ESTIMATING BENEFITS OF INFRASTRUCTURE THROUGH THE ANALYSIS OF LAND VALUE

by

Yoshitsugu Kanemoto

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Water Supply and Urban Development Department
Operations Policy Staff
The World Bank

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Yoshitsugu Kanemoto *

University of Tsukuba and Queen's University

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1. **Introduction**

An investment in urban infrastructure such as roads, electricity, water supply, sewerage, and telecommunication requires careful cost-benefit analysis because financial profits of a project do not in general indicate the social desirability of the project. A major problem is that tariff revenues generally underestimate the benefits of an infrastructure investment.

Loosely speaking, the total benefit of an investment (which must be compared with the total cost in cost-benefit analysis) is the total willingness-to-pay for the project, i.e., the total amount of money that people would pay for the project. For various reasons, the total willingness-to-pay is larger than the total revenue.

First, some infrastructure components cannot be priced or the cost of enforcing collection of charges is excessive, e.g., roads and parks. Even if prices are charged, price levels which are determined by public authorities are usually very low. Moreover, in developing countries, illegal use of services, such as illegal connections and failure to pay the bills, is not rare. Quite often, there are also externalities to infrastructure services. For example, benefits from the consumption of better water connections accrue not only to the individual consumers, but also to their neighbors in the form of better health due to less infectious diseases. The same would be true of roads, garbage disposals, etc. Tariff revenues in these cases are not good signals of the benefits of infrastructure.

Second, there is considerable scale economy in the production of infrastructure services and an investment in infrastructure is usually "large". The benefits of a large investment include a change in the consumer's (and producer's) surplus in addition to a change in the tariff revenue. It is always difficult to measure the consumer's surplus because of
the difficulty of estimating the demand function of infrastructure services.

This paper illustrates one way of measuring the benefits of infrastructure which uses observations of land value differentials. This approach is not, of course, complete although it works well under certain circumstances. However, considering the inherent difficulty of estimating the benefits of infrastructure and drawbacks of other approaches (see Diewert (1985)), this approach deserves serious attention.

The idea behind the use of land value in measuring the benefits of infrastructure is the renowned capitalization hypothesis. According to this hypothesis, the benefits of infrastructure are capitalized into a rise in land prices, and the benefits can be inferred by observing these land prices. In particular, we use cross-sectional capitalization: land values at different locations are different if they have different endowments of infrastructure, and land value differentials reflect the benefits of different levels of infrastructure. Thus, our objective is to estimate economic benefits of infrastructure services in urban areas through measurement of land value differentials.

The main text provides guidelines for empirical implementation of this approach. Since details of empirical implementation depend on specific circumstances, this paper falls short of being a manual, and many additions and modifications must be made to apply it to a specific urban area. For a successful application, therefore, sound understanding of the theoretical foundations, which are reviewed in the appendices, is essential.

The organization of this paper is as follows. In Section 2, conditions and constraints which would either increase or impede the applicability of the land-value-based approach are described. Guidelines for collection of data are provided in Section 3. This section deals with a sample design of
selected plots and the selection and measurement of variables to be observed. Section 4 illustrates a statistical procedure for estimating the hedonic land price function which is used in benefit estimation. How the benefit estimates of an infrastructure investment can be obtained from the estimated hedonic price function is explained in Section 5. Finally, Section 6 discusses interpretation and reliability of the results.

In Appendix A, theoretical foundations for cross-sectional capitalization are reviewed; this is not technical and should be accessible for readers who do not have a strong mathematical background. Appendix B reviews literature on hedonic estimations of the benefits of non-market goods. Appendix C contains a theoretically rigorous analysis of a certain aspect of cross-sectional capitalization to accompany Appendix A.

2. **Conditions for the Applicability of the Hedonic Approach**

Whether or not land value differentials yield reasonable estimates of benefits of infrastructure depends on many conditions. They may be classified into two categories: (i) theoretical conditions for land value differentials to reflect benefits of infrastructure and (ii) statistical conditions which are required for successful empirical implementation.

According to the capitalization hypothesis, the benefits of better infrastructure are reflected in higher land values. Examination of this hypothesis will reveal the conditions for applicability of the land-value-based approach to benefit estimation of infrastructure. Even if all the theoretical conditions are met, however, empirical implementation is by no means easy. The main reason is that many factors other than infrastructure influence land value. In order to isolate the effects of infrastructure, one has to control for other factors, which leads to many statistical problems.
In the following, the theoretical and statistical conditions will be discussed separately.

2.1 Theoretical Conditions: Validity of the Cross-Sectional Capitalization Hypothesis

The theoretical foundations of the capitalization hypothesis summarized in Appendix A suggest the following conditions for the applicability of the hedonic approach:

1. The most important assumption in the cross-sectional capitalization hypothesis is that movement of households and producers between different areas is free and costless. An area with better infrastructure endowment commands a higher land price because otherwise many households and producers would want to move into the area and there would be excess demand for land. For land value to reflect the benefits of infrastructure, therefore, mobility between different areas is crucial.

This shows that the hedonic approach yields better benefit estimates if moving costs (both social and pecuniary) are smaller. This also implies that if there is public control of locational decisions of households and firms such as land use zoning, the hedonic approach may not be applicable. Note, however, that what is required for cross-sectional capitalization is mobility between sampled locations. If, for example, samples are taken from both commercial and residential zones and if there is land use zoning for these two uses, the hedonic approach may yield misleading results. However, if all samples are from either one of the two zones, land use zoning causes no problem for our analysis.

Theoretical discussions in Appendix A also suggest that if mobility is less than perfect, land value differentials tend to underestimate the benefits of infrastructure. Land value differentials reflect the benefits of
infrastructure if the utility levels and the profit levels are equalized across different areas. With significant moving costs, immigration is not sufficient to equalize the utility and profit levels, and higher utility and profit levels may capture some of the benefits of better infrastructure.

2. The land market must be competitive. In particular, demanders of land must not have monopoly power. Otherwise, the monopoly profit may capture part of the benefits of infrastructure. The market for residential and commercial land is usually quite competitive, but this may not be true of the land market for the manufacturing sector. Obviously, a rent-controlled area must be avoided because rents in such a region are usually lower than the competitive market rents.

3. Households and firms may choose different lot sizes when the levels of infrastructure services are different. This creates a tendency for land rent differentials to overestimate the benefits of infrastructure, since cross-sectional differentials ignore the fact that an infrastructure investment changes the lot sizes.

Consider two otherwise homogeneous areas with different levels of infrastructure endowment, where area 2 has better infrastructure than area 1. Land rent is obviously higher in area 2 with superior infrastructure than area 1 with inferior infrastructure. Consider next an investment in infrastructure in area 1 which equalizes the levels of infrastructure in the two areas. The difference in before-investment land rents in the two areas measures the benefits of superior infrastructure relative to inferior structure. Since land rents depend on lot sizes, however, the benefits measured in this way do not necessarily coincide with the benefits of improving the infrastructure in area 1. That is, the land rent differential measures the benefits of superior infrastructure at the before-investment lot
size in area 2, whereas the benefits of infrastructure investment in area 1 are the benefits of the superior infrastructure at the after-investment lot size in area 1.

Appendix C shows that this effect tends to make land rent differentials overestimate the benefits of infrastructure investment. The magnitudes of errors depend on the substitutability between land and other goods and in general they can be very large for a large investment. This approach, however, yields better estimates if the substitutability between the lot size and other goods is smaller, the infrastructure investment is smaller, and the area which benefits from the investment is smaller; and in the limit land rent differentials provide precise benefit estimates.

4. If prices or tariffs are charged for services of infrastructure, land value differentials measure only the consumer's surplus part of the benefits and an appropriate benefit measure is the sum of the tariff revenue and the measure derived from land value differentials. If infrastructure services are fully or partially financed by local taxes, which vary across jurisdictions, these taxes will work in a similar way to tariffs and the differences in taxes between different locations must be added to land value differentials.

5. If households and firms which benefit from infrastructure have different valuations of the infrastructure, land value differentials tend to overestimate the benefits of a large investment. The method therefore works better if samples are drawn from a relatively homogeneous population.

In Appendix C, it is shown in a two region model that land value differentials tend to overestimate the benefits of even a small investment if households and firms are heterogeneous. This problem arises, however, because different types of consumers live in a homogeneous area (either one of the two areas) and pay the same rent. In reality, it is difficult to find a
homogeneous area of significant size, since land is almost continuously
differentiated by locational and other characteristics. In such a case, land
rent differentials yield correct measures at least in the case of an
infinitely small investment.

6. Land value is a discounted sum of expected future rents. If a future
investment in infrastructure is expected, this will also be capitalized into a
rise in land value. Regression of land value on current levels of
infrastructure may lead to seriously biased benefit estimates in this case.
One must therefore avoid collecting data from locations where people expect an
infrastructure investment in the near future.

Expectations may play another important role in the capitalization effect
in developing countries. For example, in squatter communities the provision
of some infrastructure may be taken as a signal that risk has been reduced and
may be taken as a signal that risk has been reduced and may cause a
disproportionately large increase in land prices.

2.2 Statistical Conditions: Reliability of the Hedonic Regression

Even if capitalization is perfect, there may still be many difficulties
in empirical implementation of the hedonic approach, since many factors other
than infrastructure affect land value. In order to control for other factors,
the hedonic approach regresses land value on all relevant characteristics such
as proximity to the city center and neighborhood quality in addition to
infrastructure endowments. In actual estimations, some or many of the
important variables may be difficult to measure and some of the
characteristics may be correlated with others, which lead to the following
statistical problems.
1. It is of course essential to have good data on market values of land. If price data from actual transactions are available, these must be used. If such data are not available, the best substitute among those available must be used. Possible substitutes are "assessed" values by real estate experts, the government, and owners. Note that these data may not be good substitutes for market prices, since we are interested in evaluations by demanders while these represent evaluations by real estate assessors and the government. Furthermore, it is quite often difficult to know the value of land alone because buildings and land cannot be separated. For example, the price of a house usually includes the values of both land and structures. In such a case, property values instead of land values have to be used. Since property values reflect characteristics of structures in addition to those of land, data on structural characteristics are needed to control for differences in structures.

2. Land is a highly heterogeneous commodity differentiated by locational, environmental, and topographical characteristics in addition to infrastructure endowments. If property value data are used, structural characteristics must also be considered. Since market prices reflect all these characteristics, it is difficult to isolate the effects of infrastructure. In order to control for other characteristics, the hedonic approach regresses land value on all relevant characteristics and examines the effect on the land value of a change in infrastructure keeping all other characteristics unchanged.

3. In the hedonic regression, best efforts must be made to include all the important characteristics of land. If an important characteristic is omitted, the estimated coefficients are biased due to the omitted variable problem. If, for example, the levels of infrastructure services are
positively correlated with the environmental quality which is not observable (for the researcher), the value of infrastructure will tend to be overestimated, since it captures part of the contribution of the environmental quality.

4. In order to estimate the contribution of infrastructure to land value, it is essential to have sufficient variation in the levels and/or qualities of infrastructure services. If, for example, infrastructure is uniform for the entire samples, there is no way of knowing the value of infrastructure.

5. Researchers using the hedonic approach have often encountered the multicollinearity problem: since correlation between characteristics is very strong (better neighborhoods tend to have better houses, better public facilities, better environment, better infrastructure, and so on), the estimated coefficients have high standard errors and are unreliable. Although some statistical techniques such as the use of the ridge regression and the principal component analysis have been proposed, multicollinearity is basically a problem of samples and the best cure is to make sure that samples have sufficient variations in the combination of different characteristics. The main reason why many researchers encountered severe multicollinearity problems is that they used samples which are not suitably designed for the purpose of hedonic regression. For a successful implementation of the hedonic approach, it is crucial to use an appropriate sampling procedure which ensures sufficient variation in the variables. This will be discussed more fully in the following section on the collection of data.
3. **Collection of Data**

Since no statistical procedure is capable of extracting any more information than that already contained in the data, data collection and sample design are extremely important. The objective of our research is to estimate the benefits of infrastructure and sampling of plots must be geared to this objective. In this respect, it is imperative to obtain a sufficient number of samples from areas with different levels of infrastructure services. The first task is therefore to study the spatial distribution of infrastructural services in terms of their availability and quality, and to classify the areas by infrastructure characteristics. For example, there could be an area with no power connection, an area with low quality power connection (e.g. frequent blackouts), and an area with high quality power connection (e.g. stable electricity supply).

A sufficient number of samples must be drawn from each of these areas. If possible, stratified random sampling is recommended. A city is first stratified into areas with different infrastructure characteristics, and samples are drawn randomly from each area. It is customary to set the number of samples in each area in proportion to its relative population size. That is, if there are two areas with 500 houses and 1,000 houses respectively, the number of samples in the first area is a half of that in the second area. There is, however, no strong reason to use this procedure. If some area has a disproportionately small population size, it may be better to draw (proportionately) more samples from that area.

There is no definite rule as to the total number of samples that need to be taken. A larger sample size makes the estimates more precise, but this advantage must be weighed against the cost of obtaining the samples. It also depends on the number of attributes that have to be considered: more samples
are necessary to achieve the same level of precision if more attributes have
to be considered. Since most of the existing hedonic studies have more than
200 samples, it would be advisable to aim at collecting at least 200
observations. Note also that there is certain scale economy in data
collection so that it is less costly to collect a large number of observations
than to do the same survey twice if the original sample size is found too
small.

In the design of sampling, it is always necessary to clearly define the
population to draw samples from. If residential land is considered, for
example, we must specify what type of houses are included in the population.
The population may be all owner-occupied houses, or houses occupied by a
certain income group. In the case of industrial land, the population may be
all manufacturing industry or only the textile industry, for example. Since
perfect capitalization for a large investment requires a homogeneous
population, the benefit estimates are more reliable if we consider a finer
classification. In the case of industrial land, for example, it is desirable
to analyze different industries separately.

When a sufficient number of samples cannot be obtained from one city, it
is necessary to sample from more than one city. Since various conditions are
different in different cities, there is no reason to believe that all cities
have the same hedonic price function. If the benefits of infrastructure are
approximately the same across cities, however, we can estimate a hedonic price
function by adding a dummy variable representing different conditions in
different cities.

Next, the variables which must be observed at each plot are:

(i) land value (or property value)
(ii) attributes of the plot, and
(iii) attributes of the occupant.

First, land value per unit area (e.g. per square meter) should be observed. Actual transaction prices are preferable, but if they are not available, assessment by real estate specialists may have to be used. Land value here does not include the value of structure. If it is impossible to separate the value of land from the value of property including structure, the property value may be used. In such a case, however, the attributes of structure must be measured and included in the attributes of the plot. If the inflation rate is high, land values obtained at different points in time must be deflated suitably and measured in constant prices. This also applies to a real price increase over time if such a price increase is significant.

Second, attributes of a plot include infrastructural, locational, topographical, and environmental attributes which are important determinants of demand for land. The criterion for the selection of the attributes to be observed is therefore the importance of the attributes for decisions of the occupant. Before conducting a survey, it is recommended to ask some or the occupants about what sorts of attributes are important for them.

The most important in our context are attributes of infrastructural services. They include availability, quality, and tariff schedules of infrastructural services. Since the quality of services can be very important, quality characteristics must be observed (e.g. road width and pavement, water supply with yard connections or community tap with distance specified, power connection with frequencies of blackouts, distance and quality of schools and health posts). Specific selection of quality attributes depends on the circumstance and must be determined in such a way that important attributes for occupants can be represented.
In developing countries, the supply side of infrastructure services may be quite complex. First, there may be private supply of the same type of services, e.g., private garbage collectors and privately owned electricity generators. This does not, however, change our analysis significantly. Since the benefits of infrastructure must be judged relative to its private alternatives, private supply represents an alternative situation without public infrastructural services and it can simply be treated as non-existence of public infrastructure. Second, there are often illegal tapping of water supply sources and electricity connections. In such a case, the benefits accrue to illegal users in addition to legal users and land prices in areas where illegal use is easy are higher than in other areas. Ideally, one wants to include the possibility of illegal connections in the quality characteristics of infrastructure, although this may be difficult in reality.

Tariff schedules are one of the determinants of market land value and they must be included if they differ at different locations. Since the tariff revenue must be added to land rent differentials to compute the benefits of infrastructure, revenue data must also be collected.

There are many other attributes which are important determinants of land value. Prominent examples are accessibility as measured by distance to city center, a port, major highway, and a train station; environmental quality such as air and water pollution; neighborhood characteristics such as crime rate; the shape and the frontage to the street; and so on. If property value instead of land value is used, structural attributes such as the number of rooms and construction materials must be added to the list.

The hedonic price function which explains the value of land by attributes of a plot yields a "willingness to pay" function for land of its occupant if all occupants are homogeneous. If they are heterogeneous, however, these two
functions are equal only locally and the hedonic price function provides biased benefit estimates, as explained in Appendix A. In order to estimate a willingness-to-pay function, or a bid price function, we need observations of attributes of occupants. Although consensus has not emerged concerning which technique should be used to estimate a bid price function, it is advisable to collect data on attributes of occupants and to try some of the proposed techniques.

Examples of attributes of occupants are income, family size, the age of the head of the family, and so on. In the case of firms, they are the industry type, number of employees, the output level, the wage rate, the nature of capital equipment, and so on.

4. The Estimation of the Hedonic Price Function

In a hedonic approach, each plot of land is identified by a bundle of its attributes such as the availability and quality of infrastructural services, accessibility to the city center and a major highway, neighborhood characteristics, frontage, and so on. The equilibrium price is then determined as a function of these attributes. Given the observed equilibrium price function, each household (or each firm) chooses a plot of land which maximizes its utility (or profit). Rosen (1974) characterized a market equilibrium in an hedonic model using the concept of the bid price function. The bid price function is defined as the maximum price that a household is willing to pay for a certain plot while attaining a certain utility level. The bid price function then represents the willingness-to-pay for a plot. Since a plot of land is bought by a household with the highest bid price, the equilibrium price is the upper envelope of bid price functions of different households. 2/
Although the bid price function which can be interpreted as the willingness-to-pay function yields more appropriate benefit measures, it is difficult to estimate. The first task in estimating the benefits of infrastructure is therefore to estimate the equilibrium price function (or the hedonic price function) which is much easier to estimate.

If a linear form is chosen for the hedonic price function, the equation to be estimated looks like

\[ p = a_0 + a_1 z_1 + a_2 z_2 + \ldots + a_n z_n + u, \]

(4.1)

where \( p \) is the price of land, \( z_i \) is the \( i \)-th attribute, \( a_i \)'s are parameters to be estimated, and \( u \) is an error term. In this case, \( a_i \)'s can be estimated by ordinary least squares (OLS). Unfortunately, however, there is no guarantee that the linear form is the best one. The form of the hedonic price function cannot be specified on theoretical grounds and must be determined statistically. An alternative form would be log-linear where all or some of the variables are transformed into logarithmic form, i.e., \( \log p \) or \( \log z_i \) is used instead of \( p \) or \( z_i \) in (4.1).

It should be noted that when the dependent variable, \( p \), is transformed, the coefficient of determination, \( R^2 \), cannot be used to compare the goodness of fit of different functional forms. In such a case, the value of the likelihood function is used as an indicator of goodness of fit and a functional form which maximizes the likelihood function should be chosen.

Recently, the Box-Cox transformation is often used in the choice of functional form. For example, see Goodman (1978) and Linneman (1980). The Box-Cox transformation is defined as
where $v$ is a parameter to be chosen. The transformation can be interpreted as a general form of a power function and includes linear ($v = 1$) and logarithmic ($v = 0$) forms as special cases. Using the Box-Cox transformation, we can write the hedonic price function as

$$p^*(v) = a_o + a_1 v_1 + \ldots + a_n v_n^n + u,$$

where $v_i$ is a parameter in the Box-Cox transformation.

Since equation (4.3) is nonlinear in $v_i$'s, a nonlinear estimation method must be used. The following two-step procedure is commonly used.

(i) For some arbitrary choice of $v_i$'s, estimate $a_i$'s by the ordinary least squares (OLS) method.

(ii) Compute the value of the likelihood function and change $v_i$'s to raise the value. For new values of $v_i$'s, repeat the first step, and continue changing $v_i$'s until the value of the likelihood function converges to its maximum.

A computer package called SHAZAM contains a program which carries out this procedure automatically. If other packages, such as TSP, are used, one has to write a program for this procedure.

In practice, this procedure works reasonably well in terms of convergence if one or two parameters in the transformation are estimated. If more than three parameters are estimated, however, convergence is difficult to attain. It should also be noted that the transformation is meaningless for a dummy variable such as $z_i$ with $z_i = 1$ if there is power connection and $z_i = 0$ if
there is no power connection, since any transformation of the variable can be undone by a change in the coefficient, $a_i$.

It is possible to use a more general functional form. For example, Halvorsen and Pollakowski (1981) applied the Box-Cox transformation to a flexible functional form which is a second-order approximation of any twice continuously differentiable function.

As noted before, the hedonic price function tends to overestimate the benefits of infrastructure if occupants of the plots are not homogeneous. In order to correct this bias, we have to estimate the bid price function. As explained in Appendix B, a number of estimation methods have been proposed for the bid price function, but at this stage it is not clear how reliable they are. I do not, therefore, spell out the details of the estimation methods here. Interested readers are referred to Appendix B and references therein. It is worthwhile, however, to try some of the methods and to see how different the benefit estimates are, since once the data are collected and prepared for estimation, actual estimations do not require much time and effort. It should be noted that I am not recommending the use of the estimated bid price functions in benefit estimation of infrastructure at this stage. Rather, I am hoping that by accumulating the experience of estimating the bid price function we eventually find out the reliability of various estimation methods.

5. Identification of the Benefits of Infrastructure Services

Now, suppose that the hedonic price function has been successfully estimated: $p = p^* (z_1, z_2, \ldots, z_n)$. Consider an infrastructure investment in a certain area which changes the quality (or availability) of services from $z_1^0$ to $z_1^1$ and the price of services from $z_2^0$ to $z_2^1$. Then, for each sampled
plot in the area, we can compute the part of the benefits capitalized into land value by

$$B^j = p^*(z_1^j, z_2^j, z_3^j, ..., z_n^j) - p^*(z_1^0, z_2^0, z_3^0, ..., z_n^0),$$

(5.1)

where superscript $j$ denotes attributes for the $j$-th sample. Note that since land value is measured per unit area, the benefit here is also measured per unit area.

If samples are taken randomly, their benefit distribution approximates the benefit distribution over the entire area. In such a case, the total benefit is obtained by

$$B = \frac{\bar{H}}{\sum_j H_j^j} \sum_j H_j^j B_j^j,$$

(5.2)

where $H_j^j$ is the area of the $j$-th plot and $\bar{H}$ is the total area of the region which receives the benefits of the investment.

If tariffs are charged for infrastructure services, the total tariff revenue in the region, $Q$, must be added to the above land-value-based benefit measure, $B$. If the sum, $Q+B$, exceeds the sum of the cost of the investment and the operating cost of infrastructure services, the investment is worth undertaking.

6. **Interpretation of the Results**

There are two distinct issues on the reliability of the benefit estimates. One is whether or not land value capitalizes the benefits of infrastructure, and the other is whether the estimated hedonic price function is statistically reliable. The second problem remains even when capitalization is perfect, and the first problem may still exist even when parameter estimates are statistically accurate.
So far, no statistical (or any other) procedure has been developed to evaluate the magnitude of bias caused by the first problem. The importance of this problem, therefore, should be judged somewhat subjectively according to the conditions for perfect capitalization explained in Section 2.

The second problem, however, may be evaluated by a statistical procedure. First, consider the case where the estimated hedonic price function is linear in parameters as in (4.1). Let \( \hat{a}_1 \) denote the estimate of the true value, \( a_1 \). The estimated benefit at the \( j \)-th plot is then

\[
\hat{B}_j = \hat{a}_1 (z_1^j - z_0^j) + \hat{a}_2 (z_2^j - z_2^0)
\]

and the true benefit is

\[
B_j = a_1 (z_1^j - z_1^0) + a_2 (z_2^j - z_2^0).
\]

The difference between \( \hat{B}_j \) and \( B_j \) is normally distributed if the error term, \( u \), is normal. The confidence intervals for the estimate can be constructed by noting that \( (\hat{B}_j - B_j) / s \) is distributed according to the t-distribution with \( N-n-1 \) degrees of freedom, where \( s \) is the estimated standard error of \( \hat{B}_j \), \( N \) is the sample size, and \( n+1 \) is the number of estimated parameters. The estimate of the standard error of \( \hat{B}_j \) can be easily obtained by using the ANALYZ routine in TSP. The confidence interval for the total benefit, \( \hat{B} \), follows directly from that for \( \hat{B}_j \): \( \hat{B} = \bar{B}_j \hat{B}_j \), since in this linear case all \( \hat{B}_j \)'s are equal.

If the estimated hedonic price function is not linear in parameters, then statistical analysis is more difficult, since we cannot in general obtain finite-sample distributions of estimated parameters. However, it is known that maximum likelihood estimates have normal distributions asymptotically, i.e., as the number of samples tends to infinity. If the sample size is large enough to justify the use of asymptotic distributions, we can use this property and obtain approximate confidence intervals for the benefit estimates.
Since in a nonlinear case the benefit estimate, \( \hat{B} = b(\hat{a}) \), is a nonlinear function of parameter estimates, \( \hat{a} \), precise computations of confidence intervals are difficult even if asymptotic distribution can be used. An approximation can be obtained, however, by taking a first-order Taylor expansion of \( \hat{B}(\hat{a}) \):

\[
\hat{B} - B = \frac{\partial b(a)}{\partial a} (\hat{a} - a) = D.
\]

Consequently, \( D \) is asymptotically normal and confidence intervals can be constructed by using the estimated standard error of \( D \).

Note that these statistical procedures assume that there will be no change in the area between the time when data are collected and the time when new infrastructure services are provided. If there is a change in population and income levels, for example, the benefit estimates may be biased. Since the hedonic price function is merely a locus of equilibrium prices, it contains no information on the effects of a change in exogenous variables. The bid price function, on the other hand, is a function of exogenous variables such as income levels which affect demand for land and can be used to incorporate such a change.

Finally, the hedonic approach can be applied to the benefits received by industrial and commercial firms. In the case of firms, the capitalization hypothesis requires that firms obtain the same profit level at different locations. All the results obtained in the case of households hold as long as this assumption is satisfied.

Profit levels are equalized at different locations if firms are perfectly mobile, i.e., can change their locations with no costs. In many cases, however, mobility of firms is restricted because factories are often firm specific and it may be very costly to convert them into other uses. In such a
case, land value after the construction of a factory reflects the cost of conversion. Since the cost of conversion is difficult to observe, the resulting estimates may be unreliable. One way to avoid this problem is to use data from new purchases of lots with no buildings. Another possibility is to consider an industry where firms use the same or similar equipment. In the case of commercial land used for office and retail buildings, this problem seems less severe.

Even if mobility is limited, the assumption of equal profits are satisfied in the long-run equilibrium when there is free entry, since in such a case (economic) profits are zero. A stationary industry which is experiencing very little change in technology would approximate this case. Thus, the hedonic approach would yield reasonable benefit estimates when applied to a stationary industry with many small firms.

Finally, when the government is developing land for industrial use, it often gives subsidies to firms either directly or by selling the land at less than market price. Obviously, land price is not a good signal of the benefits of infrastructure in such a case.
APPENDIX A.

Theoretical Foundations

1. The Capitalization Hypothesis

The well-known capitalization hypothesis provides a theoretical basis for using land values to estimate benefits of a public project such as a transportation improvement, abatement of air and water pollution, and infrastructure investment. The capitalization hypothesis states that the benefits are capitalized into a rise in land prices (or equivalently, a rise in land rent in a static framework which we use below). The hypothesis has been examined by a number of economists, e.g., Polinsky and Shavell (1976), Pines and Weiss (1976), and Starrett (1981). The most important assumption in the hypothesis is that the population of the region affected by the project is endogenous: migration of households into and out of the region is possible. A public project first benefits residents of the community, but with the possibility of migration the story does not end here. The project causes immigration of new residents, since the community becomes more attractive. Demand for residential land then rises, which results in a rise in residential land rent. The commercial land rent also rises because firms can now hire workers at a lower wage rate and the marginal product of land rises. This argument suggests that the benefits of a public project are at least partially capitalized into a rise in land prices:

It has been shown that capitalization is perfect in a small open area which satisfies the following assumptions.

A. The area affected by the project is open in the sense that migration into and out of the area is free and costless.
B. The area is small compared with the rest of the economy.
C. There are a sufficient number of identical households.
D. The economy is in long-run competitive equilibrium with free entry of firms.

Assumptions A, B, and C together imply that the utility levels of the residents cannot change. If the utility level were to rise, there would be immigration of households and by Assumption A immigration would continue until a resident obtains equal utility levels in the area and the rest of the world. But, by Assumptions B and C, any change within the area causes only a negligibly small change in the utility level in the rest of the world. The public project, therefore, will not affect the utility level of the residents. By Assumption D, profits of firms are zero both before and after the project and hence constant. Since neither the residents nor the firms gain from the project, the only place where the benefits can go is landowners. Thus, if these four assumptions are satisfied, a change in land rent can be used to measure benefits of a public project.

It is extremely unlikely that all these assumptions are fully satisfied in reality. As long as they approximate the reality, however, a change in land rent provides a reasonable approximation of the benefit of a public project. We can identify whether approximations are good by checking whether the assumptions are close to the reality. Assumption A indicates that, in a society where the costs of migration are lower, land rents yield better benefit estimates. In a traditional society where migration is discouraged or in a region where mobility is limited by social and legal regulations, therefore, the use of land rents in benefit evaluation is not recommended. Also, capitalization is more perfect in the long run than in the short run,
since moving costs are one-time costs. For a person who decided to live in the new place for 50 years, the moving costs would not be very important.

If moving costs are significant, undercapitalization is more likely to occur than overcapitalization. When a public project raises the utility levels of residents, immigration of new residents will be induced. With significant moving costs, however, immigration is not sufficient to reduce the utility levels to the previous levels and some of the benefits accrue to residents. Land rent therefore captures only part of the benefits of the project.

Assumption B suggests that if a project affects a large area such as a whole city or region, a rise in land rent is not a good measure of the benefit of the project. It is not therefore advisable to use land rents to measure the benefits of the entire transportation system of a city, for example, but they may be used successfully to measure the benefits of an improvement of some part of the system. It is also expected that undercapitalization occurs if the area affected by a project is not small. Pines (1984) showed that this is true under fairly reasonable assumptions.

If households value a public project differently, then capitalization is also imperfect. In this case, too, undercapitalization is likely to occur, since new immigrants who chose to live elsewhere before the project do not value the area as much as old residents and they are not willing to pay the same rent as old residents.

Finally, in the short run, firms may be able to obtain excess profits because of a public project. A fall in wage rates caused by increased population may, for example, result in an increase in profits instead of a rise in land rent. In this case, too, undercapitalization is likely to be
obtained. In the long run, however, entry of new firms dissipates the excess profits and landowners capture the benefits.

In sum, an induced rise in land rent provides a better benefit measure of a public project, if moving costs (both social and pecuniary) are smaller, the project affects a smaller area, the long-run effects rather than short-run effects are considered, and households are more homogeneous in their evaluations of the project. The violation of these assumptions tends to cause underestimation of the true benefits.

2. **Cross-Sectional Capitalization**

The capitalization hypothesis is normally applied to a change over time: the difference between the after-the-project and before-the-project land rent levels reflects the benefits of a project. In practice, however, the assumptions required for perfect capitalization are not often satisfied and a change in land rent does not provide a good approximation of benefits. Most empirical works, therefore, use cross-sectional (or locational) variation in land rent instead of an over-time change. The capitalization hypothesis can obviously be applied to differences in land rent between regions with different levels of infrastructure if the utility levels and profit levels in the two regions are equalized. If migration between the regions is free and costless, therefore, cross-sectional variation in land rent can be used to measure the benefits of externalities.

Ridker and Henning (1967) regressed property values on measures of air pollution and other locational characteristics such as accessibility to highways and school quality, and used the regression coefficients to measure the benefits of pollution abatement. This paper generated a controversy over the interpretation of econometric studies of the relationship between air
pollution and property values. The debate was summarized by Polinsky and Shavell (1975) and the issue has been clarified by Polinsky and Shavell (1975), (1976) and Freeman (1974).

Recently, Scotchmer (1983) re-examined the use in benefit evaluation of cross-sectional differences in land rents within a general equilibrium framework. She found that even if the population is homogeneous, cross-sectional differences in land rents do not correctly measure the benefits of a large improvement, although they do provide a correct measure of an infinitesimally small improvement. The reason is that a large improvement changes the spatial distribution of the population through an induced change in lot sizes of the houses.

In Appendix C, simple general equilibrium models are developed to illustrate the problems associated with the use of spatial variations in land rent to measure the benefits of infrastructure investment. Major results are explained in the rest of this subsection.

Suppose there are initially two otherwise homogeneous areas with different levels of infrastructural capital. Land rent in area 2 with the higher level of infrastructure, \( r_2 \), is naturally higher than that in the other area (area 1) \( r_1 \). Then, consider an investment in infrastructure which raises the level of infrastructure in area 1 to the same level as in area 2. The question is whether the land rent differential in the initial equilibrium measures the welfare improvement from such an investment. More specifically, if \( \bar{H}_1 \) is the amount of land in area 1, does \( B = (r_2 - r_1) \bar{H}_1 \) yield a correct benefit measure of the improvement?

First, consider a case where no prices are charged for the services of infrastructure. The main result in this case is that if households and firms are homogeneous, then cross-sectional differences in land rents will, in
general, overestimate the benefits of a large infrastructure investment. They provide correct estimates, however, in any of the three following cases: (i) the investment is infinitesimally small, (ii) there is no substitutability between the lot size and other goods, and (iii) the area affected by the improvement is infinitesimally small relative to the rest of the world. These results hold for benefits received by firms as well as by households if profit levels are equalized across different locations, e.g., if firms are in long-run equilibrium with free entry, where they all earn zero profits.

The reason why land rent differentials overestimate the benefits of an infrastructure investment is that the lot sizes depend on the level of infrastructure. Land rent captures the benefits of infrastructure, but it depends on the lot sizes chosen by households (and firms if they receive benefits of infrastructure). Land rent in area 2 before the investment does not, therefore, measure the benefits obtained in area 1 after the investment, unless the lot sizes in these two cases are equal. Since the lot size chosen, after the investment, is optimal at the post-improvement land rent, it is not in general optimal at the pre-improvement land rent in area 2. The benefits obtained in area 1 are not, therefore, as large as the pre-improvement land rent indicates.

As this argument suggests, land rent differentials yield correct benefit estimates if the lot size chosen after the investment is the same as that before the investment. This is the case when the utility function is of the Leontief type, that is, there is no substitutability between the lot size and the consumer good. Note that what is required for correct estimation is that the optimal lot sizes before and after the investment are equal even if land rent changes. In the short run the lot size changes very little because of the durability of housing. This does not, however, imply that short-run
benefits are correctly measured by rent differentials, since in the short run the lot size is not chosen optimally but is predetermined historically. It is shown in Appendix C that if the lot size is optimal at the pre-improvement equilibrium, rent differentials overestimate the short-run benefits as well as the long-run benefits. If the lot size is suboptimal initially, then rent differentials may either underestimate or overestimate the benefits.

If the investment is infinitesimally small, the estimation is precise because the effect of a change in lot size is of second-order magnitude. If area 1, where the investment takes place, is infinitesimally small compared with area 2, then the estimation is also correct. In this case, there is no change in area 2 and, in particular, the rent there remains unchanged. Since the two areas have the same level of infrastructure after the investment, rents in the two areas must be equal. Rent in area 1 after the investment then equals rent in area 2 before the investment, and the rent differential in the pre-improvement equilibrium yields a correct benefit measure.

So far, we have assumed that services of infrastructure are provided free. Quite often, however, prices are charged for the services. For example, tariffs are usually levied on the consumption of electricity and water. Even in the case of roads, a tax on fuel consumption works in a similar way to a price of road services. When consumers pay a price, land rent captures the part of the benefit of infrastructure which is not already reflected in the price. That is, only the consumer's surplus is capitalized into land rent and the gross benefit, which is to be compared with the total cost of infrastructure in a cost-benefit analysis, is the sum of the tariff revenue and the consumer's surplus. Thus, the same results as before are obtained if the tariff revenue is added to the rent-based measure, B.
Although land rent differentials are usually used to estimate benefits received by households, the same results are obtained for benefits received by firms under the assumption that they are in long-run equilibrium with free entry. Under this assumption all firms earn zero profits and land rent reflects the benefits of infrastructure.

For intra-city variations in infrastructure, it is reasonable to assume that the wage rate is constant regardless of the locations of households and firms. In such a case, the benefits received by households are reflected in residential land rent and those received by firms are capitalized in industrial land rent. However, wage rates are not equal in different cities because, for example, consumers are willing to work at a lower wage rate in a city with better amenities. The benefits received by consumers may not, therefore, be entirely captured by a rise in residential land rent. In this case, industrial land rent as well as residential land rent must be taken into account. A lower wage rate raises the profits of firms but this causes new entry of firms and in the long run the lower wage rate is reflected in a higher industrial land rent. Thus, for inter-city variations, the sum of industrial and residential land rent differentials must be considered even if only firms or consumers receive benefits of infrastructure investment.

Finally, if households and/or firms are heterogeneous in their evaluations of infrastructure, the benefit measure based on land rent differentials is more biased. Consider two types of consumers, where those of type 2 value infrastructure more than those of type 1. Naturally, consumers of type 2 tend to live in area 2 with a higher level of infrastructure. Suppose, however, that there is a sufficient number of consumers of type 2 so that they live both in areas 1 and 2. Consumers of type 1 live only in area 1. Then, the land rent differential between areas 1 and 2 is determined in
such a way that consumers of type 2 are indifferent between the two areas. Since consumers of type 1 receive less benefit than those of type 2, the land rent differential overestimates the benefit of infrastructure improvement in area 1 where both types of consumers live. The upward bias does not disappear even in the cases where there is no substitutability between lot size and other goods, or if the investment is small, or area 1 is small compared with area 2.

Note, however, that this problem arises because different types of consumers live in a homogeneous area (i.e., consumers of both type 1 and type 2 live in area 1) and pay the same rent. In reality, it is difficult to find a homogeneous area of significant size, since land is differentiated by locational and other characteristics. The hedonic model discussed in the next subsection assumes that land is differentiated continuously by locational characteristics such as distance to the city center. In such a case land rent differentials yield correct measures at least in the case of an infinitesimally small investment.

In sum, the fact that the optimal lot size varies, depending on market and non-market conditions, creates a tendency for land rent differentials to overestimate the benefits of infrastructure. If households and firms are homogeneous, however, they provide correct estimates if there is no substitutability between the lot size and other goods, if the investment is infinitesimally small, or if the area affected by the investment is infinitesimally small relative to the rest of the world. Thus, benefit measures based on land rent yield better approximations if the substitutability is smaller, the investment is smaller, and the area which benefits from the investment is smaller. If consumers and/or firms are heterogeneous, an additional tendency for rent differentials to overestimate
the benefits is created. The land-value-based measure therefore works better if consumers and firms are more homogeneous in their valuations of infrastructure. If prices or tariffs are charged for services of infrastructure, an appropriate benefit measure is the sum of the tariff revenue and the rent-based measure. Finally, for inter-city variations of infrastructure, benefit estimation requires the use of both residential and industrial land rents even when only consumers or only producers benefit from infrastructure, since an infrastructure investment changes the wage rate.

3. **The Hedonic Approach**

Land is a highly heterogeneous good differentiated by its locational, topographical, and environmental characteristics such as distance to the city center, the nature of the ground, and distance to parks and major highways. Furthermore, because of the non-availability of land price data, property prices instead of land prices must often be used to estimate benefits of infrastructure. Since property prices reflect structural characteristics of buildings in addition to all the characteristics relevant to land prices, the heterogeneity problem is more severe. When many different attributes influence land values, the benefits of infrastructure are difficult to measure, since it is difficult to isolate the effect of infrastructure.

In dealing with differentiated commodities such as land and housing, the hedonic approach (which represents a good by a vector of its attributes) is very convenient. The equilibrium price of a commodity is then a function of the attribute vector, and this function may be statistically estimated. The regression carried out by Ridker and Henning (1967) can be interpreted as that of the hedonic price function. The hedonic approach has been developed by Griliches (1971), Rosen (1974), and others. Theoretical and empirical issues
involved in the use of the hedonic approach in measuring environmental benefits were surveyed by Freeman (1979).

Let us consider a simple hedonic model to illustrate major issues in the estimation of benefits of externalities from property value data. There are many households each of whom buys one house out of many houses with different characteristics. A house can be completely characterized by an attribute vector \( z \) which includes the structural, locational and environmental characteristics of the house. A household can also be characterized by an attribute vector, \( y=(y_1,y_2,\ldots,y_m)^T=(y_1,s)^T \), where \( y_1 \) denotes the income and \( s=(y_2,\ldots,y_m)^T \) other characteristics such as the age of the head of the family and the number of children.

An individual with an attribute vector \( y \) has the utility function \( U(x,z,s) \) and the budget constraint, \( y_1=x+p^*(z) \), where \( x \) denotes the consumption of the composite consumer good and \( p^*(z) \) the market price of a house with an attribute vector \( z \). Observing the equilibrium price function, \( p^*(z) \), an individual chooses \( x \) and \( z \) to maximize utility. It is convenient to reformulate this problem in terms of the bid price function. The bid price function represents the maximum price that an individual with characteristics \( y \) is willing to pay for a house with attributes \( z \) at a certain utility level \( \bar{U} \). Define \( x^*(z,s,\bar{U}) \) by identity \( U(x^*(z,s,\bar{U}),z,s)=\bar{U} \). Then, the bid price function is \( r(z,y,\bar{U})=y_1-x^*(z,s,\bar{U}) \).

Figure 1 depicts the relationship between the bid price functions and the equilibrium price function when only the first attribute is variable and all others are fixed. There are many bid price curves of individual \( y_1 \) corresponding to different levels of utility. Of course, a lower bid price curve corresponds to a higher utility level. The optimal choice of the attribute is then attained at \( z_1^1 \) where a bid price curve is tangent to the
equilibrium price curve from below. If there are many households with different attributes, i.e., with differently shaped utility functions and different income levels, the equilibrium price function is an upper envelope of their bid price functions.

Now, suppose that attribute $z_1$ represents the level of infrastructural capital. An improvement of infrastructure from $z_1$ to $z_2$, with all other characteristics fixed, raises the bid price of household $y_1$ from $p^1 = r(z_1, y_1, U_1)$ to $p^2 = r(z_2, y_1, U_1)$. The difference, $p^2 - p^1$, is the maximum amount that this household is willing to pay for the improvement and can be considered as the benefit of the improvement received by the household. Since the benefit, $p^2 - p^1$, is not in general equal to the difference in equilibrium prices, $p^2 - p^1$, the equilibrium price function does not correctly reflect the benefits of the improvement. Thus, the regression of property values on housing and environmental attributes as in Ridker and Henning (1967) does not in general provide a correct estimate of the value of environmental quality. The benefit of an improvement tends to be over-estimated, since $p^2 - p^1$ exceeds $r^2 - p^1$ as in Fig. 1. It can also be seen from Fig. 1 that the cost of deterioration of infrastructure is underestimated.

As pointed out by Freeman (1974) and others, there are two special cases where the equilibrium price function correctly reflects the value of infrastructure. First, since the bid price function and the equilibrium price function are tangent at the optimum point for a household, their slopes are equal there. The equilibrium price function, therefore, yields a correct benefit measure for an infinitesimally small change in infrastructure. Note that this is true even if households are heterogeneous. Second, if all households have identical utility functions and equal incomes, then they all have the same bid price functions and the equilibrium price function coincides
Fig. 1. The equilibrium price function, the bid price function, and the benefit of infrastructure.
with the bid price function. In this case, the equilibrium price function can be used to measure the benefit of a large infrastructure investment. Polinsky and Shavell (1976) and Pines and Weiss (1976) assumed identical households and considered a marginal change. They naturally obtained the result that cross-sectional differences in land price provide correct measures of the benefits of environmental quality.

It is important to note that this analysis ignores an induced change in lot size which is the central issue in the preceding subsection. Since lot size is one of the attributes of land or housing, we must have an endogenous choice of attributes to carry out an analysis similar to that in subsection 1.2. The result here must be interpreted as being concerned with a short-run equilibrium where housing characteristics do not change. Considering the durability of buildings, this is usually a reasonable assumption. The analysis also assumes that an infrastructure investment does not induce households to relocate to other houses. If relocation occurs, we have to consider the benefits (and losses) received by households who moved into and out of the area as well as those who remain.

If households have different tastes and incomes and if a large change is considered, the equilibrium price function yields a biased estimate of the benefit and the bid price function must be estimated to obtain a correct estimate. As will be shown later, however, the bid price function is much more difficult to estimate empirically than the equilibrium price function.

Finally, the same results are obtained for benefits received by producers. The bid price function in this case is the maximum price (or rent) that a firm is willing to pay for land (or a factory) with attributes $z$ given a certain profit level. Although there is very little difference theoretically, empirical implementation is more difficult for manufacturing
firms, since factories tend to be firm specific. In such a case, there is little mobility of firms once they build factories and the property price of an existing factory may not be a good signal of the benefit of infrastructure. It is therefore advisable to concentrate on recently built factories.

4. Land Values vs. Land Rents

So far, our analysis has been completely static and used land rent as a "price" of land. In empirical hedonic studies, land value (or property value) is more often used than land (property) rent. There are both advantages and disadvantages to the use of land value in estimating benefits of infrastructure.

First, data are more easily available for land value than for land rent. However, this depends on market conditions in a specific city and there may be some cases where rent data are easier to collect than value data.

Second, land value is a discounted sum of expected future rents and includes long-run effects as well as short-run effects. Since capitalization is more perfect in the long run, land value tends to reflect the benefits of infrastructure more fully than current land rent.

Third, if a future improvement in infrastructure is expected, this will also be capitalized into land value. Regression of land value on current levels of infrastructure may lead to seriously biased estimates of the benefits of infrastructure. When value data are used, therefore, care must be taken not to collect data from locations where people expect an infrastructure investment in the near future.
APPENDIX B

Hedonic Estimations of the Benefits of Non-Market Goods

1. The Estimation of the Bid Price Function

As seen in Section 4 of the main text, the estimation of the hedonic price function (or the equilibrium price function) is straightforward. Unfortunately, if households and/or firms are not homogeneous and if a large change in infrastructure is considered, it yields a biased estimate of the benefit and the bid price function instead must be estimated to obtain a correct estimate. The estimation of the bid price function, however, is much more difficult. This section provides a brief survey of major estimation techniques of the bid price function. See Follain and Jimenez (1983a) for an earlier and more detailed survey and Follain, Gross, Jimenez and Malpezzi (1984) for an annotated bibliography of recent papers on the hedonic approach.

Rosen (1974) proposed a two-step procedure to estimate structural demand and supply functions for the characteristics of differentiated products. His procedure has been applied to the estimation of the benefit of air quality by Nelson (1978) and to the estimation of housing demand functions by many economists such as Witte, et. al. (1979) and Linneman (1980), (1981).

In Rosen's procedure, the equilibrium price function is first estimated by regressing the housing prices on structural, locational and environmental characteristics. If the estimated equilibrium price function is \( p = p^*(z) \), the marginal implicit price of a characteristic, \( q_i(z) \), \( i=1, \ldots, n \), can be found by differentiating \( p^*(z) \) with respect to that characteristic: \( q_i(z) = \frac{\partial p^*(z)}{\partial z_i} \). Note that the marginal prices are different for different houses unless the
equilibrium price function is linear. In the second step, the inverse demand functions for housing characteristics are estimated by regressing the marginal implicit prices on housing and household characteristics. This estimation yields equations of the form,

\[ q_1(z) = q^D_1(z,y), \quad i=1,\ldots,n, \]

where \( q^D_1(z,y) \) is the inverse demand function for attribute \( i \). As noted by Freeman (1974) (1979), the benefit of a non-marginal change in environmental quality is approximated by the area under the inverse demand curve for the change in question, and aggregate benefits for an urban area are found by summing the benefit measures of all households.

Although Rosen's procedure has been widely used, Brown and Rosen (1982) recently pointed out its major difficulties in identifying the structural demand and supply functions. Using an example of a quadratic equilibrium price function and linear inverse demand and supply functions, they showed that Rosen's procedure yields nonsense estimates of demand and supply functions: the estimated coefficients are simple functions of the coefficients of the equilibrium price function and do not provide any more information than that included in the equilibrium price function. Since their criticism relies on special functional forms, its general validity is not quite clear.

Kanemoto and Nakamura (1984) clarified the source of the problem and showed that there is a fundamental difficulty in the estimation of structural demand and supply functions in an hedonic model. An hedonic model contains many differentiated products with different characteristics and an equilibrium allocation in the model requires that markets for all these products be in equilibrium simultaneously. Then, even though there are many prices in a cross-sectional data set, we essentially have only one sample of a set of
prices that equilibriate all the markets. It is, of course, impossible to estimate structural equations with only one sample.

In order to illustrate this problem, consider the estimation of a bid price function in the completely deterministic case where there are no observation errors, no unobserved attributes, and no specification errors. Suppose that household y obtains the utility level $U^*(y)$ in equilibrium. Then, the bid price function of the household is $r(z, y, u^*(y))$. Since a house is bought by the highest bidder in equilibrium, the equilibrium price of house $z$ must satisfy $p^*(z) = \max_{y} r(z, y, u^*(y))$, where $y^*(z)$ denotes the characteristics of the individual who has the highest bid for $z$. Thus, the equilibrium price function is an upper envelope of bid price functions of different households.

Since the observed price is the highest bid price among all potential buyers, all the observations lie on the equilibrium locus, $p^*(z)$, in Fig. 1. The information contained in the observations is the characteristics of the individual who bought a house with certain characteristics and the price at which it was bought. If, for example, individual $y^1$ bought house $z^1$ at price $p^*(z^1)$ as in Fig. 1, then we can infer that the bid price curve of the individual is tangent from below to the equilibrium price locus and the slope of the bid price curve at the tangency point $z^1$ can be found. It is impossible, however, to know the shape of the bid price function at any point other than $z^1$. Even at $z^1$, the curvature of the bid price function cannot be known. Thus, the estimation of the bid price function is impossible even in the completely deterministic case.

Since the situation is quite different from the estimation of structural equations in a model of a homogenous good, the usual identification conditions obtained for the market of a homogeneous good cannot be applied to an hedonic
model. In particular, even if the supply of houses is fixed, this does not mean that the bid price function can be identified. Thus, the claim of Harrison and Rubinfeld (1978) that, if the supply of air quality is perfectly inelastic, a fully identified inverse demand curve can be estimated by regressing equilibrium marginal prices on housing and household attributes is not valid for an hedonic model.

As pointed out by Brown and Rosen (1982), there are two ways of circumventing this difficulty. One is to use observations from separate markets, e.g., those from spatially distinct markets or a time series of cross-section data. This approach was also suggested by Freeman (1974), although in his later paper (1979) he seems to imply that Rosen's procedure works even in a single integrated market. If samples are drawn from many segmented markets, there are many equilibrium price functions and the bid price function can be estimated if we are willing to assume that preferences of households do not vary across markets. This case has not been fully analyzed, however, and we still do not know whether or not Rosen's two-step procedure is an appropriate estimation method in this case.

The other way is to impose a priori restrictions on the functional form of the bid price function $r(z, y, U)$. If the restrictions are strong enough, all parameters of the bid price function may be estimated from the observations only along the equilibrium locus. Quigley (1982) took this approach by assuming that the utility function is of the generalized CES form. If

In Quigley's model all consumers have the generalized CES utility function,

$$U(x, z) = \sum_{i=1}^{n} \beta_{i} z_{i} x^{\alpha_{i}} + \varepsilon,$$
and the utility function is maximized under the budget constraint, \( y = x + p^*(z) \), where \( \alpha, \beta, \) and \( \varepsilon \) are parameters to be estimated. The first order conditions for the utility maximization problem are

\[
\log \frac{\partial p^*(z)}{\partial z_i} = \log \frac{\alpha \beta}{\varepsilon} + (\beta - 1) \log z_i - (\varepsilon - 1) \log x, \quad i = 1, \ldots, n. \tag{B.1}
\]

Quigley proposed the following two-step estimation procedure. First, estimate the equilibrium price function by an appropriate nonlinear estimation technique. Second, compute the partial derivatives of the estimated equilibrium price function for each sample and estimate the first order condition (B.1) using the computed derivatives as dependent variables. The second-step estimation yields the estimates of parameters in the utility function, \( \alpha, \beta, \) and \( \varepsilon. \)

Even if we accept the restriction of the utility function to the generalized CES form, there are at least two difficulties in Quigley's procedure. First, the functional form of the equilibrium price function must be estimated accurately, since its partial derivatives are used in the second-step estimation. In estimating the first order conditions (B.1), how the partials change as \( z \) and \( x \) change is crucial and it is not enough to know the approximate levels of the partials. The estimated price function must at least provide a good second-order approximation of the true function. If the functional form is misspecified, therefore, the second-step estimation may be seriously biased. Usually, however, the data do not allow us to obtain an accurate estimate of the functional form.

Second, in order to obtain unbiased estimates of parameters, independent variables must not be correlated with the error term. There is, however, a reason to believe that they are correlated in Quigley's estimation method. In
econometric studies of housing demand, the major sources of errors are unobserved attributes of houses and individuals because of data limitations. Since the independent variables in the second-step estimation are choice variables for a household, they are affected by (and hence correlated with) unobserved attributes of houses and individuals. The second-step estimation is then likely to be biased.

Kanemoto and Nakamura (1984) developed another estimation method which explicitly takes into account unobserved attributes of housing. This method, however, yields biased estimates if there are unobserved attributes of households.

Ellickson (1981) developed a multinominal logit model of household bids for dwelling units, treating the bid prices of households as random variables. Lerman and Kern (1983) extended this model by making use of observable information on the price paid by the winning bidder. The extended specification makes it possible to estimate the bid price function. This approach is attractive because the bid price function can be estimated directly without estimating the equilibrium price function. At this stage, however, it is not clear whether or not it provides a fully identified bid price function.

Quigley has been working on a research project which compares the performance of different estimation methods using Monte Carlo simulations. Some results are reported in Quigley (1985), but they are still too preliminary to determine the reliability of the proposed estimation methods.

2. The Use of Wage Differentials

Next, consider the other method which uses variations in wage rate instead of property values to measure the benefits of non-market goods such as
externalities and local public goods. This approach has been applied mostly to differences in amenities between cities, whereas the one based on property values has been more often applied to different locations in a certain city. The reason is obvious. On one hand, spatial variations in wage rate are small inside a city, which makes it difficult to obtain estimation results sharp enough for intra-city variations. On the other hand, it is difficult to apply the land-value-based approach to inter-city variations in infrastructure because the hedonic estimation in this case must use the data on the total land values of various cities which are difficult to obtain. Thus, the two approaches are complementary in the sense that the wage-based approach is suitable for inter-city variations while the land-value-based approach is more appropriate for intra-city variations.

An intuitive justification of the wage-based approach is that the wage rate must be higher in cities which have inferior infrastructure such as low-quality water and electricity supply, since otherwise those cities cannot attract workers. Consider households which are faced with a problem of choosing a city to live in. All households have identical ability and an identical utility function, $U(x,h,z)$, where $x$ is the consumption good, $h$ is the amount of space occupied, and $z$ is amenities specific to a city. Let $r(z)$ and $w(z)$ denote land rent and wage rate at a city with amenities $z$. The budget constraint for a household is then $w(z) = x + r(z)h$, where the consumption good is taken as numeraire and non-wage income is ignored. The indirect utility function is then $V(r,w,z) = \max \{U(x,h,z): w + rh\}$. [x,h]

Since all households are identical, they must receive the same utility level in equilibrium. Hence, $V(r(z),w(z),z) = u = \text{const}$. Consider two cities whose amenity levels are different only by an infinitesimal amount. The difference between them can be represented by
\[
0 = \frac{du}{ds} = v \frac{dr}{ds} + v \frac{dw}{ds} + v \frac{ds}{s},
\]
where subscripts, r, w, and s, represent partial derivatives of the indirect utility function. By Roy's Identity and the envelope theorem, the above equality can be rewritten as

\[
\frac{U_s}{U_x} = -h \frac{dr}{ds} + \frac{dw}{ds}. \quad (B.2)
\]

The left side is the marginal rate of substitution between amenities and the consumption good which can be interpreted as the marginal benefit of amenities. Equation (B.2) shows that the marginal benefit of amenities does not equal a difference in residential land rent or a difference in wage rate, but equals a combination of these two. Note that the capitalization hypothesis discussed earlier in this section still holds if rental price of land in production use is included, since a difference in wage rate induces a difference in land rent in production use.

Rosen (1979) developed a theoretical foundation for his approach using an unconventional definition of real wage, i.e., the wage rate divided by land rent, \( w/r \), but his empirical study uses the conventional one, i.e., the wage rate divided by a cost-of-living index. It turns out that the conventional definition provides a more straightforward theoretical foundation. The cost-of-living index is the cost of a fixed representative bundle of goods that a household purchases. Thus, in our context it is \( c(r) \equiv x + hr \) with fixed \( x \) and \( h \). A difference in real wage rate is then

\[
\frac{d}{ds} \left( \frac{w(s)}{c(r(s))} \right) = \frac{w}{c^2} \left[ \frac{c}{w} \frac{dw}{ds} - \frac{hdr}{ds} \right]
\]

\[
= -h \frac{dr}{ds} + \frac{dw}{ds} = \frac{U_z}{U_x} \text{ if } w=c. \quad (B.3)
\]
Thus, if the cost-of-living is defined so that it equals the wage rate initially, a difference in real wage rate equals the value of amenities.

Note that this argument applies only to an infinitesimally small difference in amenities. For a finite difference, we encounter the usual index number problem in choosing the correct cost-of-living index and a difference in real wage rate in general yields only an approximation to the true benefit of amenities. Furthermore, if households are not identical, we have another difficulty similar to that discussed earlier in the property value approach.

If a proper cost-of-living index can be found for different locations, the above approach is very convenient, since a single-equation regression yields at least an approximate measure of the value of amenities. In many cases, however, it is difficult to find good data on the cost of living in different locations. Also, approximation may not be good for a finite difference in amenities. Some authors, such as Getz and Huang (1978) and Cropper (1981), took the approach of building a model of cities by specifying explicit forms of utility and production functions and estimating their parameters by a simultaneous regression of structural equations in the model. A shortcoming of this simultaneous estimation approach is that because of the complexity of the model, it only permits very simple functional forms such as the Cobb-Douglas form. The possibility of extending their methods to more flexible functional forms must be explored. It is also left for future research to compare the performances of different approaches.

Although the wage-based hedonic approach is appealing in its simplicity and the ready availability of wage data, there are several difficulties in implementing this approach. First, the cost-of-living index must be obtained for each city, which is often difficult. Note that the cost-of-living index naturally includes housing costs. Second, mobility is more limited for inter-
city migration than for intra-city migration, so that the utility levels may not equal in different cities. Third, since many different kinds of infrastructure are working simultaneously in a city, it would be difficult to measure the benefit of each kind separately.
First, consider an economy consisting of homogeneous consumers and producers. Consumers have an identical utility function, \( U(x, h, z) \), where \( x \) is the consumption of the composite consumer good, \( h \) is the lot size of a house, and \( z \) is the level of infrastructural capital, such as roads and water supply. Note that in this formulation the structural part of housing is included in the composite consumer good. See Wheaton (1979) for a rationale of this formulation. The budget constraint for a consumer is \( I = p_x x + rh \), where \( I \) is income, \( p_x \) is the price of the consumer good, and \( r \) is land rent. The income can be divided into wage income, \( w \), and other income, \( s \), such as dividend and rent incomes, \( I = w + s \).

For later use, define the expenditure function, \( E(p_x, r, z, u) \)

\[
E(p_x, r, z, u) = \min_{[x, h]} \{ p_x x + rh : U(x, h, z) > u \}
\]

which gives the minimum cost of achieving a fixed level of utility. We can also define the bid rent function,

\[
R^h(I, p_x, z, u) = \max_{[x, h]} \{(I-x)/h : U(x, h, z) > u \}
\]

which represents the maximum rent that a consumer can pay while attaining a fixed level of utility. The expenditure function and the bid rent function are related by the identity, \( I = E(p_x, R^h(I, p_x, z, u), z, u) \).

Applying the envelope theorem to the bid rent function yields demand for land as a function of \( I, z, p_x \), and \( u \):

\[
h^h = 1/R^h_1(I, p_x, z, u) \equiv h^h(I, p_x, z, u),
\]

where subscript \( I \) denotes a partial derivative with respect to \( I \). Demand for the consumer good can also be expressed as a function of \( I, z, \) and \( u \):

\[
x^h = E(p_x, R^h(I, p_x, z, u), z, u) \equiv x^h(I, p_x, z, u),
\]
by applying the envelope theorem to the expenditure function and substituting
the bid rent function, where subscript $p_x$ means a partial derivative with
respect to consumer good prices, $p_x$.

The profit maximizing behavior of a producer can be summarized by the
profit function, $\Pi(r, w, p_x, z) = \max_{[x, n, h]} [p_x - w_n - r_h : (x, n, h, z) \in S]$, where $z, n,$ and $h$ are quantities of output, labor input, and land input, respectively,
and $S$ is the production possibility set. The bid-rent function can also be
defined: $R^f(w, p_x, z, \pi) = \max_{[x, n, h]} [(p_x - w_n - \pi)/h : (x, n, h, z) \in S]$.

In the producer case, the profit level is fixed (at $\pi$) instead of the
utility level. The bid-rent function satisfies $\Pi[R^f(w, p_x, z, \pi), w, p_x, z] = \pi$.

Applying the envelope theorem to the profit function and substituting the bid-
rent function, we can express output supply and input demand as

$$x^f = \Pi_{p_x} (R^f(w, p_x, z, \pi), w, p_x, z) \equiv x^f(w, p_x, z, \pi)$$
$$n^f = -\Pi_w (R^f(w, p_x, z, \pi), w, p_x, z) \equiv n^f(w, p_x, z, \pi)$$
$$h^f = -\Pi_r (R^f(w, p_x, z, \pi), w, p_x, z) \equiv h^f(w, p_x, z, \pi).$$

The consumer good is taken as a numeraire, $p_x = 1$, and its price is
suppressed. Except when otherwise stated, we assume a long-run equilibrium
with free entry. The profit is then zero and we also suppress the profit
level in any of the functions where it appears. The plan of this appendix is
as follows. First, we consider benefits of infrastructure which accrue to
consumers in a model with two residential areas and one industrial area.
Second, the analysis is extended to benefits received by producers in a model
with two industrial areas and one residential area. Third, benefits received
simultaneously by consumers and producers are analyzed in a model with two
areas each of which contains both producers and consumers.
1. **Benefits Received by Consumers**

There are three zones in the economy: one industrial zone with area $H_0$ and two residential zones with areas $H_1$ and $H_2$. The two residential zones have different levels of infrastructural capital, $z_1$ and $z_2$. Infrastructure in the industrial zone is ignored. The total population is fixed at $N$ and everyone works in the industrial zone and lives in one of the two residential zones. We assume a long-run equilibrium with free entry so that firms receive zero economic profits, $\pi = 0$. Market clearing conditions for labor and land in zone 1 are then

\[
\begin{align*}
\text{\textbf{m}}_{nf}(w) &= \bar{N} \\
\text{\textbf{m}}_{h}(w) &= H_0,
\end{align*}
\]

where $m$ is the number of firms and $p_x(=1), z$, and $\pi(=0)$ are suppressed. These two equations determine the number of firms, $m$, and the wage rate, $w$. Note that the wage rate is determined independently of conditions in the residential areas.

The total population is divided into two residential zones,

\[
\bar{N} = N_1 + N_2,
\]

where $N_i$ is the population in zone $i$, $i=1,2$. Migration between the two areas is free and costless so that the utility levels of residents are equalized between the two areas. Denoting the common utility level by $u$, we can express market clearing conditions for land and the consumer good as

\[
\begin{align*}
\bar{H}_1 &= N_1 h(w+s, z_1, u) \\
\bar{H}_2 &= N_2 h(w+s, z_2, u) \\
m x^f(w) - N_1 h(w+s, z_1, u) - N_2 h(w+s, z_2, u) &= 0
\end{align*}
\]

These four equations (C.3)-(C.6) determine four unknowns, $N_1, N_2, s$, and $u$. 

Now, let us consider the benefits of an infrastructure improvement. Suppose that inequality, \( z_1 < z_2 \), holds initially and consider a rise in \( z_1 \), to the same level as \( z_2 \). There are many different ways of measuring the benefits of this change, e.g., Marshallian consumer's surplus, Hicksian compensating variation and equivalent variation, Debreu's coefficient of resource utilization, and the social welfare function. In this appendix, we use a benefit measure similar to Debreu's coefficient of resource utilization. In this measure, we ask how much surplus the improvement generates when the utility level is kept constant. This type of measure depends on which good (or which set of goods) is left as the surplus. Debreu's coefficient of resource utilization reduces all primary inputs proportionally. Here, we assume that the composite consumer good is left as the surplus. This measure is appropriate when the cost of the improvement is incurred in the form of the consumer good: if the surplus exceeds the cost, the improvement is beneficial to the society.

Now, in order to obtain the amount of surplus, we have to characterize the equilibrium after the improvement. Since the change occurs only in a residential area, the wage rate, \( w \), and the number of firms, \( m \), which are determined by conditions only in the industrial area, remain the same as before. By assumption, the utility level remains the same also. The only variables that change are the rent/dividend income, \( s \), and the numbers of residents in the two residential areas, \( N_1 \) and \( N_2 \). These variables are determined by the market clearing conditions for land,

\[
\begin{align*}
H_1^{*} = N_1 h^{*} (w+s^*, z_2, u) \\
H_2^{*} = N_2 h^{*} (w+s^*, z_2, u)
\end{align*}
\]

and the population constraint,
\[ N_1^* + N_2^* = \bar{N}, \tag{C.9} \]

where asterisks denote after-the-project values.

Since the levels of infrastructure are equal in the two residential areas, land rents, consumption of the consumer good, and the lot sizes are equal in the two areas:

\[ r_1^* = r_2^* = r = R^h(w+s^* , z_2^* , u), \]
\[ x_1^* = x_2^* = x = x^h(w+s^* , z_2^* , u), \]
\[ h_1^* = h_2^* = h = h^h(w+s^* , z_2^* , u) = (\bar{H}_1 + \bar{H}_2)/\bar{N}. \]

The surplus generated by the improvement is then

\[ S = mx^* - N_1^* x_1^* - N_2^* x_2^* \]
\[ = N_1^* x_1^* + N_2^* x_2^* - N_1^* x_1^* \tag{by C.6} \]
\[ (C.10) \]

where \( x_i = x^h(w+s_i, z_i, u) \), \( i=1, 2 \), is the pre-improvement consumption of the consumer good in area \( i \).

Now, the benefit measure based on cross-sectional differences in land rent is

\[ B = (r_2^* - r_1^*) \bar{H}_1, \tag{C.11} \]

where \( r_i = R^h(w+s_i, z_i, u) \), \( i=1, 2 \), is the pre-improvement rent in area \( i \). The following proposition shows that the rent-based measure, \( B \), is always larger than, or equal to, the surplus measure \( S \).

**Proposition 1.**

The rent-based benefit measure is always larger than or equal to the surplus measure: \( B \geq S \).

**Proof:**

Noting the budget constraints, \( w+s = x_1 + r_1 h_1 = x_2 + r_2 h_2 \) and \( w+s^* = x^* + r^* h^* \), we can rewrite the surplus measure as
\[ S = (s-s^*)\bar{N} + (r-r_1)\bar{H}_1 + (r-r_2)\bar{H}_2. \]

The difference between \( B \) and \( S \) is then
\[
B-S = (r_2-r^*)(\bar{H}_1+\bar{H}_2) - (s-s^*)\bar{N}
\]

\[
= \bar{N}[r_2^*h - s - (r_1^*h - s^*)] \quad \text{(by } h = (\bar{H}_1+\bar{H}_2)/\bar{N})
\]

\[
= \bar{N}[r_2^*h + x - (w+s^*)] \quad \text{(by } w+s^* = x + r_1^*h) \\
\geq 0,
\]

where the last inequality results from the fact that \((x_2^*,h_2^*)\) minimizes the expenditure at land rent \( r_2 \), i.e.,
\[
\sigma + s = \min_{x, h} \{ x, h \}
\]

\[
[x + r_2^*h : U(x, h, z_2^*)] \geq x + r_2^*h.
\]

Q.E.D.

The Proposition shows that land rent differentials tend to overestimate the benefits of infrastructure investments. As can be seen from the proof, the reason is that the consumption choice after the improvement is different from the choice in area 2 before the improvement. This shows that if there is no substitution between the consumer good and the lot size, then land rent differentials yield correct benefit estimates. The envelope property suggests that they are also correct if the improvement is infinitesimally small. Furthermore, it can be shown that if area 1, where the improvement takes place, is infinitesimally small compared with area 2, then they provide correct benefit estimates even for a large improvement. These results are contained in the following corollary.

**Corollary.**

The rent-based benefit measure equals the surplus measure if one of the following conditions hold:

(i) There is no substitution between the consumer good and the lot size.

(ii) An improvement is infinitesimally small.
The area affected by an improvement is infinitesimally small compared with the other area.

Proof:

(i) Obvious from the proof of Proposition 1.

(ii) let \( y = z_2^2 - z_1 \) and consider the limit as \( y \) approaches zero with \( z_2 \) fixed. Since \( s, s^*, u \) depend on \( y \), we write \( s(y), s^*(y), u(y) \). Then

\[
S = [s(y) - s^*(y)]N + [R^h(w+s^*(y),z_2,u(y)) - R^h(w+s(y),z_2-y,u(y))]\tilde{H}_1
+ [R^h(w+s^*(y),z_2,u(y)) - R^h(w+s(y),z_2,y,u(y))]\tilde{H}_2.
\]

and

\[
B = [R^h(w+s(y),z_2,u(y)) - R^h(w+s(y),z_2-y,u(y))]\tilde{H}_1.
\]

Taking limits of \( S/y \) and \( B/y \) as \( y \) tends to zero and applying L'Hospital's Rule yields

\[
\lim_{y \to 0} \frac{S}{y} = \lim_{y \to 0} \frac{B}{y} = \frac{h^*}{\tilde{H}_1}.
\]

(iii) Consider the limit as \( \tilde{H}_1 \) tends to zero. In the same way as in (ii), we can write \( s(H_1), s^*(\tilde{H}_1), u(\tilde{H}_1) \) and take limits of \( S/\tilde{H}_1 \) and \( B/\tilde{H}_1 \) as \( \tilde{H}_1 \) tends to zero. Applying L'Hospital's Rule then yields

\[
\lim_{\tilde{H}_1 \to 0} \frac{S}{\tilde{H}_1} = \lim_{\tilde{H}_1 \to 0} \frac{B}{\tilde{H}_1} = r_2 - r_1.
\]

Q.E.D.

Note that, if the lot sizes are fixed, land rent is indeterminate since both demand and supply of land are fixed. Therefore, condition (i) of this Corollary has to be interpreted as a limit since substitutability tends to zero.
So far we implicitly assumed that the surplus is generated in both areas. Next, consider a case where the surplus is taken only from the area where the improvement occurs. Since there is no change in area 2 in such a case, the population of area 1 does not change. This further implies that there is no change in the lot size in area 1. Thus, the new equilibrium must satisfy

$$U(x^{**}, h_1, z_2) = u,$$

(C.12)

where double asterisks denote new equilibrium values. The surplus is then

$$S_1 = N_1(x_1^{**} - x_1^*).$$

(C.13)

The following Proposition shows that the rent-based measure, $B$, is larger than or equal to this surplus measure and that the previous surplus measure, $S$, is larger than or equal to this measure.

**Proposition 2.**

The surplus taken from area 1 only, $S_1$, is smaller than or equal to the surplus taken from both areas, $S$, and hence it is smaller than or equal to the rent-based measure, $B$:

$$B \geq S \geq S_1.$$  

**Proof:**

By definitions of $B$ and $S_1$, we have

$$B - S_1 = (r_2 - r_1)h_1 - (x_1 - x_1^{**})N_1$$

$$= N_1[x_1^{**} + r_2 h_1 - (x_1 + r_1 h_1)]$$

$$= N_1[x_1^{**} + r_2 h_1 - (w+s)]$$

$$\geq 0$$

where the last inequality follows from $w+s = E(r_2, z_2, u) \leq x_1^{**} + r_2 h_1$.

Next, combining (C.10) and (C.13) yields

$$S - S_1 = N_1x_1^{**} + N_2x_2^{**} - Nx^*$$

$$= \bar{N} \left[ \frac{1}{N} (N_1x_1^{**} + N_2x_2^{**}) - x^* \right].$$
Now, observe that \((x_1^*, h_1), (x_2, h_2),\) and \((x^*, h^*)\) are on the same indifference curve, where the last point is between the first two points. From \(h^* = \left(\frac{1}{N} (N_1 x_1^{**} + N_2 x_2), h\right)\) is on a line segment connecting \((x_1^{**}, h_1)\) and \((x_2, h_2)\). The quasi-concavity of the utility function then implies that this point cannot be below \((x^*, h^*)\) which is on the indifference curve. Thus
\[ S - S_1 \geq 0. \] Q.E.D.

Next, consider several extensions of the above results to more general cases. First, prices or tariffs are often charged for services of infrastructure such as electricity and water supply. Even in the case of roads, a tax on fuel consumption works in a similar way to a price of road services. Since consumers pay the price, the benefit of infrastructure capitalized into land price is the part of the benefit which is not captured by the price. That is, only the consumer's surplus is capitalized into land price and the gross benefit is the sum of the tariff revenue and the consumer's surplus.

Let us extend the simplest model above to include a price of infrastructure services. The new utility function and the budget constraint are respectively \(U(x, h, m, z)\) and \(w + s = x + pm + rh\), where \(m\) is the amount of infrastructural service consumed and \(p\) is the price of the service. The argument, \(z\), is retained in the utility function to represent the quality of infrastructure. For example, a new electricity plant may be more reliable so that blackouts occur less often. The expenditure function and the bid rent function now become \(E(r, p, z, u)\) and \(R^h(I, p, z, u)\) respectively, and the lot size and the consumption of the consumer good satisfy \(h^h(I, p, z, u)\) and \(x^h(I, p, z, u)\) respectively. With these changes, the analysis is the same as before.
Suppose that before an improvement, \((p, z) = (p_1, z_1)\) in area 1 and \((p, z) = (p_2, z_2)\) in area 2, and consider the benefit of a change from \((p_1, z_1)\) to \((p_2, z_2)\) in area 1. The surplus generated by this change is given by (C.10). The following proposition compares the surplus measure, \(S\), and the rent-based measure, \(B\), given by (C.11).

**Proposition 3.**

The sum of the rent-based measure, \(B\), and a change in the total tariff revenue, \(Q = p_2 m N - p_1 m_1 N - p_2 m_2 N\),

is larger than or equal to the surplus measure, \(S\):

\[ B + Q \geq S \]

**Proof:**

Using the budget constraints,

\[ w+s = x_1 + p_1 m_1 + r_1 h_1 = x_2 + p_2 m_2 + r_2 h_2 \quad \text{and} \quad w+s = x + p_2 m + r h, \]

we can rewrite \(S\) as

\[ S = (s-s) N + (r_2 - r_1) H_1 + (r - r_2) H_2 + p_2 m N - p_1 m_1 N - p_2 m_2 N. \]

Hence, the difference between \(B+Q\) and \(S\) is

\[ B+Q - S = (s-s) N + (r_2 - r_1) H_1 + (r - r_2) H_2 \]

\[ = N [x + p_2 m + r_2 h - s - (x + p_2 m + r h - s)] \]

\[ = N [x + p_2 m + r_2 h - (w+s)] \]

\[ \geq 0, \]

where the last inequality follows from

\[ U(x^*, h^*, m_2, z_2) = u. \]
Note that the revenue change here includes a change in area 2 as well as a change in area 1. In the same way as before, we can see that \( B+Q = S \) if the lot sizes are fixed, if the change in infrastructure is infinitesimally small, or if the area where the change occurs is infinitesimally small compared with the rest of the world. Moreover, in these three cases there is no change in the tariff revenue in area 2 so that \( Q \) includes only a change in the tariff revenue in area 1.

**Corollary.**

The sum of the rent-based measure and a change in tariff revenue equals the surplus measure in the following three cases:

(i) **There is no substitutability between the lot size and other goods.**

(ii) **The change in infrastructure is infinitesimally small.**

(iii) **The area where the change occurs is infinitesimally small compared with the other area.**

**Proof:**

Similar to the proof of the corollary of Proposition 1.

Second, the assumption of long-run equilibrium with free entry in the industrial sector can be relaxed without changing the result. In the short run, where the number of firms is fixed, the profit may not be zero, and labor and land demand functions are now \( n^f(w,\pi) \) and \( h^f(w,\pi) \). However, since the number of firms, \( m \), is fixed, \((C.1)\) and \((C.2)\) completely determine both the wage rate and the profit level. With the wage rate independent of conditions in the residential areas, the analysis proceeds in exactly the same way as in the long-run case.

Third, the analysis can be extended to the case where there is more than one consumer good. An infrastructure investment may then change relative
prices of consumer goods. Even in such a case, the same results are obtained if the surplus is generated only in the form of the numeraire good. Let 
\[ p_x = (p_1, \ldots, p_n) \]
denote the price vector of the consumer goods, where the first good is taken as a numeraire, \( p_1 = 1 \). Then, the equilibrium before the improvement satisfies
\begin{align*}
\text{m h} & (w, p_x) = H_0 \quad \text{(C14a)} \\
\text{m n} & (w, p_x) = N \quad \text{(C14b)} \\
N_1 & h(w+s, p_x, z_1, u) = H_1 \quad \text{(C14c)} \\
N_2 & h(w+s, p_x, z_2, u) = H_2 \quad \text{(C14d)} \\
\text{m x} (w, p_x) - N_1 & x(h(w+s, p_x, z_1, u) - N_2 x(h(w+s, p_x, z_2, u) = 0 \quad \text{(C14e)} \\
N_1 & + N_2 = N, \quad \text{(C14f)}
\end{align*}
and the equilibrium after the change is
\begin{align*}
\text{m h} & (w, p_x) = H_0 \quad \text{(C15a)} \\
\text{m n} & (w, p_x) = N \quad \text{(C15b)} \\
N_1 & h(w+s, p_x, z_1, u) = H_1 \quad \text{(C15c)} \\
N_2 & h(w+s, p_x, z_2, u) = H_2 \quad \text{(C15d)} \\
\text{m x} (w, p_x) - N_1 & x(h(w+s, p_x, z_1, u) = N_2 x(h(w+s, p_x, z_2, u) = 0, \quad \text{(C15e)} \\
N_1 & + N_2 = N. \quad \text{(C15f)}
\end{align*}
Equation (C15e) assumes that only the numeraire good is used as the surplus.
The surplus measure is
\[ S = m x^*_1 - N x^*_1 \]
and the rent-based measure is the same as before (C.11).
Proposition 4.

Suppose there are \( n \) consumer goods. If only the numeraire good is left as the surplus, then the rent-based measure is larger than or equal to the surplus measure: \( B \geq S \).

Proof:

Multiplying the market clearing condition \((C.14e)\) by the price vector \( p_X \) and noting the budget constraints, \( w+s = p_X x_1^* + r_1 h_1 = p_X x_2^* + r_2 h_2 \), yields

\[
p_x^{mx} + r_1 h_1 + r_2 h_2 - (w+s)N = 0.
\]

Since \( u(x_2^*, h_2^*; z_2^*) = u(x^*, h^*, z_2^*) = u \) and \( (z_2^*, h_2^*) \) is the optimal choice at prices \((p_X, r_2^*)\), we have

\[
w+s = p_X x_2^* + r_2 h_2 \leq p_X x^* + r_2 h^*.
\]

Hence, the above equality implies

\[
B = (r_2 - r_1)H_1 \geq p_x^{mx} - N x^*.
\]

Now, \((x^f, n^f, h^f)\) maximizes profit at prices \((p_X, w, r_0)\):

\[
O = p_X x^f - w n^f - r_0 h^f \geq p_X x^f - w n^f - r_0 h^f^*.
\]

This yields

\[
O = p_X^{mx} - w N - r_0 H_0 \geq p_X^{mx} x^f - w N - r_0 H_0^*.
\]

Hence, \( p_X^{mx} \geq p_X^{mx} x^f \) and

\[
B \geq p_X^{mx} (m x^* - N x^1) = m x^1 - N x^1 = S.
\]

Q.E.D.

This result is similar to that obtained in Kanemoto and Mera (1984) in a different context. There, the surplus measure equals the change in the area to the left of the general-equilibrium demand curve under the same assumption that only the numeraire good is used as the surplus.

Finally, we have so far assumed a long-run equilibrium in the housing market so that lot sizes are chosen optimally both before and after the
improvement. In a short-run equilibrium where lot sizes are fixed at historically predetermined levels, the rent-based measure may or may not exceed the surplus measure. Let \( h_1 \) be the lot size in area 1 and assume that it remains the same after the improvement. Then, it is easy to see that the difference between the two measures in the simplest case is

\[
B - S = N_1 [(r_2 h_1 + x_1^*) - (r_2 h_2 + x_2)],
\]

where \( r_2 \) and \( x_2 \) are pre-improvement levels of land rent and consumption of the consumer good in area 2, respectively, and \( x_1^* \) is the post-improvement consumption of the consumer good in area 1. Since \( (x_1^*, h_1) \) and \( (x_2, h_2) \) must yield the same utility level, inequality, \( r_2 h_2 + x_2 \leq r_2 h_1 + x_1^* \), is satisfied if the lot size is chosen optimally in the pre-improvement equilibrium. In this case, the same result as before is obtained: \( B \geq S \). If \( h_2 \) is suboptimal in the pre-improvement equilibrium, however, the rent-based measure may be smaller than the surplus measure.

2. Benefits Received by Producers

Next, consider an infrastructural improvement which affects only producers. There are two industrial zones, zone 1 and zone 2, where infrastructure before the improvement is \( z_1 \) in zone 1 and \( z_2 \) in zone 2. Zone 1 has area \( H_1 \) and zone 2 area \( H_2 \). All workers live in the same residential zone with area \( H_0 \). The crucial assumption in obtaining a definite relationship between land rent differentials and benefits of infrastructure is that firms are in long-run equilibrium with free entry. This assumption insures that all firms earn zero profits in equilibrium.

The equilibrium before the improvement satisfies

\[
m_1 h^f(w, z_1) = H_1 \quad \text{(C16a)}
\]

\[
m_2 h^f(w, z_2) = H_2 \quad \text{(C16b)}
\]
The first three equations determine three unknowns, \( w, m_1, \) and \( m_2 \). Given these variables, the last two equations determine \( S \) and \( u \).

The improvement does not affect the consumption choice of consumers since the utility level, \( u \), and the lot size, \( h^h = \bar{H}_0/\bar{N} \), must remain the same. The consumption of the consumer good therefore remains unchanged: \( x^{h^*} = x^h \).

The equilibrium after the improvement satisfies

\[
\begin{align*}
  m_1 f^*(w,z_1) + m_2 f^*(w,z_2) &= \bar{N} \\
  Nh^*(w+s,u) &= \bar{H}_0 \\
  m_1 x^*(w,z_1) + m_2 x^*(w,z_2) - N h^*(w+s,u) &= 0.
\end{align*}
\]

and the surplus measure is

\[
S = (m_1 + m_2) x^* (w,z_2) - m_1 f^*(w,z_1) - m_2 f^*(w,z_2).
\]

The following proposition obtains the same result as for consumptive infrastructure.
Proposition 5

The rent-based measure is larger than or equal to the surplus measure: \( B \geq S \).

Proof

Since profits of firms are zero in equilibrium, we have
\[
x^* - r^* h^* - w^* n^* = x^*_1 - r^*_1 h^*_1 - w^*_1 n^*_1 = x^*_2 - r^*_2 h^*_2 - w^*_2 n^*_2 = 0,
\]
\[h^* = h^*(w^*, z^*_2), n^* = n^*(w^*, z^*_2), h^*_1 = h^*(w, z^*_1), n^*_1 = n^*(w, z^*_1), i = 1, 2.
\]

Hence, the surplus measure can be rewritten as
\[S = r^* (\bar{H}^*_1 + \bar{H}^*_2) + w^* N - r^*_1 \bar{H}^*_1 - r^*_2 \bar{H}^*_2 - w^* N,
\]
which yields
\[B - S = (r^*_2 - r^*_1) (\bar{H}^*_1 + \bar{H}^*_2) + (w^* - w^*) N\]
\[= (m^*_1 + m^*_2) [x^* - r^* h^* - w^* n^* - (x^* - r^*_2 h^*_2 - w^*_2 n^*_2)]\]
\[\geq 0.
\]

The last inequality follows from
\[0 = x^*_2 - r^*_2 h^*_2 - w^*_2 n^*_2 \geq x^* - r^*_2 h^* - w^* n^*.
\]

Q.E.D.

It is easy to see that the same corollary as before is obtained. Thus, land rent differentials of industrial land may be used to estimate the benefits of infrastructure if the assumptions of the corollary hold.

3. Intercity Differentials in Land Rents

The results obtained so far have to be interpreted as being concerned with intra-city differentials. Inter-city variations in infrastructure may produce variations in wage rates in addition to those in land rents. It will be shown that even in such a case land rent differentials may be used to estimate benefits of infrastructure. The only complication is that even if an
infrastructure investment affects only producers or consumers, differentials in both residential and industrial land rents must be taken into account.

Let us consider two cities each with fixed amounts of industrial land, $\overline{I}_i^f$, $i=1,2$, and residential land, $\overline{H}_i^h$, $i=1,2$. Infrastructure may benefit both producers and consumers. The equilibrium before an improvement in infrastructure satisfies

$$m_i h_i^f(w_i, z_i) = \overline{F}_i^f, \quad i=1,2$$
$$m_i n_i^f(w_i, z_i) = \overline{N}_i^f, \quad i=1,2$$
$$\overline{H}_i^h(w_i + s, z_i, u) = \overline{H}_i^h, \quad i=1,2$$
$$\sum_{i=1}^{2} m_i^* x_i^f(w_i^*, z_i^*) - \sum_{i=1}^{2} N_i^* h_i^h(w_i^* + s, z_i^*, u) = 0$$
$$N_1 + N_2 = N.$$

The equilibrium after changing infrastructure in city 1 from $z_1$ to $z_2$ is

$$m_i h_i^f(w_i, z_2) = \overline{F}_i^f, \quad i=1,2,$$
$$m_i n_i^f(w_i, z_2) = \overline{N}_i^f, \quad i=1,2,$$
$$\overline{H}_i^h(w_i + s, z_2, u) = \overline{H}_i^h, \quad i=1,2,$$
$$N_1 + N_2 = N.$$

and the surplus measure is

$$S = \sum_{i=1}^{2} m_i^* x_i^f(w_i^*, z_2^*) - \sum_{i=1}^{2} N_i^* h_i^h(w_i^* + s, z_2^*, u).$$

The rent-based measure now includes differentials in both residential and industrial areas:

$$B = (r_2^f - r_1^f) \overline{F}_i^f + (r_2^h - r_1^h) \overline{H}_i^h,$$

where $r_i^f = R_i^f(w_i, z_i)$ and $r_i^h = R_i^h(w_i + s, z_i, u), \ i=1,2$, denote land rents in industrial and residential areas in city $i$, respectively. With this change in the rent-based measure, the same results as before are obtained.
Proposition 6.

The Rent based measure is larger than or equal to the surplus measure: $B \geq S$

Proof:

Using the budget constraints, $w_i + s - x_i^f h_i^* - r_i h_i^* = w_i + s - x_i^h r_i h_i^* = 0$, $i=1,2$, and the zero profit conditions, $x_i^f r_i h_i^* - w_i n_i = 0$, $i=1,2$, we can rewrite the surplus measure as

$$S = \sum_{i=1}^2 (r_i^f - r_i^h) H_i^f + \sum_{i=1}^2 (r_i^h - r_i^h) H_i^h - N (s - s)$$

and hence

$$B - S = \sum_{i=1}^2 (r_i^f - r_i^h) H_i^f + \sum_{i=1}^2 (r_i^h - r_i^h) H_i^h - N (s - s).$$

Multiplying the budget constraint in each city by the number of that city's residents, and the zero profit condition by the number of firms, yields

$$N_i x_i^* r_i^f h_i^* - h_i^* = N_i x_i^* - m_i x_i^* = 0, i=1,2.$$ 

Combining these equations, we obtain

$$N_i s - r_i^f H_i^f - r_i^h H_i^h = N_i x_i^* - m_i x_i^*, i=1,2.$$ 

Substituting this equation into $B - S$ and rearranging terms yields

$$B - S = \sum_{i=1}^2 [N_i x_i^* - r_i^f h_i^* - w_2 - s] - m_i [x_i^* - r_i^f h_i^* - w_2 n_i] \geq 0,$$

where the inequality follows from

$$x_i^* - r_i^f h_i^* \geq x_i^f - r_i^f h_i^* - w_2 + s$$

and

$$x_i^f - r_i^f h_i^* - w_2 n_i \geq x_i^f - r_i^f h_i^* - w_2 n_i = 0.$$ 

Q.E.D.
4. Heterogeneous Consumers

Finally, consider a case with heterogeneous consumers. For simplicity, assume that consumers have the same skills but different preferences for infrastructure. There are two types of consumers, where those of type 2 value infrastructure more than those of type 1. Other than heterogeneity of consumers, the model is the same as the first simplest one, with two residential areas and one industrial area. Before an improvement in infrastructure takes place in residential zone 1, there is better infrastructure in zone 2 and consumers of type 2 tend to live there. It is assumed, however, that the number of consumers of type 2 is so large that they live both in zone 1 and zone 2. Consumers of type 1 live only in zone 1.

Let superscripts denote the type of consumers. Then, the equilibrium before the improvement is

\[
\begin{align*}
N^1_h1(w+s,z_1,u^1) + N^2_h2(w+s, z_2,u^2) &= \bar{H}_1 \\
N^2 h^2(w+s,z_2,u^2) &= \bar{H}_2 \\
N^1_N^2 + N^2 &= \bar{N} \\
m^x_f(w) - \left[ N^1 x(w+s,z_1,u^1) + N^2 x(w+s,z_1,u^2) + N^2 x(w+s,z_2,u^2) \right] &= 0 \\
R^1(w+s,z_1,u^1) &= R^2(w+s,z_2,u^2)
\end{align*}
\]

Since consumers of type 1 prefer not to live in zone 2, the level of expenditure necessary to achieve the same utility level is larger in zone 2 than in zone 1:

\[ E(r_2,z_2,u^1) > E(r_1,z_1,u^1) = w+s. \]

After improving infrastructure in zone 1 from \( z_1 \) to \( z_2 \), the two residential zones have identical characteristics for consumers, and land rents in the two zones must be equal. Since consumers of type 1 as well as those of type 2 are indifferent between zone 1 and zone 2, the allocation of consumers of the two types between the two zones is indeterminate. The equilibrium conditions
after the improvement are then
\[ \bar{N}^2 h^1(w+s^1, z_1, u^1) + \bar{N}^2 h^2(w+s^2, z_2, u^2) = \bar{H}^1 + \bar{H}^2, \]
\[ R^1(w+s^1, z_2, u^1) = R^2(w+s^2, z_2, u^2) \]
and the surplus measure is
\[ S = \bar{N}^1 x^1 + N_1^1 x_1^1 + N_2^2 x_2^2 - \bar{N}^1 x^1 - \bar{N}^2 x^2, \]
where
\[ x_1^1 = x^1(w+s, z_1, u), \quad x_2^2 = x^2(w+s, z_1, u), \quad x_2^1 = x^2(w+s, z_2, u), \quad x^1 = x^1(w+s^1, z_2, u), \quad x^2 = x^2(w+s^2, z_2, u). \]

It is shown that the rent-based measure, \( B = (r_2^2 - r_1^1) \bar{H}^2 \), is strictly larger than the surplus measure, \( S \). Furthermore, unlike the homogeneous consumer case, the difference does not vanish even if the lot sizes are fixed, the improvement is infinitesimally small, or if zone 1 is infinitesimally small.

**Proposition 7.**
The rent-based measure is strictly larger than the surplus measure:
\[ B - S \geq \bar{N}^1 [E(r_2, z_2, u^1) - E(r_1, z_1, u^1)] > 0 \]

**Proof.**

By the budget constraints,
\[ \bar{N}^1 x^1 + r_1^1 h^1 - w-s = \bar{N}^2 x^2 + r_2^2 h^2 - w-s \]
\[ = x_1^1 + r_2^2 h^2 - w-s = x^1 + r h - w-s_1 = x^2 + r h - w-s_2 = 0, \]
the surplus measure becomes
\[ S = (r - r_1^1) \bar{H}^1 + (r - r_2^2) \bar{H}^2 + (s-s_1^1) \bar{N}^1 + (s-s_2^2) \bar{N}^2, \]
where \( r = R^1(w+s^1, z_2, u^1) = R^2(w+s^2, z_2, u^2) \). The difference between \( B \) and \( S \) is then
\[ B - S = (r_2^2 - r_1^1) \bar{H}^2 - (s-s_1^1) \bar{N}^1 - (s-s_2^2) \bar{N}^2 \]
\[ \geq \bar{N}^1 \left[ (r_2^2 h^2 + x^2) - (w+s) \right] \]
\[ \geq \bar{N}^1 \left[ (r_2^2 h^2 + x^2) - (w+s) \right] = \bar{N}^1 [E(r_2, z_2, u^1) - E(r_1, z_1, u^1)] > 0 \]

Q.E.D.
Corollary.
The rent-based measure is strictly larger than the surplus measure even if (i) there is no substitutability between the lot size and other goods, (ii) the improvement is infinitesimally small, or (iii) zone 1 is infinitesimally small compared with zone 2.

Proof: Omitted.

Thus, land rent differentials yield more biased benefit estimates if there are different types of consumers who value infrastructure differently. Note, however, that this problem arises because different types of individuals live in a homogeneous area (in our case, zone 1, before the improvement) and pay the same rent. In reality, it is difficult to find a large homogeneous area, since land is differentiated by locational and other characteristics. If land is differentiated continuously by location (e.g., distance to the city center), this problem will not occur and land rent differentials will, at least, provide a correct benefit measure of a small improvement.
Footnotes

1. Malpezzi, Bamberger, and Mayo (1982) and Malpezzi (1984) provide guidelines for the planning and the analysis of an urban housing survey. They will be useful especially when residential land values or residential property values are used to estimate benefits obtained by households.

2. See Appendices A and B for more detailed discussions.

3. SHAZAM can be obtained from Professor Kenneth White at the Department of Economics, University of British Columbia, Vancouver, B.C. V6Y1Y2, CANADA.

4. This and the next appendices owe much to Kanemoto (forthcoming).

5. If land is collectively owned by all individuals in the entire economy, including both the region considered and the rest of the world, the benefits are spread over all individuals and the utility level of each individual rises by an infinitesimal amount. The sum of benefits over all individuals is, however, finite and equals the increase in the total land rent in the small region. On the other hand, if land is owned by absentee landlords who are of a different type from residents in the region, the benefits are received by the landlords.

6. See Follain and Jimenez (1983b) for an application of Quigley's method.

7. See Kanemoto (1980, Ch.1) for this result.

8. A similar measure was proposed by Dierker and Lenninghaus (1983) and their version was shown to attain positive values if and only if the move passes the (Kaldor-Hicks) compensation test. See Schweizer (1983) for further analysis of the measure.
References


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