1	32.8	32.9	8.9	18.8
City A half size								
Correlation	0.994	0.998	1.000	0.997	0.986	0.975	0.981	0.983
Elasticity	0.268	0.137	0.100	0.090	0.089	0.092*	0.285	0.132
CV for EDs (%)	9.7	19.0	26.6	31.1	32.8	32.6	15.9	28.6
City B irregular								
Correlation	0.974	0.993	1.000	0.993	0.980	0.972	0.960	0.986
Elasticity	0.316	0.154	0.100	0.076	0.066	0.065	0.184	0.097
CV for EDs (%)	10.5	21.0	30.4	37.1	40.7	41.3	17.2	30.9
City C random								
Correlation	0.949	0.979	1.000	0.947	0.772	0.625	0.930	0.954
Elasticity	0.203	0.118	0.100	0.093	0.073	0.056	0.104	0.067
CV for EDs (%)	7.0	12.1	14.3	15.1	17.3	19.6	13.1	20.2

Notes: CV = coefficient of variation (%) = standard deviation \times 100 / mean.

* The two starred elasticity values of 0.92 are not identical. They differ by 0.00055.

The simulations for city B with an irregular spread of masses and city C with a random distribution show that city layout can affect productivity elasticities depending on the choice of decay curve. It seems that productivity elasticities, regardless of decay curve specification, may not be transferable between cities with greatly dissimilar layouts in the spatial distribution of economic mass. To explain the relationship between city layout and productivity elasticity requires further investigation elsewhere.

Econometric studies of effects of distance decay on total factor productivity or wages based on concentric distance or travel time bands generally find the decay rate to be steep. Using travel time bands between 20 and 90 minutes, Melo et al (2017, p 190) concluded that, “The results suggest that the spatial scope of the productivity effects of agglomeration can extend up to 60 minutes’ driving time, although the bulk of the effects occur within the first 20 minutes”. Rosenthal and Strange (2003, p. 378) wrote that, “The initial attenuation is rapid, with the effect of own-industry employment in the first mile up to 10 to 1000 times larger than the effect 2 to 5 miles away. Beyond 5 miles attenuation is much less pronounced” (p. 378). They suggested that information spillovers (learning) that require frequent contact between workers dissipate over a short distance as walking to a meeting place becomes difficult or as random encounters become rare. Benefits of labour market pooling (matching) and shared inputs (sharing) might extend over greater distances because they rely on car trips (pp. 387-8). This is consistent with the finding of Graham et al (2009) that distance decay is faster for business service industries for which knowledge spillovers are likely to be more important, compared with manufacturing industries for which matching in labour markets and input sharing might be more important.

If the high decay-rate curves in table 2 ($\alpha = -2.0$, $\alpha = -2.5$ and $(\beta, \alpha) = (0.02, -3)$) better represent reality, agglomeration elasticities estimated assuming lower rates of decay would be exaggerated. The next two sections show that WB1 would also be over-estimated.⁹

6 Decay curve effect on static WB1 estimate

The next two simulations test the effects of different decay curves on WB1 estimates from transport projects. WB1 is estimated for two hypothetical projects in City A using the base productivity elasticity, 0.1, and decay curve, $DF = g^{-1.5}$. The result is compared with WB1 estimated using each alternative decay curve with the corresponding productivity elasticity estimate from table 2. Since the elasticities of decay factor with respect to impedance vary along the last three of the eight curves tested, simulations were undertaken for a short distance and a long distance transport project.

For the long distance project, travel times fall by one percent between all 10 zones north of the centre along the vertical axis from (0, 0) to (0, 40) representing a piece of improved infrastructure extending from the CBD to the northern edge of the city. Travel between zones (0, 0) to (0, 40) takes 40 minutes in the base case and 39.6 minutes in the project case. In the project case, for all OD pairs, travellers choose the minimum of the simple Manhattan distance and the Manhattan distance using the improved links. A trip from (30, 20) to (-10, 4) would benefit from using the improved infrastructure for the north-south component of the trip by traveling along the vertical axis between (0, 20) and (0, 4). A trip with origin and destination entirely in the southern quadrants or in one of the northern quadrants between say (28, 20) and (40, 40) would not benefit at all from the improved infrastructure.

For the short distance project, the one percent travel time improvement was assumed to occur only from (0,0) to (0,16), that is, four zones north of the origin, requiring 16 minutes to traverse in the base case and 15.84 minutes in the project case. Project lengths were halved for the half-size city.

For the purposes of converting ED increases into WB1 estimates, it was assumed that gross value added in each zone equals economic mass, so the absolute values are meaningless. The productivity elasticities used with each decay curve were the estimated values in table 2.

Figure 4 shows the percentage increases in EDs for the long and short distance projects for the inverse decay curve with $\alpha = -1.5$. For the long distance project, extending right up the northern edge of the city, ED increases are highest towards the edge because their EDs do not include access to zones further to the north with small or zero changes in trip times.

Results are presented in table 3 as ratios of WB1 for the particular decay curve to the base WB1 obtained using the inverse decay curve $DF = g^{-1.5}$. For inverse decay curves, WB1 estimates fall as α becomes more strongly negative. This might seem surprising because from equation 9 (that the elasticity of $WB1_i$ with respect to g_{ij} is $\eta_{s_{ij}}\varepsilon_{ij}$), the falling productivity elasticity, η , and the rising decay curve elasticity, ε ,

⁹ Another interesting finding from some of the econometric studies of distance decay is that distance decay can be lumpy, with some intermediate distance bands not having statistically significant coefficients or coefficients smaller than for bands further out (Melo and Graham 2009b; Melo et al 2017).

might be expected to approximately offset one another. The explanation lies with the changing shares, s_{ij} , in the EDs. Faster decay rates concentrate the shares of contributions to ED for a given zone into nearby zones, away from more distant zones. Slower decay rates spread the net more widely, giving greater weight to large numbers of small WB1 gains from far-away zones. Of the $441^2 = 194\,481$ potential contributors to WB1, almost a third, 64 588, actually contribute ($\Delta g_{ij} > 0$) in the case of the short project. The number is large because travellers use part or all of the upgraded infrastructure to reduce journey time between numerous origin–destination pairs. Switching from $\alpha = -0.5$ to $\alpha = -2.5$ increases WB1 for just 136 terms and reduces WB1 for 64 452 terms. The increases in WB1 from reducing the decay rate occur for short distance zone pairs close to the upgraded infrastructure. These increases are swamped by the vast number of small decreasing terms. In practice, the number of small contributors to a static WB1 estimate could be extremely large for a project with extensive network effects (diverted traffic altering congestion levels on many links).

Figure 4: Percentage increases in effective densities for long and short distance projects with travel time savings — city A, inverse decay curve with $\alpha = -1.5$

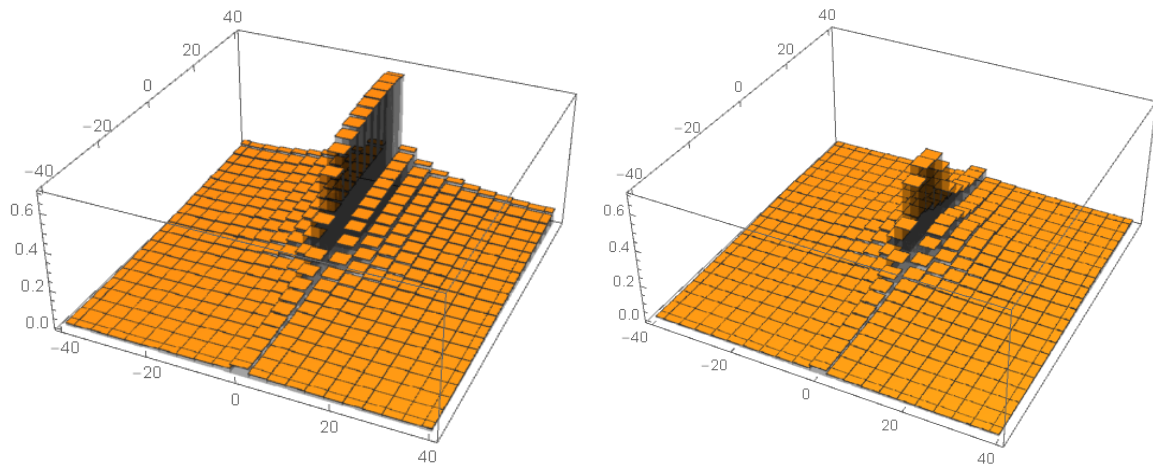


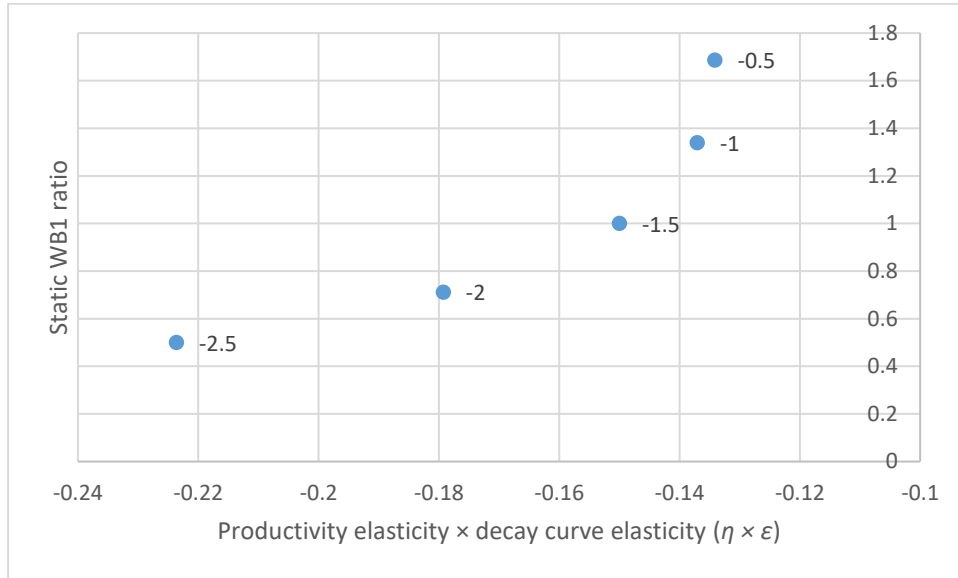
Table 3: Static WB1 with different decay curves

(Ratio to WB1 for inverse decay curve with $\alpha = -1.5$)

Decay curve type	Inverse curves — constant elasticity					Falling elasticity	Exponential curves — rising elasticity	
Decay curve β	0	0	0	0	0	0.02	-0.02	-0.05
Decay curve α	-0.5	-1	-1.5	-2	-2.5	-3	0	0
City A								
Long project	1.67	1.33	1.00	0.71	0.50	0.40	1.84	1.28
Short project	1.69	1.34	1.00	0.71	0.50	0.40	1.82	1.25
City A half size								
Long project	1.67	1.33	1.00	0.71	0.50	0.38	2.11	1.73
Short project	1.69	1.34	1.00	0.71	0.50	0.38	2.09	1.70

Figure 5 plots WB1 ratios from table 3 against productivity elasticity times decay curve elasticity from table 2 (the $\eta\epsilon$ value in equation 9) for the inverse curves. The chart illustrates the impact changing shares in EDs (s_{ij}) has on static WB1 estimated with different decay curve elasticities. WB1, when estimated with low decay rates ($\alpha = -1$ and -1.5), accumulates benefits from large numbers of longer trips.

Figure 5: Static WB1 ratio for city A plotted against $\eta\varepsilon$ for inverse decay curves



Project length has a large effect on the absolute levels of WB1 (about 70% greater for the long distance project for all trials) but relative to the base estimate in table 3 ($\alpha = -1.5$), it has little effect for all decay curves. This is perhaps unexpected for the non-constant elasticity decay curves because the decreasing elasticity curve, $DF = e^{0.02}g^{-3}$, gives less weight to time savings for long trips and conversely for the increasing elasticity exponential curves. The explanation is that, first, changing the project length has no effect on the shares (s_{ij}) in equation 9, and second, for both the short and the long distance projects, there are gains evaluated along the entire length of the decay curve. Many longer distance trips use the improved infrastructure of the short distance project for part of the journey, while many short distance trips benefit from the long distance project. As an example of the latter, short distance trips between cells (0,16) to (0,40) gain from the long distance project but not the short distance project.

Halving city size has no effect on relative inverse decay curve WB1 estimates but increases WB1 in relative terms for increasing elasticity decay curves.¹⁰ In the half-size city, the longer distance parts of the decay curves are not used, reducing the range of decay factors applied.

7 Decay curve effect on dynamic WB1 estimate

To investigate how changes in economic masses affect WB1 estimates, the long distance project was assumed to cause one percent increases in masses for all 11 zones along the Y-axis from the origin northward, (0, 0), (0, 4), (0, 8) ... (0, 40), and the short distance project to do the same for the five zones north of the origin, (0, 0), (0, 4), (0, 8), (0, 12) and (0, 16). Impedances were not changed so as to isolate the effects of the changes in masses. Figure 6 shows the percentage increases in EDs for the long and short distance projects for the inverse decay curve with $\alpha = -1.5$.

¹⁰ In absolute terms, the WB1 estimates are also the same for the half-size city for inverse curves. This is the result of keeping total economic mass the same.

Figure 6: Percentage increases in effective densities for long and short distance projects with mass increases — city A, inverse decay curve with $\alpha = -1.5$

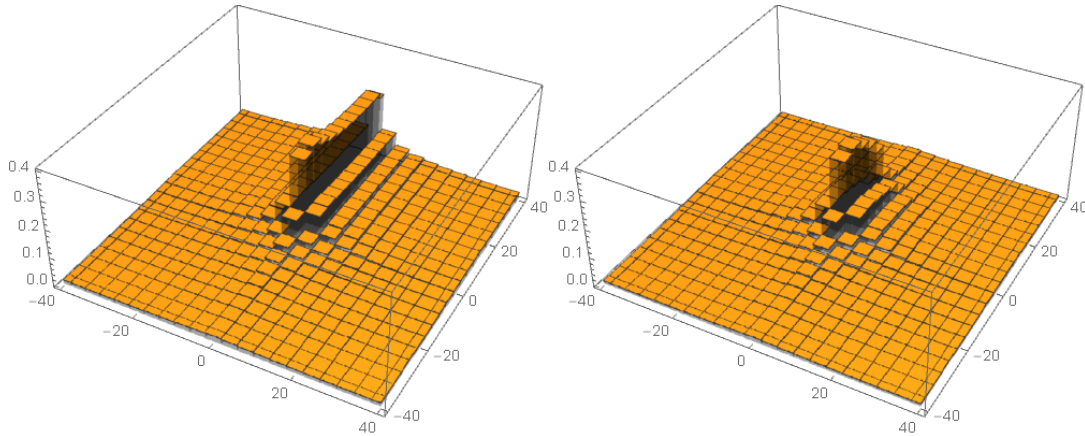


Table 4 presents the results. City size and project length make little or no difference to WB1 estimates relative to the base value at $\alpha = -1.5$. In common with static WB1, higher decay rates reduce dynamic WB1 estimates. In both cases, the reduction in WB1 between $\alpha = -0.5$ and $\alpha = -2.5$ is roughly a factor of three.

Table 4: Dynamic WB1 estimates with different decay curves

(Ratio to WB1 for inverse decay curve with $\alpha = -1.5$)

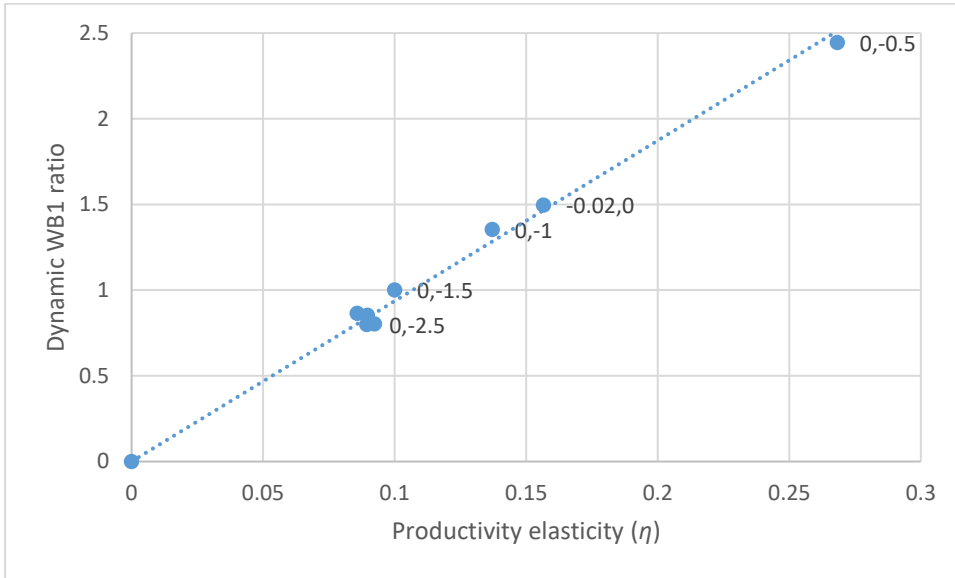
Decay curve type	Inverse curves — constant elasticity					Falling elasticity	Exponential curves — rising elasticity	
Decay curve β	0	0	0	0	0	0.02	-0.02	-0.05
Decay curve α	-0.5	-1	-1.5	-2	-2.5	-3	0	0
City A								
Long project	2.53	1.36	1.00	0.86	0.83	0.84	1.53	0.87
Short project	2.44	1.35	1.00	0.85	0.80	0.80	1.50	0.87
City A half size								
Long project	2.53	1.36	1.00	0.86	0.83	0.83	2.66	1.31
Short project	2.44	1.35	1.00	0.85	0.80	0.79	2.54	1.29

Dynamic WB1 is comprised of a much smaller number of non-zero terms compared with static WB1. For the short distance project, with masses increasing in five zones, only $5 \times 441 = 2205$ terms out of the 194 481 are affected ($\Delta M_{ij} > 0$) — the five mass increases in each of the 441 EDs. For the inverse curves, as α becomes more strongly negative, only 25 terms increase and other 2180 non-zero terms fall. The terms that increase are close to the zones where the mass increases occur.

For dynamic WB1, equation 6 showed that the elasticity of $WB1_i$ with respect to M_{ij} is $\eta_{s_{ij}}$. Figure 7 plots the eight WB1 ratios in table 4 for the city A against the productivity elasticities for city A in table 2 along with a line through the origin. The WB1 estimates are shown to be approximately proportional to the productivity elasticities indicating that the positive and negative changes to the terms of dynamic WB1 approximately cancel out as the decay curve is changed.

To explain this, from equation 7, if economic mass increased in just one zone j , the total dynamic WB1 would be

$$\text{Dynamic WB1} \approx \eta \sum_{i=1}^n (s_{ij} \cdot GVA_i) \frac{\% \Delta M_j}{100} \quad (13)$$

Figure 7: Dynamic WB1 ratio for city A plotted against η for all decay curves


Note: All eight points are shown, but not all labels to avoid cluttering

While $\sum_{j=1}^n s_{ij} = 1$ for all i regardless of decay curve (the shares in ED_i must sum to one), $\sum_{i=1}^n s_{ij}$ (the sum of shares in all EDs for zone j with one term from each ED_i) varies, although, on average, they sum to one ($\sum_{j=1}^n (\sum_{i=1}^n s_{ij}) / n = 1$). For a mass increase in a given zone j , the share terms in equation 13 represent the full range of trip lengths along a decay curve, so that $\sum_{i=1}^n s_{ij}$ does not change greatly as the decay curve alters. The proportionality of dynamic WB1 to productivity elasticity becomes less approximate as the number of zones with mass changes rises. In the extreme, if all masses in the city increased by a uniform percentage, all project-case EDs would be higher than base-case EDs by the same percentage regardless of the decay curve.

8 Alternative impedance measures

The range of alternative impedance measures — straight-line distance, actual distance, in-vehicle time, generalised time or generalised cost — was mentioned in section 3 above. Our decay curve discussion and simulation model permit some further observations to be made about choice of units and whether there needs to be consistency between the measure used for estimating productivity elasticities and WB1 in CBA.

Equation 12 above showed that inverse decay curves are homogeneous of degree α in order to explain why changing city size in our simulations has no effect on productivity elasticity estimates based on inverse decay curves. A further implication of this property of inverse decay curves is that changing the units in which impedance is measured has no effect on relative EDs (Graham and Gibbons forthcoming). Changing units (for example, minutes to kilometres travelled with a uniform speed, or kilometres to miles) multiplies all decay factors by a constant and hence does not alter productivity elasticity and WB1 estimates. Productivity elasticities derived using one can be applied in CBAs using the other. This makes inverse curves more convenient to use than other curves, but does not imply that they better model the relationship between productivity and agglomeration.

Exponential decay curves, $DF = e^{\beta g}$, have an elasticity βg , which varies along the curve. A change of units would require an offsetting change in β to keep the decay curve elasticity the same between each pair of zones.

Graham (2007b) found that productivity elasticities estimated from EDs that use generalised costs as the impedance measure tend to be some 30% higher than elasticities estimated from straight-line distance EDs. The reason given is that road congestion reduces generalised cost-based EDs for the densest zones relative to the other zones, which lessens the variation in EDs. Graham prefers straight-line distance EDs to estimate productivity elasticities to avoid endogeneity due to higher congestion in and around dense, higher productivity areas. Straight-line distances, however, ignore effects of estuaries and rivers on actual trip distances. Thus there may be case for using actual distances travelled, though routes might be more direct to and from more dense areas.

Using a generalised cost measure that includes costs that are fixed with respect to trip distance and time such as fares, tolls, parking charges and costs of waiting, transfer, access and egress time, is equivalent to adding a constant to trip impedances. For inverse decay curves, adding a constant to transport impedance changes ED variability and hence productivity elasticity estimates. To illustrate, adding 4.0 minutes, the zone width, to all trip times for our simulation, with no changes to the artificially generated productivity data, increases the productivity elasticity estimate for the base decay curve from 0.1 to 0.109.

Adding a constant to all impedances makes no difference for exponential decay curves because the decay factors are changed proportionately, that is, $\sum_{j=1}^n M_j \cdot e^{\beta(g_{ij}+k)} = e^{\beta k} \sum_{j=1}^n M_j \cdot e^{\beta g_{ij}}$. However, in practice, generalised costs between different origin–destination pairs in a city would have different fixed amounts in their generalised cost impedances, so ED relativities between many zones would still change.

A concern with estimating productivity elasticities using generalised costs with fixed additions is that some of the additions, in particular parking charges, may be higher for trips to and from high density areas, which would add to the endogeneity in the data already present due to congestion.

To investigate the impact on WB1 estimates, WB1 was re-estimated for the simulated hypothetical projects with 4 minutes added to all trip times. For static WB1, the one percent time saving from the projects was applied only to in-vehicle time, not the 4 minute additions to trip times. Table 5 presents the results expressed as percentage changes to WB1 compared with the WB1 estimates underlying the ratios in table 2. If the 0.109 re-estimated productivity elasticity is used, both types of WB1 are higher, more so for static WB1. Since the one percent time saving engendered by the project does not extend to the 4 minutes constant, the percentage saving in impedance ($\% \Delta g_{ij}$ in equation 10) is reduced, which reduces static WB1. However, the dominant effect is a redistribution in shares in EDs (s_{ij}) in favour of the more numerous longer distance trips, which increases WB1.

Switching to the base productivity elasticity of 0.1 reduces the increase in WB1, with the change in dynamic WB1 practically zero. This corresponds to the UK and New Zealand approaches that combine productivity elasticities estimated using straight-line distance EDs with WB1 estimation using generalised cost based EDs (UK Dft 2018, NZTA 2018).

Table 5: Percentage changes in WB1 estimates with 4 minutes added to all trip times and assuming the base decay curve

Productivity elasticity	Long project	Long project	Short project	Short project
	WB1 static	WB1 dynamic	WB1 static	WB1 dynamic
0.109	23.51	9.77	23.17	9.45
0.100	12.81	0.26	12.51	-0.03

Only results for the base decay curve were presented in table 5 to avoid confounding the effects of the changing both the impedance measure and the decay curve together. However, two observations can be made from tests with other decay curves. First, adding the 4 minutes to all trip times did not alter WB1 estimates for the exponential decay curves because, as explained just above, adding a constant to impedance in an exponential decay curve multiplies the decay factor by a constant. Second, the increases in static WB1 are much larger for curves with high decay rates ($\alpha = -2.0$, $\alpha = -2.5$ and $(\beta, \alpha) = (0.02, -3)$). This suggests that greater caution is needed when using generalised costs with fixed amounts at the beginning and end of trips with decay curves with more rapid decay rates.

In conclusion, consistency in impedance measures between productivity elasticity estimation and WB1 estimation is no guarantee of methodological soundness and inconsistent approaches can be preferable. This could be investigated further with more simulations.

9 Relationship with the gravity model and trip numbers

It was pointed out in section 2 that non-linear regression analysis is required to fit a decay curve to productivity data. An easier alternative approach might be to use a decay curve estimated to explain trip numbers in a gravity model.

The decay curves for trip and productivity forecasting purposes are related. Say the quantity of trips between zones i and j is explained by a gravity model,

$$T_{ij} = k M_i M_j \cdot f(g_{ij}) \quad (14)$$

Total trips in and out of zone i are $T_i = k M_i \sum_{j=1}^n M_j \cdot f(g_{ij})$, from which

$$\frac{T_i}{M_i} = k \sum_{j=1}^n M_j \cdot f(g_{ij}) = k E D_i \quad (15)$$

Thus the ED measure can be described as an index of predicted trip numbers per unit of economic mass derived from a gravity model.¹¹ Interestingly, the share variable, introduced in section 3 above, can be interpreted as the share of trips between zones i and j in total trips in and out of zone i .

$$s_{ij} = \frac{M_j \cdot f(g_{ij})}{\sum_{j=1}^n M_j \cdot f(g_{ij})} = \frac{T_{ij}/(k M_i)}{T_i/(k M_i)} = \frac{T_{ij}}{T_i} \quad (16)$$

¹¹ The type of trips depends on the economic mass variable, M_j . If it is employment, business-to-business trips are relevant. If it is resident workforce, then commuting trips are relevant. If it is total population then all trips are relevant.

Productivity gains from agglomeration do not arise from the mere fact of physical proximity. Actual trips are required. According to the theory, agglomeration economies are caused by both the *quantity* and *quality* of trips made. Better matching of workers to jobs and matching of employees to other employees meeting to exchange knowledge could occur with the same number of trips being made. However, equation 15 implies that no change in an ED can occur without changes in trip numbers per employee. Thus the ED measure implicitly assumes that the quality and quantity of trips are strictly correlated. This is consistent with Venables' (2007) model in which a transport cost reduction for commuters causes agglomeration benefits as a result of an increase in trip numbers.

The negative exponential decay curve is more often used as the impedance function in gravity models and is the most closely tied to travel behaviour theory (Handy and Niemeier 1997 p. 1177). However, it does not necessarily follow that the negative exponential curve is best for modelling productivity due to agglomeration. The transport mode and the mix of sources of agglomeration economies are not constant along the curve for productivity impacts. As noted above, there is some empirical support for short distance walking trips being an important source of learning agglomeration economies while matching and sharing apply more for longer motorised transport trips. In case the productivity impacts of short distance walking trips differ from those of middle and long distance trips by motorised transport, it may be advisable to fit decay curves from productivity data rather than trip data. Graham and Melo (2010) fitted a gravity model to trip data to estimate decay curve factors for assessing WB1 from high speed rail. However, the aim was to estimate WB1 from long distance commuting trips only, so the transition from walking to motorised transport trips was irrelevant.

Why not use trips per employee in each zone as the accessibility measure? Then, no decay curve would be needed at all. WB1 for transport projects would be estimated from the generated traffic forecasts of strategic transport models. A reservation is that the proportions of trips associated with the different sources of agglomeration economies (walking versus motorised) hence with different productivity impacts would vary between zones. Another difficulty is obtaining comprehensive data for walking trips. Mobile phone data might be a possible source, which would allow a trips-per-employee approach to be tested.

The need for physical trips to occur in order to have agglomeration benefits and the relationship in equation 15, raises the question of how well ED predicts actual trip numbers, and if the correlation is poor, which measure is more closely related to productivity. Also, with the small zone sizes in Australian strategic transport models, many origin–destination pairs have zero trips between them during some time periods. Yet these can still give rise to WB1 benefits.

10 Conclusions

Our simulations have shown that the decay curve assumption materially affects both productivity elasticity and WB1 estimates. Generally, a faster rate of distance decay leads to lower productivity elasticity and lower WB1 estimates. For dynamic WB1, the WB1 estimate is likely to be approximately proportional to productivity elasticity over the range of plausible decay curves. For static WB1, the main effect of a higher decay rate is to reduce WB1 by giving less weight to large numbers of longer trips that benefit from the transport project.

Inverse decay curves, which are the most commonly assumed functional form, have the advantage that the same productivity elasticity can be used for cities of different sizes, although city layout is also a factor. However, it is not certain that other forms of decay curve with non-constant elasticities along them might fit the productivity data better. The effect of different city layouts on productivity elasticities warrants further investigation.

The simulation approach in developed in our paper offers a novel way investigate a range of methodological issues with WB1 estimation including effects of different city layouts and alternative impedance measures.

Greater attention should be paid to the functional form and parameter values in decay curves when estimating productivity elasticities. Ideally, a decay curve would be estimated via non-linear regression for each industry group simultaneously with the productivity elasticity.

11 References

- Ciccone A. and Hall, A.R., 1996. Productivity and the Density of Economic Activity. *The American Economic Review*, 86(1), pp. 54-70.
- Di Addario, S. and Patacchini, E., 2008. Wages and the City. Evidence from Italy, *Labour Economics*, 15(5), pp. 1040-1061.
- Douglas N. and B. O'Keeffe, 2016. Wider Economic Benefits – When and if they should be used in evaluation of transport projects, *Australian Transport Research Forum Proceedings*.
- Drucker, J. and Feser, E., 2012. Regional industrial structure and agglomeration economies: An analysis of productivity in three manufacturing industries. *Regional Science and Urban Economics*, 42(1-2), pp. 1-14.
- Duranton, G. and Puga, D., 2004. Micro-foundations of urban agglomeration economies. In *Handbook of regional and urban economics* (Vol. 4, pp. 2063-2117). Elsevier.
- Graham, D.J., 2007a. Agglomeration, productivity and transport investment. *Journal of transport economics and policy*, 41(3), pp. 317-343.
- Graham, D.J., 2007b. Variable returns to agglomeration and the effect of road traffic congestion. *Journal of Urban Economics*, 62(1), pp. 103-120.
- Graham, D.J., Gibbons, S. and Martin, R., 2009. Transport investment and the distance decay of agglomeration benefits. *Report to the Department of Transport*.
- Graham, D.J. and Melo, P.C., 2010. Advice on the Assessment of Wider Economic Impacts: a report for HS2. *Imperial College, London*.
- Graham, D.J. and Van Dender, K., 2011. Estimating the agglomeration benefits of transport investments: some tests for stability. *Transportation*, 38(3), pp. 409-426.
- Graham, D.J., and Gibbons, S., forthcoming, Quantifying wider economic impacts of agglomeration for transport appraisal: existing evidence and future directions, *Economics of Transportation*.
- Handy, S.L. and Niemeier, D.A., 1997. Measuring accessibility: an exploration of issues and alternatives. *Environment and planning A*, 29(7), pp. 1175-1194.

- Hensher, D.A., Truong, T.P., Mulley, C. and Ellison, R., 2012. Assessing the wider economy impacts of transport infrastructure investment with an illustrative application to the North-West Rail Link project in Sydney, Australia. *Journal of Transport Geography*, 24, pp. 292-305.
- Le Néchet, F., Melo, P.C. and Graham, D.J., 2012. Transportation-induced agglomeration effects and productivity of firms in megacity region of Paris basin. *Transportation Research Record*, 2307(1), pp. 21-30.
- Maré, D. and Graham, D., 2009. *Agglomeration Elasticities in New Zealand*, New Zealand Transport Agency Research Report 376.
- Melo, P.C., Graham, D.J. and Noland, R.B., 2009a. A meta-analysis of estimates of urban agglomeration economies. *Regional science and urban economics*, 39(3), pp. 332-342.
- Melo, P.C. and Graham, D.J., 2009b. *Agglomeration economies and labour productivity: Evidence from longitudinal worker data for GB's travel-to-work areas*. SERC Discussion paper 31.
- Melo, P.C., Graham, D.J., Levinson, D. and Aarabi, S., 2017. Agglomeration, accessibility and productivity: Evidence for large metropolitan areas in the US. *Urban Studies*, 54(1), pp. 179-195.
- New Zealand Transport Agency (NZTA), 2018. *Economic Evaluation Manual*.
- Rice, P., Venables, A.J. and Patacchini, E., 2006. Spatial determinants of productivity: analysis for the regions of Great Britain. *Regional science and urban economics*, 36(6), pp. 727-752.
- Rosenthal, S.S. and Strange, W.C., 2003. Geography, industrial organization, and agglomeration. *Review of Economics and Statistics*, 85(2), pp. 377-393.
- Rosenthal, S.S. and Strange, W.C., 2004. Evidence on the nature and sources of agglomeration economies. In *Handbook of regional and urban economics* (Vol. 4, pp. 2119-2171). Elsevier.
- Rosenthal, S.S. and Strange, W.C., 2008. The attenuation of human capital spillovers. *Journal of Urban Economics*, 64(2), pp. 373-389.
- UK Department for Transport (UK DfT), 2007. *The additionality of Wider Economic Benefits in transport appraisal*, Department for Transport, London.
- UK Department for Transport (UK DfT), 2018. *Transport Analysis Guidance (TAG) UNIT A2.4: Appraisal of productivity impacts*, <https://www.gov.uk/guidance/transport-analysis-guidance-webtag>
- Venables, A.J., 2007. Evaluating urban transport improvements: cost–benefit analysis in the presence of agglomeration and income taxation. *Journal of Transport Economics and Policy*, 41(2), pp. 173-188.
- Worsley, T., 2011. *The evolution of London's Crossrail scheme and the development of the Department for Transport's economic appraisal methods*. International Transport Forum Discussion Paper 27.

Acknowledgments

The author is grateful to Dr Neil Douglas, Dr Peter Tisato and anonymous reviewers for comments on earlier drafts. Any errors remain the responsibility of the author.