Spatial Modeling in Transportation III: Infrastructure, Planning, and Welfare *

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Abstract

The US Army Corps of Engineers (USACE) evaluates improvements to locks and dams on the waterway using various planning models. These models vary in terms of the underlying economic assumptions made. In this paper, we summarize these assumptions and evaluate their implications for the measurement of the welfare benefits of improvements. In our evaluation, we develop a "full" spatial equilibrium model wherein geographically dispersed shippers choose where and how to ship and how much to produce both in the short and long-run. Because rail and barge (and truck) rates determine equilibrium market areas, we also allow for railroad pricing. The divergence in welfare benefits between USACE models and the full spatial model depends critically on how much shippers are willing to switch pools, increase production (at the extensive margin and at the intensive margin), and how railroad rates adjust in response to lower barge rates from lock improvements.

KEYWORDS: Spatial equilibrium, transportation infrastructure, traffic diversion, mode/origin/destination choice, Samuelson-Takayama-Judge shipment equilibrium, welfare measurement.

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EXECUTIVE SUMMARY

Commercial navigation of most of the Nation's waterways is facilitated by a system of locks and dams maintained by the US Army Corps of Engineers (USACE). USACE routinely reviews the lock system using a variety of planning models to evaluate the welfare benefits from capital investments to reduce congestion costs. In this paper, we develop a model of spatial competition between truck-barge and rail movements and assess welfare benefits is a fully spatial model. Truck and barge sectors are taken as competitive, while railroads may hold some market power. In the USACE models, origins and destinations are "pools" (a pool is a body of water between two locks). Demands are defined as movements between originating and terminating pools for different commodities. Demands are perfectly inelastic up to a threshold (a "Zap" price) above which demand shifts completely to rail. We consider three variants of the transportation infrastructure and compare the welfare consequences of imposing the inelastic demand assumption. First, we set up a spatial model to highlight the implicit assumptions in the USACE models by assuming that there is no substitutability between river terminals, and that all shipments originate from the same point (rail and river). We then allow rail to originate from a distinct rail location. The demand side is next expanded to allow for an extensive margin of cultivation, and for both short- and long-run adjustments to changes in modal prices. Second, we allow rail access from all points in space, but still constrain river access to a single point in a pool. Third, we allow river transportation to be unconstrained too. These three variations allow for evaluation of the USACE model's restrictions on demand substitutability across modes. The possibility of switching shipment origin is a source of potential error. Other important factors leading to misestimation of benefits include adjustment by shippers to prices and adjustment of the margin of cultivation, and a lowering of rail prices leading to greater efficiency even in areas not served by truck-barge.

1 Introduction

The US Army Corps of Engineers (USACE) uses estimates of future user benefits in planning infrastructure developments. In the case of evaluating the economic case for lock improvements, the Corps uses a particular suite of models called ORNIM (Ohio River Navigation Investment Model). The ORNIM model (implicitly) imposes a particular spatial structure. It uses as input data demands at the level of river "pools," which are bodies of water between two points (e.g., adjacent locks). Demands are defined as the annual volume of traffic for a particular commodity between an origin and a terminating pool. These *demands are assumed to be not substitutable between originating or terminating pools.*

This assumption follows the tradition of Samuelson (1952) and Takayama and Judge (1964) (S-TJ). The S-TJ set-up does allow for spatial differences between locations. These differences are arbitraged through a competitive transportation sector. However, the set-up treats all supply or demand nodes as spaceless points, and does not consider the underlying geographic dispersal of supplies or demands that are funneled together to form the point demands. Allowing for a richer spatial structure, where producers choose whence to ship, suggests that the net demands at neighboring shipment points ought not be treated as independent, but instead the allocation of shipments from a particular location depend also on prices for shipping from neighboring shipment points. That is, the market area generating a given pool demand depends not only on its own price, but also on the prices at neighboring pools. As such, the regions of Samuelson-Takayama-Judge and ORNIM are, in a sense, themselves endogenous.

To make comparisons, we first set up a model that generates exactly the ORNIM solution as an equilibrium outcome within a full spatial setting (i.e., with spatially separated farmers generating the demand for transportation services). To do this, we assume that there is only one transportation access point from which both river and rail shipments must start. However, even if we make this assumption, we must also assume that there is no possibility of shipping from another access point. We start out with this model with a full spatial distribution of production. We then allow for the possibility that shipments can be sent from other river terminals. This consideration implies that there is greater interdependence in demands than is allowed for in the benchmark model.

We first describe the basic shipping model of the ORNIM set-up in Section 2, and the Samuelson-Takayama-Judge framework in Section 3. In Section 4, we provide the relevant geography for our model and indicate how the various infrastructure variations are generated within that geography. We then sketch the implicit assumptions that render ORNIM consistent with an underlying spatial distribution of production in Section 5, and indicate how the model evolves as these assumptions are relaxed. We then investigate the implications of allowing for denser transportation infrastructure, first for rail in Section 6, and then for barge too in Section 7. Some welfare considerations and comparisons are highlighted in Section 8. Final comments are given in Section 9.

2 The Ohio River Navigation Investment Model (ORNIM)

The basic idea in ORNIM is that a fixed set of shipments must be made. These are categorized as Origin-Destination-Commodity triples. The origins and destinations are pools. In what follows, we index a particular Origin-Destination-Commodity triple by i. The shipments that are made for any commodity between any pair of pools are derived from a forecast model. The forecast levels are based on past levels of shipments of the commodity between the specified origin and destination.

Shipments are assumed to either go by one of two shipping modes, rail or barge. If a shipment goes by rail, it goes overland at "rail" rate R_i per ton which is exogenous (to the model). If it goes by barge, the rate is w_i, which is endogenous to the model. The barge rates, w_i, are determined by historical data using a base year level plus a correction for changing congestion from traffic on the river through various locks.

The algorithm works as follows. Start with a given set of waterway rates, w_i, and a set of rail rates, R_i. First, all shipments go by the cheaper mode, and so choose the waterway if and only if w_i is less than R_i. This step yields a set of quantities to be shipped by river. For each i, either all the shipment is shipped by river (if $w_i < R_i$) or else none is (if $w_i > R_i$), leaving rate equality ($w_i = R_i$) as the only possible reason for observing a mixed shipment.[1] Having determined the set of shipments made by river for given w_i (these are the full prices faced by shippers, including time costs, etc.), the next step is to update the w_i from the induced shipments. This procedure is the task of the module WAM (Waterway Analysis Model) in the ORNIM suite.[2]

WAM takes the total shipments and considers the geography of the waterway to derive congestion costs that depend on shipping levels through the locks. This process generates a new set of barge prices which are then fed back to the first module of determining induced shipments. An equilibrium is therefore a fixed point of this algorithm whereby a set of barge prices induce a set of shipments that in turn induce the original barge prices.

Given the above algorithm, the benefit-cost analysis of a structural change (lock refurbishing, for example) is readily performed. This surplus analysis uses the rail rate (which acts as the default option) as the benchmark. Since a

[1] Since the w_i are calibrated from congestion data, this should almost never happen in practice with the algorithm.

[2] The presentation of Oladosu et al. (2004) invokes a procedure whereby shipments are allocated to where $R_i - w_i$ is highest. This is equivalent to the description in the text.

shipment either goes by rail or waterway, the shipment sent by barge returns a surplus equal to shipment size times the net saving over the rail option.

The model is commendable for carefully separating out the perfect competition assumption of price-taking shippers from the computation of the equilibrium barge rate. This warrants the two-stage procedure used in the model, and is moreover appropriate because of the presence of congestion externalities (which are determined in the waterway cost calculation in WAM).

The above description of the "Zap-price" demand formulation applies to the basic ORNIM and TOW-COST models (TCM) used by USACE. Recognizing the abrupt behavioral assumption that the entire shipment must go by one mode or the other, a second model, the ESSENCE model, introduces some elasticity into this process. In particular, ESSENCE stipulates that the demand for barge shipments depends on the barge price in a continuous manner, with higher shipments demanded at lower price, in line with standard economic analysis The demand curve is parameterized by a value N which indicates the elasticity of demand (with respect to the rail-barge differential, $R_i - w_i$).[3] The case $N = 1$ is easiest to explain. This gives rise to a linear demand function.[4]

There are several shortcomings in the basic ORNIM model. The demand forecast model has been quite roundly criticized by Berry et al. (2000).[5] More-

[3] The formula for the volume of shipments demanded is $\left[\frac{R_i - w_i}{R_i - w_0}\right]^N$ where w_0 is a base period price for the waterway. This is a constant elasticity of demand form with respect to the price differential $R_i - w_i$. The elasticity with respect to w_i is $\frac{-Nw_i}{R_i - w_i}$.

[4] One way to think of it is to imagine a uniform density of types of shipper between the old price (w_0) and the rail price (R_i). The differences in preferences across shipper types could arise from differential evaluations of the time or reliability of barge relative to rail.

[5] Berry et al. (2000) offer a tough critique of the approach used to justify expanding lock capacity. Their review was based on a one-day conference presentation, and the main findings are presented in an Executive Summary, although they do not go into much detail. The main points include:

Forecasts of future demands lack credibility;

Demand elasticity is arbitrary, and ought to be estimated;

Missing factors (other terminal points, regional economies);

Congestion pricing should be investigated, along with alternative infrastructure investment.

They concluded that the project ought to be delayed until the justification is properly documented. For the present purpose, the following quote is revealing: “the specific form of the N equation does not match the form of the appropriate spatial demand models... there over, the demands are assumed fixed at the pool Origin-Destination-Commodity level. This is the issue we concentrate upon in the current paper. Even with data limitations, it may be possible to generate the observed demands at the pool levels from an underlying spatial economy and let the data constrain parameters.

In the work presented below, we seek to identify the determinants of the differences between the benefit from using a full spatial model and those from using the ORNIM/ESSENCE models. If these differences are "small", then the tractability of the programming program may warrant their use. In the National Research Council (2004) review of the latest round of the Upper Mississippi-Illinois waterway cost/benefit analysis, they proposed that USACE consider the use of spatial competition models of the Samuelson and Takayama and Judge variety. As noted in the present work, such a proposal may run into serious theoretic flaws which are shared by both the ORNIM and ESSENCE models.

3 The Samuelson-Takayama-Judge framework

The ORNIM framework can be interpreted in the context of the work of Samuelson (1952) and Takayama and Judge (1964). We briefly review the contributions of Samuelson (1952) and Takayama and Judge (1964).[6] Both in the Samuelson-Takayama-Judge models as well as in the ORNIM/TCM and ESSENCE models, the regions are taken as fixed. This means that the "catchment area" for a pool (the set of geographic locations that use it) does not depend on prices at neighboring pools. Agents cannot "jump" locks to avoid congestion and the extra

is no value of N that would reproduce the various shapes of demand functions that are easily generated from spatial demand models." (Berry et al. 2000, p.14).

[6] Samuelson in turn drew on Enke (1951). Enke proposed the problem of determining spatial transportation patterns (under a linear demand system). His solution was inspried by the analogue to the problem in an electric system, and he could measure equilibrium prices and quantities with voltmeters and ammeters. Samuelson (1952) then set up and solved the problem as a linear programming problem. Takayama and Judge (1964) converted the Samuleson-Enke problem into a quadratic programming problem and found the solution algorithm (still for linear demands).

costs of going through a lock despite the fact that costs to avoid the lock or locks may be minimal. The benefits of improving a particular lock may therefore be overstated, as demonstrated later.

Samuelson (1952) and Takayama and Judge (1964) find equilibria with linear net demands that depend only on local prices. A simple shipping sector is responsible for transporting between markets, and it responds by an arbitrage-like process to (autarkic) price differences across markets) The USACE approach is similar in positing spatially fixed demands for transportation: the demands do not meld into each other, and there can be no overflow from one market into another. The transportation sector also bears some similarity, although the USACE version entails a more elaborate model of the transportation sector that includes congestion and the spatial geography of the waterway (that shipments from A to M and from C to N all pass through Lock K, for example).

The Samuelson-Takayama-Judge model works as follows. There is a fixed set of locations. Each location is described by a local demand for a commodity, and a corresponding local supply. These depend only on the local price. Subtracting the quantity supplied from the quantity demanded at each price yields a set of net demands, one for each given location. Where these net demands are zero determines an "autarkic" price that would prevail were no trade possible (or if transportation was prohibitively costly). There is a competitive transport sector, which responds to differences in autarkic prices and ships from low price locations to high price locations in a manner that eliminates further desire to trade by ensuring that any remaining price differences cannot exceed the cost of shipping between the corresponding locations. In that sense, the shipping sector may be viewed as carrying out arbitrage across the different markets.

A crucial feature of this set-up is that the point demands are not fungible between locations. This may indeed work well for transportation from New York to Liverpool (say), but the assumption that all producers in one region ship to a given port is a restrictive assumption when shipment points are quite flexible. For example, river shippers often have a choice of where to enter the river (or where to load onto rail), and the actual choice will depend upon the corresponding prices paid for shipping.

The ORNIM set-up has a similar structure insofar as the demands are assumed independent (so there is no flexibility in shipment points). ORNIM is special in another respect. While it does allow for alternative shipment (rail) up to a Zap price, it restricts demand to be fully inelastic up to the Zap point. Below we show how we can generate this from a spatial structure, and discuss its limitations.

To set the stage though, we first describe a simplified geography of the full spatial structure with various alternative hypotheses on the transportation infrastructure. The economic shipping models that these alternative hypotheses generate are described in the subsequent sections.

4 Geography and transport costs

We use similar assumptions on the geography of the river system as in our previous work in the river-canal context (Anderson and Wilson, 2004, 2005). We suppose that shipments by river-canal must first be transported by truck to a river terminal, and then loaded onto barges. We model interaction between a competitive transport sector (truck-barge) and one with market power (rail). Below we distinguish the different scenarios that we examine in this paper regarding the transportation infrastructure.

The river-canal system runs from North to South, and terminates at the final transshipment port. Let the East-West distance to the river-canal be in the x direction, and let the North-South direction up and down the river-canal be denoted $y \geq 0$. For the first part of the analysis below, there is a single river terminal in each pool. The cost of barge shipping from the pool is w_i per shipment. We also start out with a single rail terminal per pool. In that case, the cost of rail transportation is R_i. However, shipments still have to reach the terminals, and travel by truck to do so. Shipping by truck is perfectly competitive. The shipping rate by truck is constant per unit per unit distance shipped, at rate t. Truck transport is assumed to follow the "Manhattan metric," meaning that distances must be traversed East-West and North-South only. Hence, the cost of shipping by truck to a location $(\bar{y}, \bar{x})$ from coordinate (y, x) is $t\,|x - \bar{x}| + b\,|y - \bar{y}|$.

In the present work, we also allow for rail transport to be made from many points, and likewise for barge. Both are assumed to follow the block metric (actually, for river, this is straightforward since the river flows due South). The corresponding rates per unit per mile are b for barge and r for rail, and we assume that $t > r > b$, so that, if transport modes are priced at cost, the combination of truck and barge is the cheaper option for locations close to the river since the high per mile cost of trucking is offset by the low per unit cost of barge (see Anderson and Wilson, 2004).

We first assume that each shipment point (i.e., coordinate (y, x)) is associated to a shipment of unit size up to a reservation value that is “high enough” that it plays no role in what immediately follows. Later, we introduce a downward sloping demand at each point in space.

5 Single river terminal per pool, single rail terminal

A central purpose of this paper is to assess the assumptions of USACE models in the context of a full spatial model. To do so, there are a number of assumptions which can be imposed on a full spatial model that results in an ORNIM/TCM type configuration which serves as a baseline comparison. These assumptions are:

1. There is a single river terminal for each pool.

2. There is a single rail terminal for each pool, and it is coincident with the river terminal.

3. The quantity of agricultural production from each point in space is fixed.

4. All land within a given distance from the river is viable for farming for the range of transport cost variations considered (fixed extensive margin)

5. Farmers within the latitudes that define the pool must ship (either by river or by rail) from the pool terminal..

We lay out and discuss these assumptions below. The objective here is to build a model that has origin-destination demands (for a given commodity) at the pool level. In the model, there is but one destination pool so that each demand can be simply identified by its originating point. To generate this feature from a spatially extended economy, we suppose that each farmer within the latitudes that define the pool must ship to the river terminal that is on this pool. That is, there is a single river terminal and all farmers situated between the locks must ship to that terminal. The river terminal also doubles as a rail terminal so that farmers have a choice of whether to ship by river or by rail. Further suppose that each farmer has a fixed amount of produce to ship on the river and that the number of farmers are fixed, for example that there is a fertile valley that is cultivated, and outside of which the land is too barren to farm. Then suppose too that all these farmers will find it worthwhile to ship by rail from the terminal on the river, and that there is no other rail terminal around. This means that the price for the agricultural produce is more than sufficient to cover the rail transport costs, plus the truck transportation cost needed to get the produce to the terminal (and also covers any harvesting costs, plus, in the long run, the cost of planting and other farming costs - as well as still leaving the farming crop the most profitable land use). This basic pattern is illustrated in Figure 1.

INSERT FIGURE 1. One river terminal coincident with rail terminal, fixed catchment area.

The farmers have to choose now only which mode to use for shipping the produce to the final market (downstream to New Orleans, say). Clearly they will choose the one that is less expensive. Suppose that rail shipping from terminal i in pool i costs R_i per ton shipped. As long as the barge price per ton, w_i, is below R_i, then all produce will be shipped by barge. The resulting barge demand curve is given in the Figure 2.

INSERT FIGURE 2. Demand schedule for the ORNIM model.

Note that the rail price here, which is assumed exogenously given, is a Zap price in the sense that if the barge price rises higher than R_i, all shipments will go by rail instead of by barge. One nice feature of the ORNIM model is that the barge price w_i is determined as an equilibrium price given that it endogenously includes all delay costs at locks downstream (via the WAM module). A brief description of how this works is as follows. For any set of barge prices (w_i's), there corresponds a set of shipments (nothing from pool i if w_i exceeds R_i, and the full demand from pool i otherwise). These shipments then determine a set of lock congestion times, and hence induce a new set of barge prices. The equilibrium is an internally consistent set of barge prices (a "fixed point" in technical terms) such that the barge prices induce exactly the set of shipments that give rise to the barge prices.

Now return to the demand schedule, and suppose that all land within the pool latitudes is equally fertile, and stretches out far in both directions. Then the costs of shipping will draw a natural bound on the width of land farmed. Call the furthest away points the extensive margin of cultivation, so that all land within the extensive margin is farmed, and all land outside is not farmed. The extensive margin is illustrated in Figure 3. It has a lozenge shape and is furthest from the river at the latitude of the river terminal. This is because the costs of truck shipping determine the extensive margin for any given barge rate, and these costs are lowest for any given horizontal (East-West) distance the lower is the North-South distance.

INSERT FIGURE 3. Extensive margin of cultivation and effects of lower barge rate

In the model, allowing the extensive margin to change effectively allows the Samuelson-Takayama-Judge region to change endogenously and indicates to a demand function with a non-zero slope. In our geography, the “gathering” area (the region from which shipments occur) expands in the East-West directions. Below, we also develop a case for expansions in the N-S directions as well.

Consider now a drop in the barge rate. By making shipping less expensive, this moves out the extensive margin of cultivation to the dashed lines on the figure. This gives some elasticity to the demand curve for barge transportation. As the price of barge traffic falls, then the extensive margin shifts out and more land is cultivated for shipment.

A further reason for demand elasticity is at the level of the individual farmer within the catchment area (i.e., inside the extensive margin). As the price of barge shipping falls, then the profit per unit from shipping a ton of produce rises. This effect induces farmers to produce more - and the longer the time-frame, the more response is expected. In the short-term, a lower barge rate at harvest time causes farmers to exert more effort into reducing waste and ensuring the whole crop planted is harvested. They will also be more inclined to ship rather than use the produce for other local purposes (such as feeding to hogs or converting to ethanol in the case of corn). In the longer run, more land will be cultivated with the crop in question, and more intensive farming techniques (applying more workers and machinery as well as using higher yield seed types) will be used. For all these reasons the individual demands will be sensitive to the barge price. The implications for demand are sketched in Figure 4.

INSERT FIGURE 4. Demand effects: base case, extensive margin, short-term, long-term.

There are other important factors in demand even in this simple sketch (i.e., before we introduce more elaborate infrastructures even). Perhaps the most important of these is that the farmers farthest down-river in the pool might find it more profitable to ship from the next terminal downstream rather than from the upstream terminal to which they were assigned in the above argument. This feature has some far-reaching consequences for the ORNIM/TCM set-up because it means that the demands are interdependent – demand at each pool depends not only on the barge rate from that pool, but also depends on the rate at adjacent pools. This is a separate and additional effect to those noted above where the latitudinal boundaries in demand were fixed.

Suppose now that farmers are to choose the pool from which to ship. We revert for simplicity to the basic geography of Figure 1 where the extensive margin of cultivation is fixed by nature and assume too that there is no supply flexibility (no barge price responsiveness) within the extensive margin.

Consider a farmer towards the southern end of the pool, facing the decision of whether to truck North to ship from the pool i or whether to truck south, and ship from the terminal in the next pool down, pool $i-1$. We naturally expect the barge rate to be lower further south ($w_{i-1} < w_i$) because a smaller distance is traversed on the river and one less lock is crossed. The farmer must, therefore, weigh up the costs of trucking to the two alternative terminals. The indifferent farmer defines the market boundary for the catchment areas of the two pools. Those farmers further north of the boundary will ship to the pool i terminal, and conversely.[7]

The situation is illustrated in Figure 5, and again, points to another source of substitution from shippers located over geographic space.

INSERT FIGURE 5. Endogenous pool markets depend on local barge prices

The Figure also shows the effects of an increase in the barge rate in pool i. This means that shipments from pool i shrink as its barge price rises. They shrink on two margins here. First, shippers in the South switch to the pool below. Second, shippers in the North switch to the pool above. What is important in this simple sketch is that the number of shipments on the river does not change, but their allocation to pools does. The demand immediately upstream and immediately downstream change with the local price as farmers substitute away from the more expensive option. However, they do not switch into rail, they switch into a different pool demand. This facet of demand interdependency is not captured in the ORNIM/TCM model. We next consider more elaborate infrastructure patterns.

[7] The indifference boundary is determined as follows. Let the terminals be located on the river ($x = 0$) at y_i and y_{i-1}, with $y_i > y_{i-1}$, and let $w_i > w_{i-1}$. The indifferent farmer is at a latitude $\hat{y}_i$ such that total tranpost costs are equalized. This means that $t\,[y_i - \hat{y}_i] + w_i = t\,[\hat{y}_i - y_{i-1}] + w_{i-1}$. Simplifying,

$$\hat{y}_i = \frac{y_i + y_{i-1}}{2} + \frac{w_i - w_{i-1}}{2t}.$$

Note that this is simply the midpoint if both barge prices are equal. Otherwise, the higher the price in pool i, the further North the indifferent latitude.

5.1 Alternative rail shipping location

Suppose that there is an alternative rail shipping location to the one at the river terminal. For expediency, let the rail terminal be located at the same latitude as the river terminal, and moreover impose the restriction that all farmers between the latitudes of the locks defining the pool ship from either the river or the rail terminal. The demand for the pool is then dictated by the location of the farmer indifferent between the rail and the river terminal. Given the assumption that transportation follows the block metric, the locus of indifference is at the longitude where the difference in the distance to the river terminal and the distance to the rail terminal just offsets the rail-barge transportation cost difference.[8] Figure 6 illustrates this infrastructure and economic behavior.

INSERT FIGURE 6. Rail terminal away from river. Linear demand for pool.

As the barge rate falls, the indifference longitude moves East linearly. This pattern, therefore, generates a linear demand function that is reminiscent of the case $N = 1$ of the ESSENCE model. However, it differs in two respects. First, the demand for barge transportation falls continuously to zero, and reaches zero at a price above R_i because barge has an advantage for farmers near the river terminal by dint of its proximity enabling them to pay lower trucking costs to ship to the river rather than the rail terminal. Second, the barge mode "zaps" the rail mode at a critical price where it is just cheap enough to attract farmers at the railroad terminal - and therefore all the farmers in the hinterland of the rail terminal. This demand function is shown in Figure 7.

[8] Specifically, the distance satisfies

$$tx + w_i = t\,[x_R - x] + R_i,$$

where x_R is the location of the rail terminal. Rearranging, $x = \frac{x_R}{2} + \frac{R_i - w_i}{2t}$. This indifference location moves east linearly with decreases in the barge rate, w_i, and therefore generates a linear demand for the pool.

INSERT FIGURE 7. Pool demand given rail terminal at the same latitude as the river terminal

Having established the pattern under the constraint that farmers must ship from their "own" pools, we next relax this constraint to allow for "lock-jumping." As we noted above, this is an important feature of the spatial setting that is missing in the ORNIM set-up. In Figure 8, we take a snap-shot of two adjacent pools and delineate the demand addressed to river shipments in each pool as well as shipments from the rail terminals in the pool area. The Figure is constructed by finding the indifference longitudes between each rail and river terminal in each pool, and the indifference latitudes between the two rail terminals and the two river terminals. We then complete the graph by determining the locus of indifference between the barge terminal of each pool and the rail terminal of the other one.

INSERT FIGURE 8. Pool demands given cross-over behavior of farmers

As we noted before, the effects of a barge price decrease for a pool increase the number of shipments from that pool. This increase is drawn in part from decreasing the demand for the adjacent pools. However, there is now an additional effect that some of the increase is drawn from the nearby rail point AND the rail terminals in adjacent pools too.

6 Many rail terminals

There are many points in a pool area from which rail shipments may be made. The rail net is reasonably dense, and there are multiple branch lines. The specific geography can be modeled at a micro level by specifying all the actual possible rail pick-up points and then following the lines of the analysis of the preceding section. Note that this introduces the issue of multiple rail prices (one from each possible shipment point), and also specifying how these are determined. We, therefore, approximate a dense rail network by assuming that rail transport is available all over the geographic space. The advantage of the approximation is to give a clearer picture of the overall system equilibrium shipment pattern.

We retain for now the assumption that there is a single river terminal per pool. Once again, to emphasize the implicit assumption in ORNIM that demand at each pool is independent of the demand at each other pool, we build upon the analysis by assuming first that the area between the two latitudes defining the pool must ship from the pool's river terminal if shipping is done by the river (i.e., truck-barge is used).

As above, let t denote the cost per unit shipped per unit distance using truck. Let also w_i be the cost of shipping from the river terminal in pool i. We now also must specify how much rail shipping costs from different points. We shall use a "block metric" just as we did above for the trucking sector. What this means is that transportation can be viewed as following a grid network, and distances are traversed only North-South and East-West. We suppose that the cost of rail shipping is linear in the (block) distance shipped, at rate r per unit shipped per unit distance. Thus we can specify shipping costs from any point in space. We know that rail shipping is cheaper the closer to the river is the origin, as is also true for truck-barge (since the rail traffic effectively must traverse the same East-West mileage as the truck traffic). Rail is also cheaper the closer the original to the destination. For barge though, this is not true if the origin point is South of the pool river terminal. In that case, the further South, the greater the shipping cost because a greater distance must be travelled North by truck to reach the terminal. However, for points North of the terminal, further South is better because it is synonymous with closer to the river terminal.

To find now the catchment area for barge within the pool latitudes, it suffices to find the indifferent farmer location such that the farmer pays just as much shipping by truck to the terminal and then by barge thereafter as he does shipping by rail throughout. Figure 8 illustrates the resulting spatial catchment area. Notice that it reaches furthest East at the latitude of the river terminal: this is because the relative advantage of barge is highest there because transportation by truck needs no North-South component.

INSERT FIGURE 8. Catchment area for barge, case of one river terminal per pool, many rail terminals

The Figure also illustrates the effects on the barge catchment area of decreasing the water rate, w_i.[9] Notice that the decrease in the barge rate causes the catchment area to expand in a parallel fashion. This means that if the density of farmers is uniform over space, then the demand function for the pool is a linear function of the barge rate, w_i.[10] This latter property again accords with the ESSENCE module.

We now allow the farmers to ship to whichever river or rail terminal they wish. This means that the terminal in the pool below may well attract traffic from farmers from the South of a pool above. This is the situation illustrated in Figure 9.

INSERT FIGURE 9. Catchment area for barge, case of one river terminal per pool, many rail terminals, "lock-jumping" allowed

The picture looks quite like that of Figure 8, with the catchment areas having the same shape, except that they are shifted upwards (above the pool latitudes) by the possibility of trucking down to the river terminal in the next pool down.

[9] The water rate here, w_i, is the rate from the river terminal down to the destination. It constitutes the full price for the trip, and does not need to be broken down into a rate per mile.

[10] The same property (linearity) is true in the current formulation if the density of farm production is the same at any latitude. Even if it differs across latitudes, it still has the linearity property.

Note that this lock-jumping feature also entails there being continuity in the longitudinal boundary (as illustrated) as we pass from one pool catchment area to the next one down. The latitudinal boundary between two pools' catchment areas is horizontal, as given in Figure 9, because of the assumption of block distance in trucking: trucks must also travel in North-South and East-West patterns only. While a crow-flies distance would give a more intricate pattern, it would not fundamentally alter the qualitative result of the Figure.[11]

7 Many rail terminals and many river terminals (dense infrastructure)

The models above have assumed that there is a single river terminal per pool. In practice, there are often several locations within a pool at which barges can be loaded. We just analyzed the case of many rail terminals over space: now we develop the model for the case of many river terminals. Again, for clarity, we suppose that any point on the river is a candidate barge-loading location. There is a difference between the case of many rail terminals and many river terminals: in the former case, anywhere in the two-dimensional geographic space is a potential loading point, while in the latter case the loading points are constrained to points along the river. This means that trucks must be used to reach the river to use barge, while rail goes directly from the point of production.

We now need to also specify the rate per unit distance travelled by barge. Call this rate b. Barge must be used in conjunction with truck (which operates at rate t), and so truck-barge combines the most expensive mode (truck) with the least expensive mode (barge). Letting the rail rate per unit per unit distance be r, we assume that $t > r > b$. This pattern of costs ensures that both modes (rail and the joint truck-barge one) are viable in equilibrium. Moreover, truck-barge dominates in the neighborhood of the river. We also suppose that

[11] Using the actual road net would likely yield an intermediate pattern.

barge shipping entails an extra cost whenever locks are crossed: denote the cost associated with Lock i as c_i.

Since the terminal market is at location $y = 0$, $x = 0$, the cost of making a shipment from location with coordinates (y, x) is therefore $r|x| + ry$ using rail. Using the truck-barge mode, the cost is $t|x| + by + \sum_{\{i|y_i<y\}} c_i$ where the summation encompasses the total cost of traversing all locks between origin (y) and destination (0). For comparison purposes with what has come before, we start out by maintaining the hypothesis that each shipper must ship from his own latitude (x) if shipping by barge. This gives rise to the following pattern of barge shipment areas.

INSERT FIGURE 10. Catchment area for barge, case of many river terminals per pool, many rail terminals, "lock-jumping" not allowed

The Figure embodies the idea that crossing a lock adds to the cost of barge shipping.[12] The existence of this cost, though, means that farmers may prefer to ship down (by truck) below the costly lock.[13] Indeed, Figure 10 clearly indicates that such an arbitrage opportunity exists. Figure 11 shows the spatial pattern of the truck-barge catchment area once we allow such "lock-jumping."

INSERT FIGURE 11. Catchment area for barge, case of many river terminals per pool, many rail terminals, "lock-jumping" allowed

Notice the similarity between Figure 11 and Figure 9 which shows the catchment area for barge in the case of a single river terminal per pool and many rail

[12] The Figure, and the subsequent one, also allow for shipping by truck directly to the final (terminal) market. This explains the lowest catchment area on the Figures (i.e., below $\tilde{y}$): this consititutes truck-only traffic. In Figure 10, there is also a term ΔF that influences the position of the extensive margin for truck-barge: this represents the fixed cost advantage to rail traffic (and includes lock-crossing costs at locks further downstream). See Anderson and Wilson (2004) for further details.

[13] Analysis of this issue was one of the prime puroposes of Anderson and Wilson (2004).

terminals, when "lock-jumping" is allowed. In both cases, "arbitrage" behavior by shippers (in terms of "lock-jumping" in response to price differentials) renders the catchment area boundaries continuous (cf. the discontinuities apparent in the counterpart Figures 8 and 10 without the ability to by other than ones' own pool area). The difference between the two Figures is that when there is a single river terminal then the barge catchment area bulges out at the latitude of the terminal. When terminals are all along the river, the catchment area follows a similar pattern, except that the bulges correspond to the latitudes of the locks since locations just above the locks must incur costly truck transportation in order to "jump" the locks.

We next turn to the comparison of welfare across the different models, and the relation between the welfare derived from these explicitly spatial models and the world of Samuelson-Takayama-Judge and ORNIM.

8 Welfare Analysis

There are several potentially important sources of welfare gains and losses that are not captured by the ORNIM approach. These are discussed in this Section. The first is illustrated most simply using the model closest to ORNIM, namely our first model above (Section 5) in its stark form whereby there is a fixed amount of arable land, and no scope in terms of production at either intensive or extensive margins. Hence the total amount shipped is completely invariant to the barge rate or rates. In this model, the only important issue (and the one we highlight here), concerns substitution between pools by shippers: other points are made later in more elaborate versions of the model. This issue is at the heart of our criticism of using the framework of Samuelson-Takayama-Judge to model transportation demands that emanate from locally dispersed production: no such substitution is allowed.

To see the issue, refer back to Figure 5, which illustrates the effects on the market for pool i shipments resulting from a decrease in the barge rate, w_i. To make things even simpler, suppose too that the uppermost pool is pool i: let the location denoted Lock i in the Figure represent the furthest North extent of the arable land (call this $\bar{y}$). Now, as we noted in Section 5, the critical latitude that divides the catchment area for pool i from that for pool $i-1$ is linearly increasing in w_i. This property implies that the demand for shipments from pool i is also linear. However, the ORNIM model sets it as a constant amount. This divergence in assumptions can potentially lead to a substantial difference in the welfare evaluation of a change (the empirical importance is discussed further below). This is illustrated in Figure 12.

INSERT FIGURE 12. Welfare benefits of a reduction in the barge rate in pool i

Figure 12 represents the demand addressed to the river terminal in pool i as a function of the barge rate for shipments from pool i, w_i. The demand, as derived from the spatial model, is linear in w_i. This linearity reflects the important feature of the traffic diversion effect. Namely, as the barge rate falls (due to an improvement in transit times at lock $i-1$ following lock rehabilitation there, say), and keeping the barge rate from the downstream locks (such as Lock $i-2$) constant, shippers in the Northern reaches of pool $i-1$'s catchment area switch to using the pool i terminal. In Figure 12, the original (pre-improvement) barge rate is represented as w_i^*. After improvement, it falls to w_i^{**}. The ORNIM approach takes the demand at pool i as constant – a quantity of shipments Q_i^{**} in the Figure, which we assume for illustration to be the level to which the quantity shipped rises after the reduction in the barge rate.[14] The measured

[14] Clearly, the estimated benefits depend crucially on the starting position, i.e., the demand forecast.

welfare improvement under ORNIM simply then corresponds to the reduction of costs (w_i^*-w_i^{**}) on the assumed volume of traffic (Q_i^{**}). The total improvement is measured as the product, (w_i^*-w_i^{**})Q_i^*, as given as the full shaded rectangle in the Figure. However, this neglects the induced lower volume of shipments at the initial high rate (the traffic diversion effect) whereby the high rate renders pool i pricier for more shippers than pool $i-1$. The total benefit is then properly measured as the area left of the true demand curve (the linear one in the Figure) between the two prices (the horizontally shaded area in the Figure). This constitutes only part of the rectangle measured by ORNIM (the cost saving as if there were a high volume of shipments) but this neglects the fact that diverted shipments escape cost rises.

The size of the difference depends on the size of the cost reduction, the elasticity of the true demand, and where the demand forecast lies. Note that the ESSENCE model also shares with ORNIM the problem that the demands are based on the Samuelson-Takayama-Judge formulation: no traffic diversion effect is included. In our development of the first model (single river terminal and single coincident rail terminal), we next allowed for an increase in the extensive margin of cultivation in addition to the traffic diversion effect. This effect serves to render the demand more elastic (see also Figure 4). If a lower barge price also encourages more production due to substitution into crop production, demand is larger still, and more so the longer the time period under consideration (again see Figure 4). The ESSENCE model may pick up the latter effects, but it does not pick up the demand diversion one since it is based on Samuelson-Takayama-Judge. Before proceeding, a further caveat is in order. This concerns the nature of the ORNIM quantity forecast. ORNIM must forecast demands years into the future, and a crucial point concerns for what prices the forecast is valid. Of course, for the original ORNIM/TOW-COST specification, since demand is assumed totally inelastic up to the Zap price, this issue does not matter because it does not arise. However, it matters crucially if the demand has some elasticity.[15]

The second and third models presented above introduce a further source of possible welfare gains that are not accounted for in the ORNIM approach. In these models, the rail sector earns rents at locations that it serves. The rail price is determined by the constraint that rail shipping has to meet and beat the competition from the truck-barge alternative shipping mode. This process is described in detail in Anderson and Wilson (2005). In our model, railroads beat the competition by practicing spatial price discrimination.[16]

A reduction in the barge rate now causes an expansion of the catchment area, as before, and the benefits from this are measured as the area under the barge demand curve, as above. However, there is also an effect on the rail rate from locations still served by rail. The rail rate must fall to beat the new tougher competition. If there is no demand expansion from this price reduction, this is simply a transfer of surplus from railroads to farmers. There is no efficiency effect, but simply redistribution of benefits. However, there is an additional efficiency effect if farmers respond by raising production when faced with lower shipping rates.[17] This means that there is an additional surplus benefit that is not captured simply by looking at the demand for barge transport, and this is due to the competitive effect in the rail sector. A full treatment of the extra economic surplus emanating from the lock rehabilitation should include this spill-over effect into the other transportation sector. It is overlooked in ORNIM because the ORNIM model takes the rail rate as given.

[15] Some empirical evidence is given in Boyer and Wilson (2005), Henrickson and Wilson (2004), and Train and Wilson (2004).

[16] In addition, the exogeneity of rail rates in ORNIM also implies that enough railroad capacity is available to meet whatever traffic goes by rail. If there is a capacity constraint on the rail sector, the railroad's pricing rule is correspondingly adjusted to incorporate this. Further details are given in Anderson and Wilson (2005).

[17] Recall that we are using farmers as the illustrative example. Various elasticity effects may be larger or smaller for other commodities that use the river system.

9 Conclusions

The basic US Army Corps of Engineers planning models assume that the pool level demand is perfectly inelastic up to a threshold point (where the alternative mode dominates). We develop a full spatial model and then consider the assumptions under which this framework can be consistent with the USACE ones. We also indicate possible sources of over-estimation and under-estimation of benefits within the USACE model when compared to the full spatial model.[18]

One major potential source of divergence between the full spatial model and the one used by the USACE is attributable to their taking the pool level demands to be independent of barge rates at neighboring pools. In a full spatial model, it is readily apparent that marginal shippers will switch river terminals in response to barge rate changes (or lock rehabilitation that reduces waiting times at some locks) Accounting for this traffic diversion effect can yield welfare changes from improvements that is not picked up in the USACE approach which assumes no substitutability across pools is possible. Such substitutability is a natural economic phenomenon akin to arbitrage activity: shippers will switch whenever they find a better deal. Accounting for this behavior can generate welfare changes even when there is no induced extra economic activity (crop production, say) due to the barge rate decrease. Both the standard ORNIM/TOW-COST model and the ESSENCE variant are subject to these critiques since they are based on the Samuelson-Takayama-Judge spatial equilib-

[18] This paper is the third of a series. In the first paper (Anderson and Wilson, 2004), we developed an equilibrium model of the barge market with shippers located over geographic space and deciding how to ship to market. This model explicitly allows for flow constraints on the waterway due to locks, so that the cost of using the waterway increases with the level of traffic. The model yields a unique equilibrium with barge rates, quantities, and congestion determined endogenously for *given* rail and truck rates. The model allows for shippers to by-pass locks and points to a stacking property of pool level demands that requires evaluation of lock improvements to be made at a system level.

In the second paper (Anderson and Wilson, 2005), we extended the framework to endogenize railroad prices and show the railroad sets prices so as to beat the competition. The effects of waterway improvements on rail customers are purely distributional only if quantity shipped is insensitive to prices.

rium model. Somewhat ironically, the National Research Council (2004) review of the latest round of the Upper Mississippi-Illinois waterway cost/benefit analysis, proposed that the USACE consider the use of spatial competition models of the Samuelson-Takayama-Judge type. As we have seen, such a proposal may encounter theoretical flaws which are shared by both the ORNIM and ESSENCE models.

Additional benefits will accrue following a barge rate reduction if shippers can adjust, and these are not captured in the standard ORNIM/TOW-COST model. Arguably, the ESSENCE model can pick up such effects, though its crucial elasticity parameter (N) would need to be calibrated. However, rather than calibrating that model, it would seem preferable to work directly with the spatial model that is to generate it, as indeed was suggested by Berry et al. (2000). Using the spatial model directly would obviate functional form concerns that the constant elasticity version in ESSENCE brings up.

Another form of potential benefits is more subtly hidden in the market. It is not captured (nor addressed) in the USACE models, but it is evidenced in the explicitly spatial view of the underlying market. Indeed, the USACE models take the rail rate as exogenous. The spatial approach indicates that there is not one, but many rail rates at the pool level. Furthermore, rail has to beat the competition from truck-barge in order to get shipping contracts, so these rail rates are endogenously determined. If barge rates fall, competition will get tougher and even shippers who remain with rail will gain the rent because the railroads must lower price to meet tougher competition.[19] If each shipping point generates a downward sloping demand, then waterway improvements may generate additional welfare gains as shippers experience lower prices and expand

[19] The same principle applies with rail capacity constraints. Then the railroad prefers to serve the shippers from which it can receive the highest markups. Such locations are the captive shippers to railroads i.e., the shippers located furthest from the waterway. Lower barge rates reduce the rail rates that can be charged to these shippers too.

output.[20] Thus the full effects on benefits from infrastructure improvements may spill over (and be measured from) other markets as well as the truck-barge market itself.

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Figure 1.—Stylized Network and Transportation Infrastructure

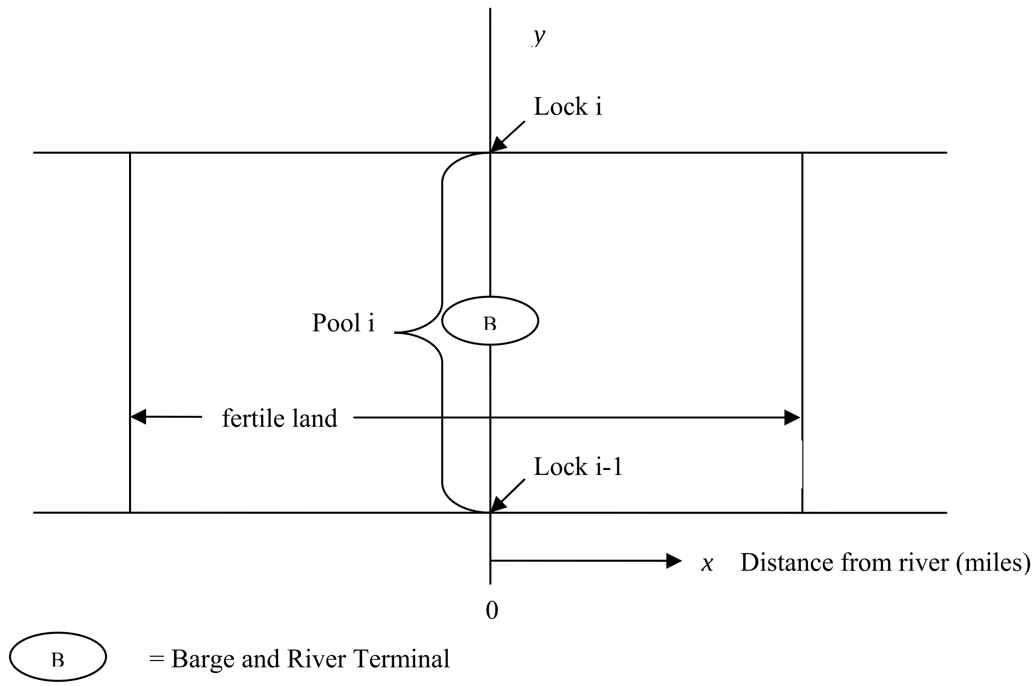

Figure 2.—ORNIM Demands

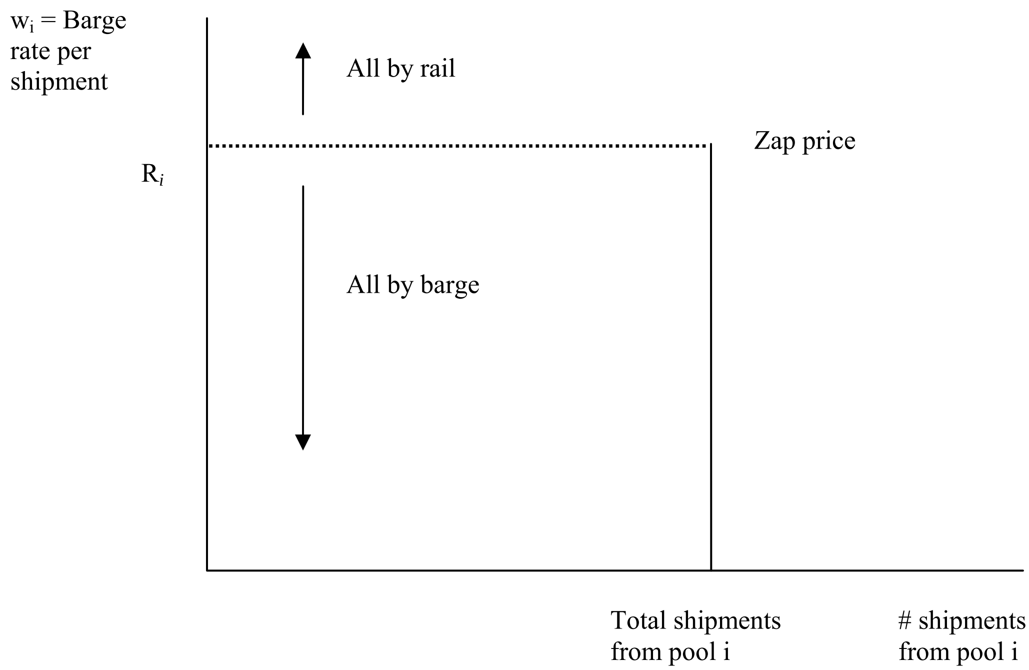

Figure 3.—Extensive Margin of Cultivation and Lower Barge Rates

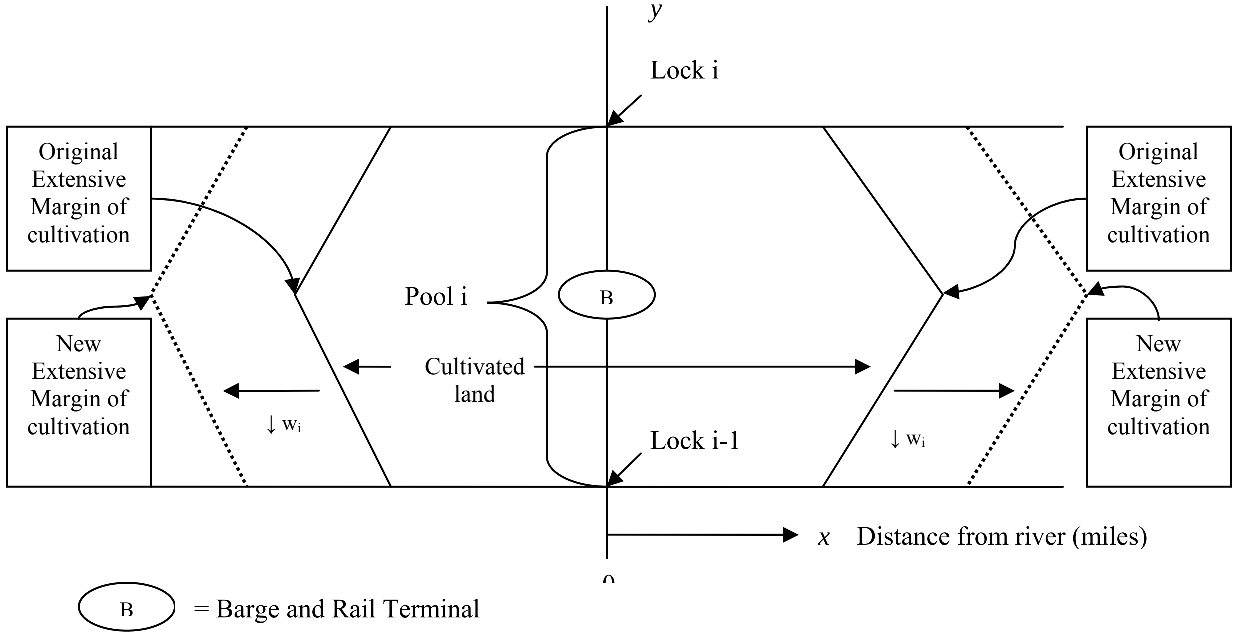

Figure 4.—Demand Effects: Base Case, Extensive Margin, Short and Long Runs

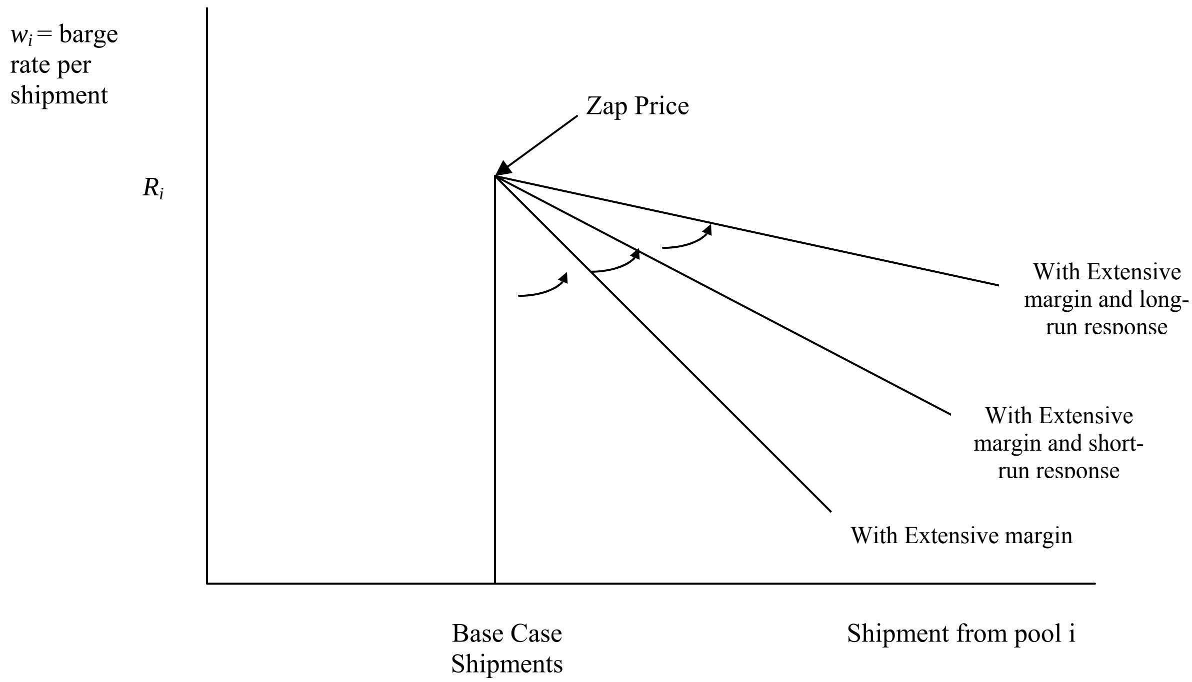

Figure 5.—Endogenous Pool Markets and Barge Rates

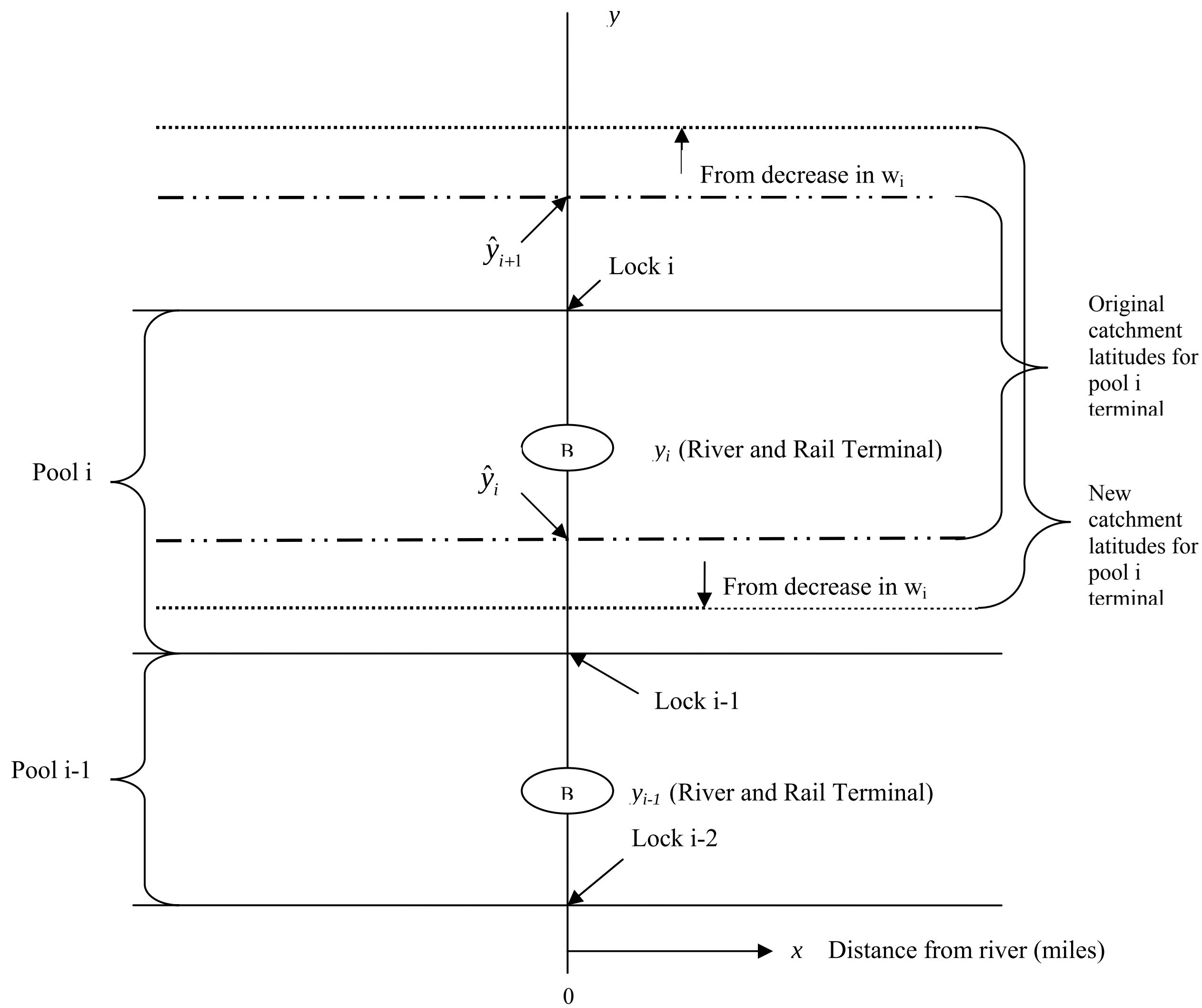

Figure 6.—Rail Terminal Off-River and Linear Demands

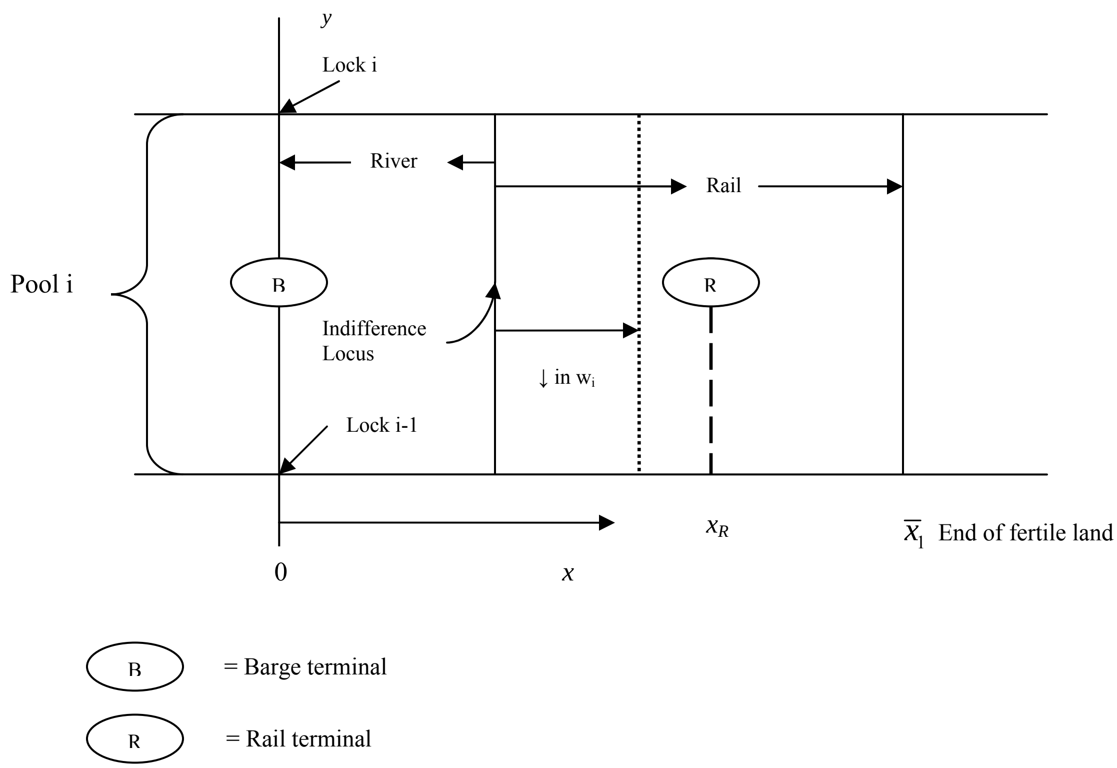

Figure 7.—Pool Demand with Rail and River Terminals at Same Latitude

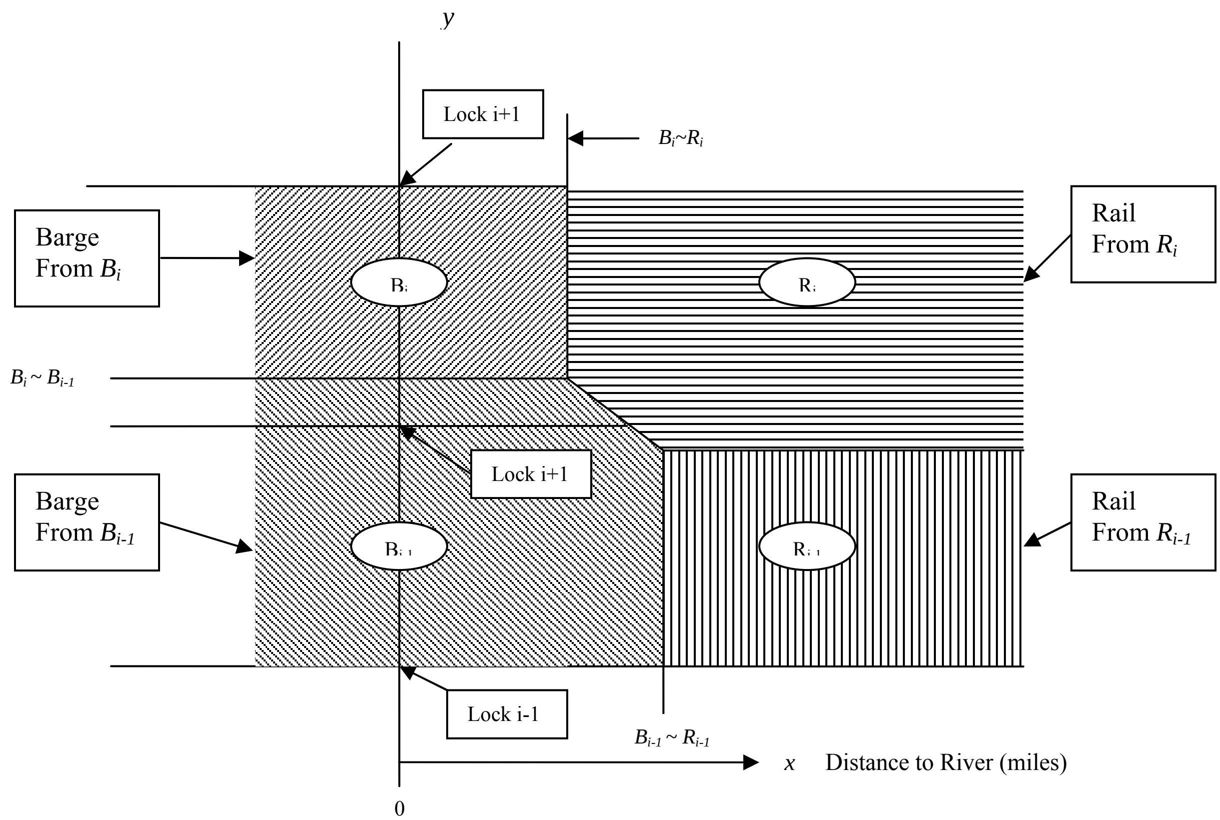

Figure 8.—Pool Demands and Lock-Jumping

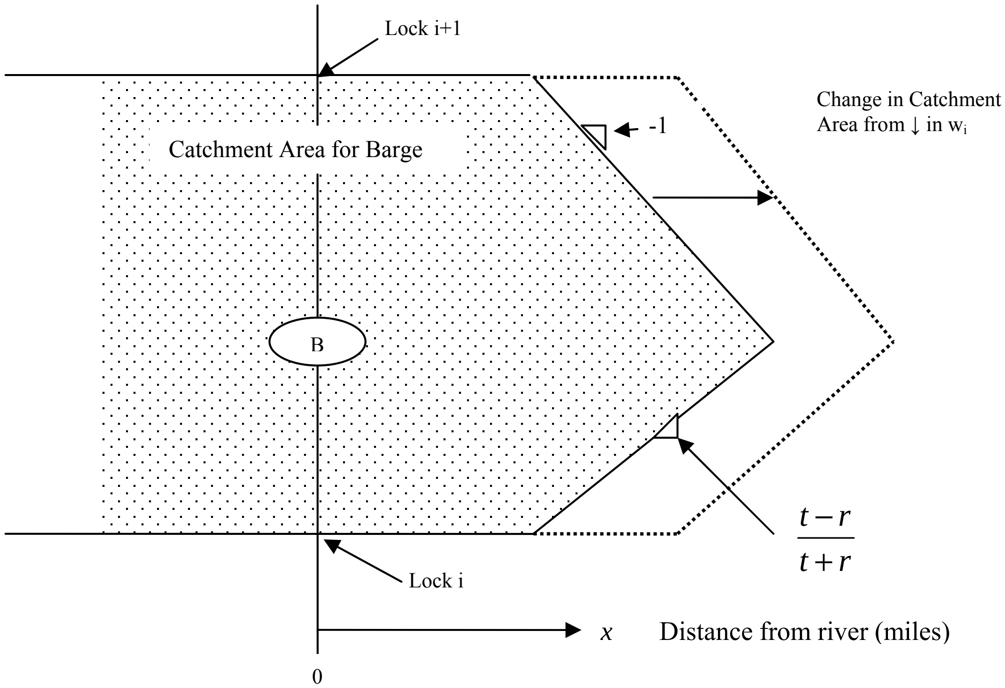

Figure 9.—Endogenous Markets

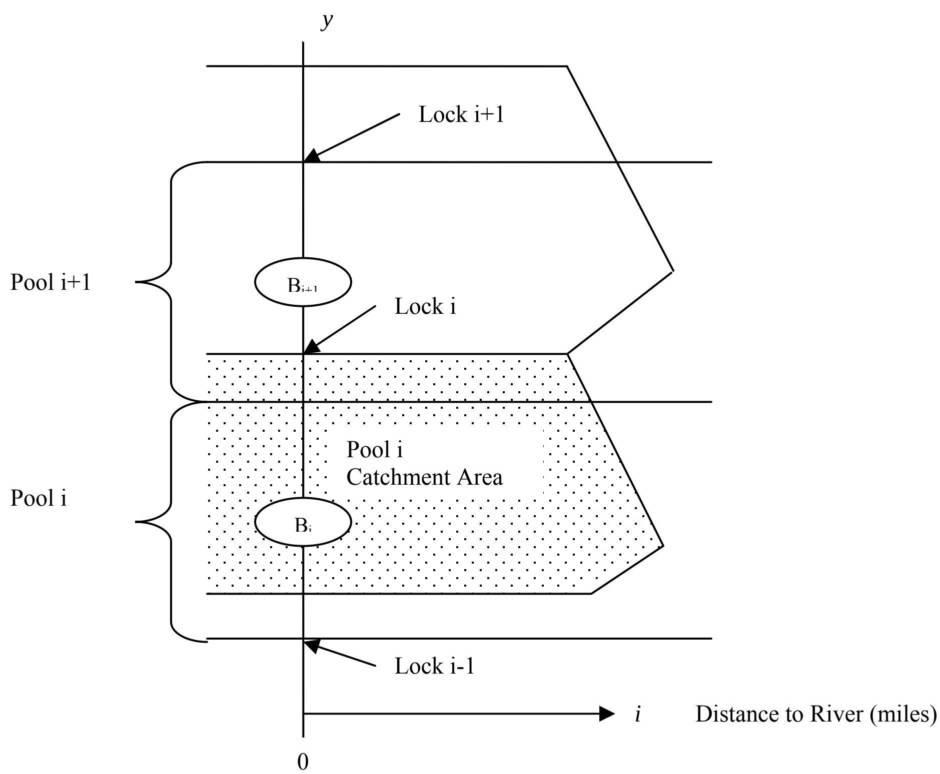

Figure 10.—Catchment Area fof Barge, case of many river terminals per pool, many rail terminals, “lock-jumping” not allowed

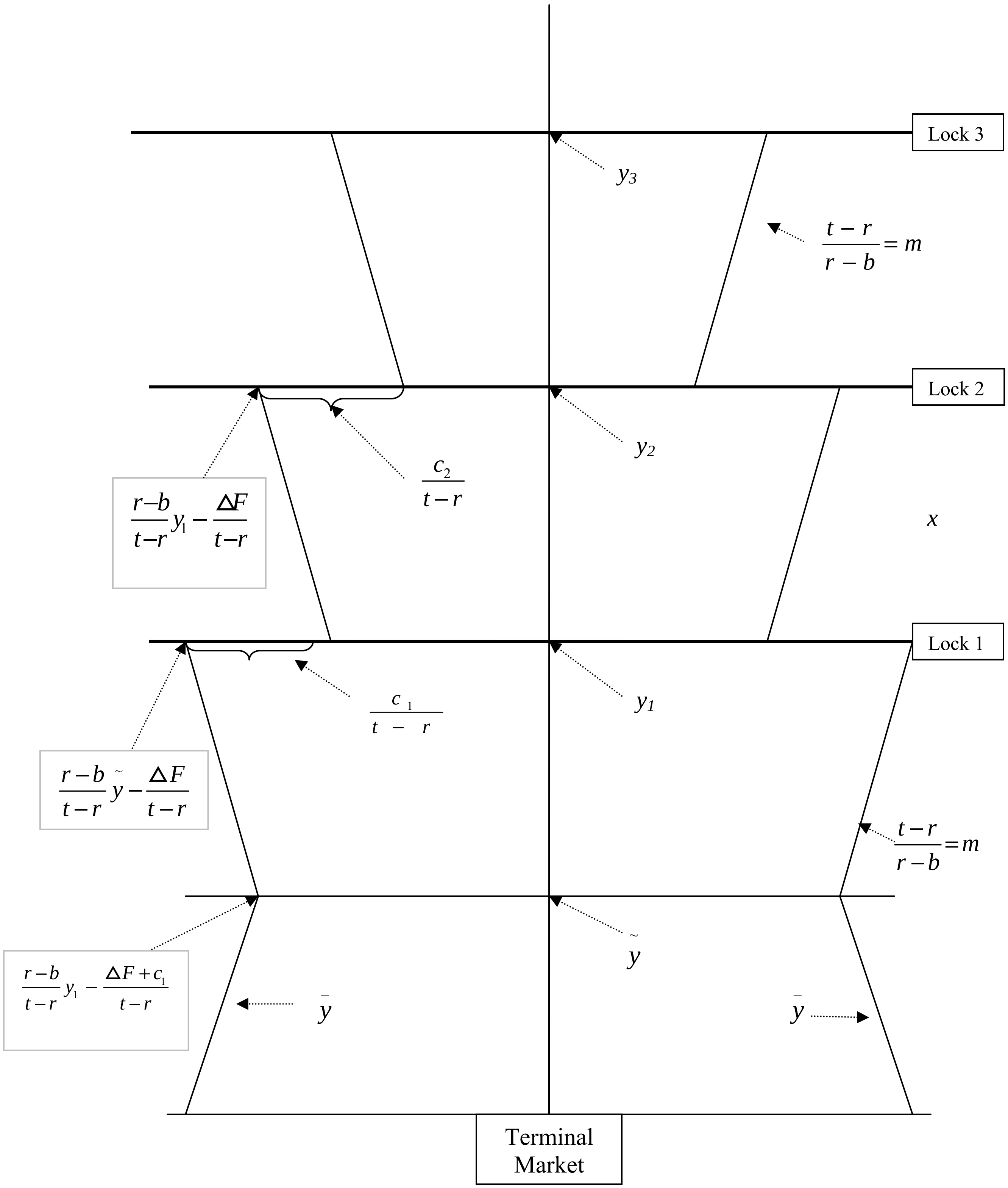

Figure 11.—Catchment Area for Barge, case of many river terminals, many rail terminals, “lock-jumping” allowed.

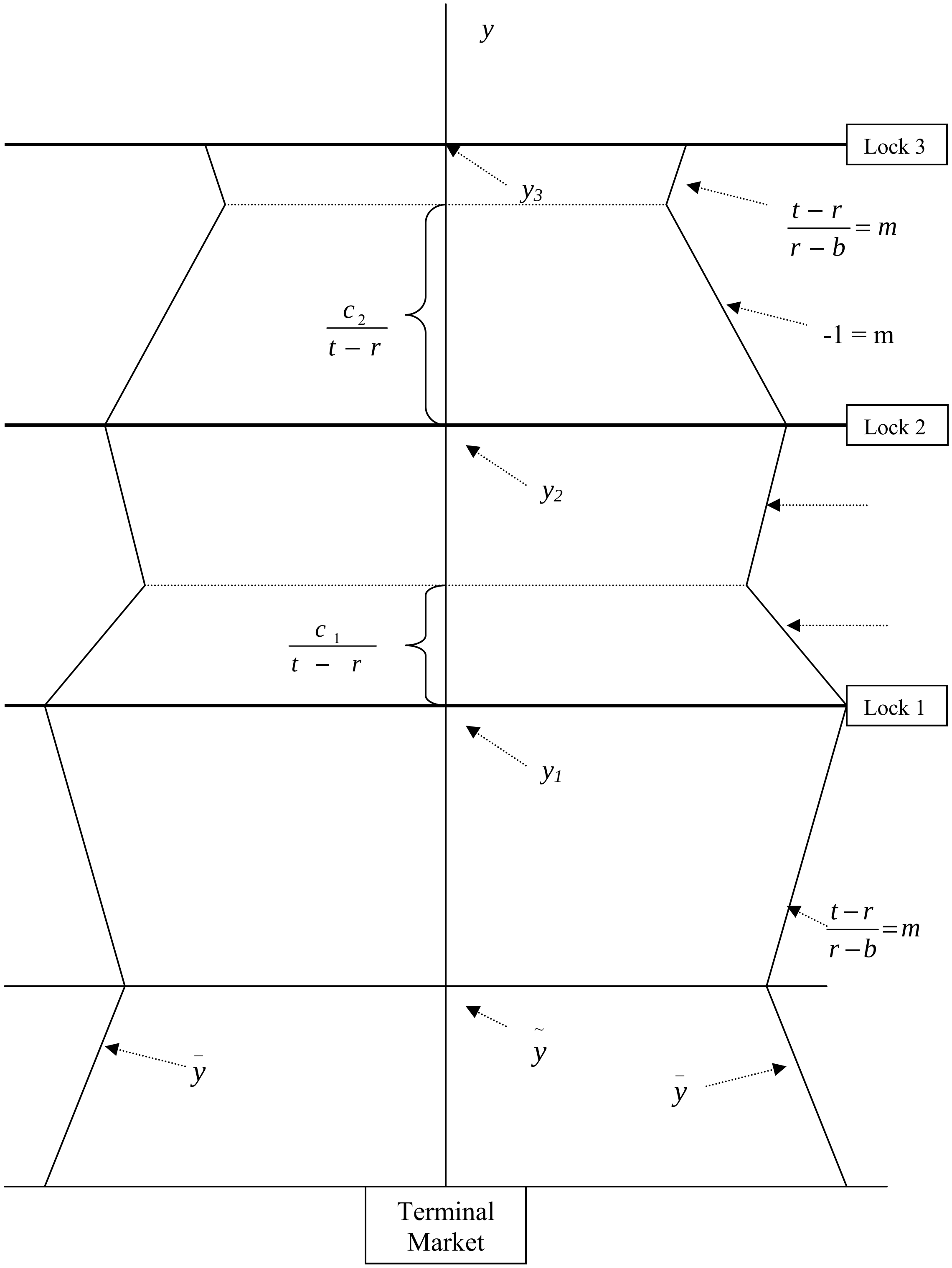

Figure 12.—Welfare Benefits of a Reduction in the Barge Rate in Pool i