LINEAR PROGRAMMING SIMULATION OF ROUTING EMPTY RAILROAD CARS

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This paper describes the application of a linear programming model to the routing of empty railroad cars to determine where excess capacity exists. One of the more important results is simply that the solution of a model of this size and complexity is feasible. The model showed that there were a number of railroad routes over which an appreciable flow of empty cars moved and that filling these cars could provide very low cost transportation. Finally, the solution of the linear programming problem provides a series of shadow prices for cars in different locations that can be used in setting rates, which is a new approach to incorporating directional factors into rate setting.

•THIS STUDY is one of several studies to improve railroad costing and transportation regulation (1, 2, 3). This research used several existing U.S. Department of Transportation data bases. As part of a national network model, the United States was divided into 529 zones. Each of the standard metropolitan statistical areas constituted a zone, and the rural counties were grouped into zones. Each zone was assigned a central point at which all traffic to and from the zone was considered to originate. These points were tied to a network model of the U.S. rail system, which included virtually all of the main lines (more than 200,000 miles or 320 000 km). Given a matrix of flows from each zone to each other zone, computer routines were available that routed traffic by the shortest route and then aggregated the flows over each link. This model was being used to determine the future flows of traffic over various links of the railroad network given the pattern of originations and destinations.

There was also available a special tabulation of the Interstate Commerce Commission 1965 1 percent waybill sample for railroad shipments between the different zones. At the time of the study this was the most recent data available although there were problems that prevented the classification of flows by car type. For zones that terminated more traffic than they originated, the number of tons (megagrams) of empty car capacity created each day was determined simply by subtracting the tons originated from the tons terminated. Likewise, for the originating zones, the car capacity required for loading was determined by subtracting the tons terminated from the tons originated. Then, the empty cars available in destination areas merely had to be matched with the cars required in originating areas.

There are of course a number of ways in which the empty cars could be assigned to the areas where cars were required for loading. In the real world, this would be determined by a host of institutional factors including the Association of American Railroads Car Service Rules. There was no way all of these complexities could be modeled in the initial effort. Thus, the decision was made to determine the assignment of empty capacity from termination zones to originating zones by a linear program instructed to minimize the total number of empty car miles incurred. The assignment was done by Control Data Corporation, which used the standard linear programming package, OPHELIE. The linear programming problem here is of the standard transportation type for which the solution procedures are well-known, and the only question was whether solving a problem of this size was practical. It was possible (at a computation cost somewhat in excess of $1,000).

After the empty capacity was assigned to traffic originating zones, the matrix of assignments was put into the network model and assigned to the shortest routes from the originating zones to the terminating zones. The flows over each link were then aggregated to give the total flow of empty capacity over that link. These parts of the computations were done by IBM and plotted by a CalComp plotter. The results showed routes over which there is a flow of empty cars that might be used to provide low-cost transportation.

THE MODEL

The study shows clearly that the dominant flow of empty cars is westbound, apparently reflecting the flow of raw materials into the industrial East. Superimposed on this is a flow toward the coalfields and away from the ports.

The Northwest

Perhaps the most important single result is the large capacity of empty cars flowing west from Chicago. The model assigns the largest single volume to the old Great Northern route from Chicago through Minneapolis to the state of Washington. Daily capacity is 23,000 tons (21 000 Mg) (1970 train average was 1,820 tons or 1650 Mg) leaving Chicago, 30,000 tons (27 000 Mg) out of Minneapolis, and 21,000 tons (19 000 Mg) across northern Montana. This represents the return of empty grain and lumber cars to the Great Plains and the Pacific Northwest.

Another flow of empty cars moves west from Chicago (38,000 tons or 34 000 Mg daily) and diminishes as it moves west, finally disappearing in Wyoming. A major branch (13,000 tons or 12 000 Mg) goes into Iowa. The flows on the other lines in the Great Plains are generally westward although in smaller volumes. There is a substantial amount of empty capacity on the Union Pacific (21,000 tons or 19 000 Mg) between Denver and Ogden. West of Ogden this capacity diminishes to 3,000 tons (2700 Mg) daily. West of Reno the flow of cars is eastbound (1,000 tons or 900 Mg daily), reflecting the return of cars used for exports out of San Francisco. On the Union Pacific from Ogden to Los Angeles, the flow becomes evenly balanced in southern Utah. In the Pacific Northwest the flow becomes eastbound near the ports of Portland and Seattle.

The policy implications of this generally westbound flow of empties are several. One is that there is a strong case for rates that are lower westbound than eastbound in this area. In particular, the cost of sending exports from the Midwest and Great Plains out through Seattle and Portland (and to a lesser degree San Francisco and Los Angeles) is much lower than the distances involved imply. Such exports can move most of the way in cars that would otherwise be returning empty. In contrast, exports through the nearer East Coast ports require not only using a car that would not otherwise be moving but also returning the empty car. On import traffic the opposite is true: The expense of importing to the West Coast is very high.

If directional rates are considered improper, the commodity rates should reflect whether the commodity can normally be handled as a backhaul or whether it is in the normal direction of commodity movement and as a result will require an equal empty car movement. For example, the movement of lumber out of the Pacific Northwest is in the direction of normal movement and as a result is relatively expensive. The rates should reflect this.

The West Coast

Along the West Coast the normal flow of empties is into the timber regions of Oregon from as far south as San Diego and as far north as Seattle.

The Southwest

In the Southwest the empty flow is westward from Houston to Los Angeles. However, the flows are relatively closely balanced, and the empty westbound capacity is small in comparison to the total flows involved. On the main track of the Santa Fe, the flow of empty capacity is only 1,769 tons (1604 Mg) daily west of Albuquerque and 0 leaving Arizona. On the Southern Pacific main line the flow drops to only 1,024 tons (928 Mg) daily in southern Arizona. The model shows no flow of empties for the Union Pacific into southern California. The flow of consumer goods into the population centers of California almost fills the empties left from the shipments or agricultural products out of California. It is likely that, with seasonal fluctuations, there is frequently no idle capacity on the southern transcontinental routes. This is a contrast with the situation for the northern routes where the large flows of eastbound lumber guarantee the possibility of using a backhaul westbound.

As a result, the marginal cost of hauling export traffic westbound is lower on the northern transcontinental routes than it is on the southern routes (where sometimes an empty backhaul cannot be found). This would make Seattle and Portland especially well suited for export traffic from the eastern United States and Los Angeles better suited for the import traffic.

The South

The flow of empties in the South is dominated by the return of empties to the coalfields and by the flow of empty cars from the ports toward the interior. Because the model does not distinguish between car types, it is difficult to separate out the two movements.

One stream of empties starts at Charleston and eventually grows to 77,000 tons (70 000 Mg) daily as it approaches the east Tennessee coalfields. Some of the empties from Savannah (4,000 tons or 3600 Mg daily) take this route. Part of this flow is clearly empty boxcars out of these ports. Virtually all southern ports show a flow inland from them, as shown below:

City	Empty Capacity (tons/day)	City	Empty Capacity (tons/day)
Wilmington	3,000	Pensacola	6,500
Charlestown	13,000	Mobile	6,000
Savannah	22,000	New Orleans	13,000
Jacksonville	17,000	Houston	34,000
Tampa	19,000		

In the case of Tampa, many of the empties are cars returning to the phosphate producing regions. In most cases, empties are moved only a relatively short distance before they are needed for loading somewhere in the interior South. One long-distance flow goes from New Orleans to Saint Louis, and another goes from New Orleans into southern Kansas although after it passes Texarkana empty capacity is less than 2,000 tons (1800 Mg) daily.

Contrary to expectations, this model shows no flow of empties from the North into the South (other than into the coalfields). The South (south of the Virginia-Kentucky line) meets its own needs for empties. Cars do, however, move from Texas and Louisiana to the Great Plains and the Pacific Northwest.

The one long-distance movement out of the South starts at Houston at 13,000 tons (12 000 Mg) daily and grows to 24,000 tons (22 000 Mg) daily northwest of Fort Worth. The movement lessens to 6,000 tons (3600 Mg) as it flows northwest through Colorado and eventually reaches the timber-producing regions of Oregon. In this case, optimal flow differs somewhat from what actually occurs inasmuch as the flow of loaded cars is not large along this route.

As shown above virtually all ports have a net flow of empties away from them. This is true of northern and Great Lakes ports also, although it is difficult to separate the flow of empty coal cars from that of box cars. As a result the cost of handling import traffic is substantially reduced because much of it can be handled as an empty backhaul. Likewise, export traffic will usually leave an empty car at a port that already has a surplus of empties. Thus, it will involve a return of the empties.

As a result export rates should generally be higher than domestic rates, and import rates should be lower. The actual pattern tends to be the reverse in which many export rates are below domestic rates and there are few special import rates. Part of the reason for this has been public pressure to improve the balance of payments by encouraging exports and discouraging imports. The reduced rates on exports are also due to the greater elasticity of demand for exports than for domestic sales. The American consumer frequently has little alternative to consuming American products, and sales will decline little if transportation costs are increased. However, foreign consumers have alternative sources of supply and, if the U.S. price is too high, will shift their purchases. Thus, American producers have frequently been able to convince the railroads that low rates are required if the traffic is to move. Although the same argument might seem to apply to import traffic, domestic producers have been able to argue that the railroads would receive less revenue from imports than they do from the domestic production that would be displaced. Thus special import rates have been relatively rare.

The Northeast

The optimal flow of empties in the East is heavily dominated by the return of empty coal cars to the coalfields. The largest single flow found on any link in the network was a capacity of almost 200,000 tons (180 000 Mg) going through western Virginia into the coalfields of West Virginia. This flow is fed from two sources. The return of empties from Hampton Roads accounts for 127,000 tons (114 000 Mg) per day. The remainder is a flow that starts at New York City and gradually grows as it moves South until it is 55,000 tons (50 000 Mg) per day passing out of Washington, D.C. This southbound flow probably includes a flow of nonhopper cars to the South, although the model sends all such cars to West Virginia. In actuality the coal trade is handled through inland lines and does not pass through Washington.

A second flow starts at Springfield and proceeds west to the Hudson and then south to Allentown where, at 15,000 tons (13 600 Mg) daily, it joins a much larger flow of 41,000 tons (37 000 Mg) daily out of New York. From there it proceeds southwest through Hagerstown into the coalfields of northern West Virginia; by then it has grown to 85,000 tons (77 000 Mg) per day.

Smaller flows go to Pennsylvania from Boston through Albany and Binghamton (peak of 34,000 tons or 31 000 Mg daily at Binghamton), from Rochester at 17,000 tons (15 000 Mg) daily, and from Buffalo at 11,000 tons (10 000 Mg) daily. Two major flows leave Toledo, Ohio. One starting at 40,000 tons (36 000 Mg) per day goes south toward Columbus, where it is joined by a flow out of Youngstown and Akron at 15,000 tons (13 600 Mg) daily and on into the coalfields of eastern Kentucky at which point it has grown to 86,000 tons (78 000 Mg) daily. The other flow out of Toledo at 40,000 tons (36 000 Mg) daily goes southwest into Indiana where at Muncie it is joined by a smaller flow from Detroit at 16,000 tons (14 500 Mg) daily. In southern Indiana the combined flow reaches 64,000 tons (58 000 Mg) daily before disappearing into western Kentucky.

There are a couple of smaller flows that do not appear to be due primarily to coal movements. There is a flow of empties of 17,000 tons (15 000 Mg) daily out of Chicago to the agricultural area south of it. Another flow of 11,000 tons (10 000 Mg) per day comes out of central Michigan and disappears into the agricultural areas of Indiana and Illinois. There are small flows of empties from Chicago, Detroit, Muskegon, Syracuse, and Albany back to the lumbering areas north of them.

Otherwise, the movement of nonhopper empties is completely concealed by the return of coal cars. Although there is certainly a movement of other cars from east to west, this is not shown by the map. Because all cars are considered identical, the model takes empty cars from cities such as New York, Boston, and Cleveland and uses them to meet the great demand for cars to carry coal from the coalfields. Any coal cars that arrive at Chicago are sent west to handle grain and lumber. It is suspected that some of the southwest flows of empties, notably those from Detroit, may not exist in practice and that the optimal pattern would be to send coal cars south to the coalfields and most other cars west.

POLICY IMPLICATIONS OF THE AVAILABILITY OF EMPTY HOPPERS

The actual amounts of available capacity in the direction of the coalfields are somewhat less than the model indicates because the flow of coal is out of the mountains toward cities at lower elevations. The empty cars usually must be hauled back against the grade. Thus, the amount they can carry without exceeding the hauling power of the locomotives is less than the amount of coal that was taken out of the coalfields. Fortunately, many of the coal-carrying lines appear to have sufficient backhaul capacity so that this constraint is not binding.

Because the flow of empties in the East is dominated by the return of coal cars, the largest economies of using backhauls will come from shipments of bulk commodities that can be moved in open hopper or gondola cars. These are principally raw ores, stone, gravels, and the like.

Perhaps the most important possibility is for movement of iron ore. Because coal and iron ore have nondirectional rates (and iron ore rates are higher than coal rates because of the threat of substituting other fuels for coal), the steel industry has tended to locate at points where iron ore could be unloaded from the boats—along the Great Lakes or the Atlantic Ocean. The desirability of a short haul for the iron ore led to much of the remaining capacity being near the Great Lakes (Pittsburgh and Youngstown). However, if iron ore is transported as a backhaul, the optimal location for much of the capacity is on or near the coalfields. The large volume of coal being shipped out for electric power generation guarantees the availability of backhauls for carrying the iron ore.

A steel firm located near Huntington, West Virginia, could use some of the large backhaul capacity from the Great Lakes ports, such as Toledo. The coal haul would be shortened by about 280 miles (450 km). The costs could be reduced further if a steel firm located in the West Virginia or Kentucky coalfields. However, to do this might lead to problems in finding a suitable plant site or a labor supply. Also the choice of coking coals might be somewhat limited. The Huntington area is where the C&O line from east Kentucky and Virginia, the C&O line from West Virginia, and the Norfolk and Western line from West Virginia converge. This gives an excellent selection of coals.

The transportation costs of steel would be reduced if a firm moved southward since the Great Lakes area has a surplus of iron and steel capacity. As a result much of the finished product must be exported from the area. Many of the markets now served by the Great Lakes industry could be served more cheaply from locations along the Ohio River. In some cases it would be practical to use the river as a shipment route.

Currently, the eastern steel mills that use foreign ore are located near Baltimore and Philadelphia where iron ore can be brought in by ship and coal by rail and where markets are nearby. A cost-minimizing location would probably be closer to the coalfields, perhaps near Roanoke, Virginia (from which products could be shipped northward along the N&W line to Hagerstown or southward to Winston-Salem and Durham and near which limestone is available). The large flow of empties out of Hampton Roads would be used to bring the iron ore inland 260 miles (420 km), which would shorten the coal haul by the same amount.

It must be realized that the cars used for hauling iron ore are not the same cars that are normally used for hauling coal. Iron ore is much denser than coal, and a coal car fully loaded with iron ore would exceed its weight limits. When iron ore is carried in coal cars, it is often loaded into two piles directly over the trucks. This calls for a more complex loading procedure and increases the risk of freezing. The other alternative is to use the short stubby iron ore cars for carrying coal. Regardless of which strategy is adopted, the advantage of using a backhaul is not eliminated because a less-than-optimal car must be used.

However, it would appear that there are significant public benefits to be gained from allowing very low rates for shipments that use what would otherwise be an empty car movement. In addition to iron ore, other commodities can probably use some of this empty capacity with suitable rates.

As can be seen, one of the major implications of allowing directional rates would be increased industrialization of Appalachia.

IMPLICATIONS FOR OTHER COMMODITIES

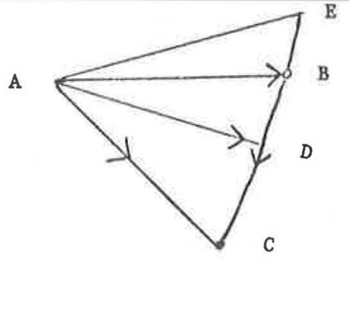
Unfortunately most commodities require cars different from those used for coal. Until the development of combination box and hopper cars, such as the ones Canada is experimenting with (such cars use a grating for the floor through which flowable materials can be emptied), the returning coal cars can be used only for certain commodities. However, the locomotive and crew capacity that was used to haul the load outbound is available for hauling a load inbound. For instance, if a shipment is made in a box car from Toledo to West Virginia, the loaded movement will be opposite in direction to the predominant flow of traffic. Going into Kentucky, the car and contents can be hauled in existing trains without additional train or crew miles. This makes the cost of the loaded line haul very low. However, when the empty boxcar is returned, it is moving in the same direction as the predominant flow of traffic. Thus the return of the car will require the running of additional trains and the hiring of additional crews. However, the weight hauled in the heavily loaded direction is only that of an empty car rather than that of a car plus load. Thus the costs for other commodities moving into the coalfields are reduced (and increased when it is outbound from the coalfields).

IMPLICATIONS FOR RATE MAKING

The discussion so far has dealt with the rather special case of shipments that parallel the predominant flow of empties. If the shipment being costed is in the direction of the flow of the empties, it is possible to use these empties for the movement. If the flow is in the opposite direction, the cost of returning the empty will be incurred. However, most real movements are not this simple. They may start out moving in the direction of an empty flow and then, after passing a point where a large number of empties are required, continue on against the empty flow.

Also shipments may move in a direction that is not the same as that of empty cars. Perhaps the simplest case is that shown in Figure 1. The normal movement of empties is from A and B to C. A and B are the same distance from C. If a carload is sent from A to B, the number of miles the empty car must travel to reach a point of loading is unchanged. The car will merely be sent to C from B instead of from A. This supposes that the car can be sent to C in accord with the car service rules. If the three links were owned by different railroads, it might be necessary to return the cars to A rather than C.

Figure 1. Possible movement of empties.



Assume that all three lines and the car are owned by the same railroad. Now suppose the shipment is to point D. After it is unloaded it is closer to C than it was before. In particular, the cost of moving the car the distance BD has been saved and can be used as an offset to the cost of the haul. Likewise on a shipment from A to E, the car is moved farther from where it will next be required. The added cost of hauling the car for the distance E to B represents a cost of the movement A to E.

Thus, it is possible to compute the cost of movements link by link if it is known whether they move cars closer to or farther from areas of surplus.

USE OF SHADOW PRICES

However, there is a simpler approach. In the course of the original linear programming assignments of capacity to points of need, shadow prices were derived that represent the increase in the total empty ton miles produced by additional demand for cars in each zone. For instance, the New York metropolitan region has a value of 2,661 miles (4282 km). This indicates that a 1-ton (0.9-Mg) increase in unloadings at New York would increase the number of empty ton miles by 2,661. (The timber region of central Oregon is zero.) Likewise, Chicago has a value of 2,201 miles (3541 km). This means that 2,201 empty car miles would be added if the supply of empty cars was increased by one car at Chicago. The shadow price will be referred to as the car potential because it is analogous to the concept of potential in electrical engineering.

If a car is transported from New York to Chicago, the supply of cars in New York is decreased by one and that in Chicago increased by one. The car moved out of New York reduces the needed empty car miles by 2,661 and the added car at Chicago increases the empty car miles by 2,201. The net effect is a reduction of 460 miles (740 km) in hauls needed to return empties to where they are required. It should be noted that this is substantially less than the minimum railroad distance between the two points. Thus if a carload shipment between New York and Chicago would reduce the required empty car miles by 460, the cost of moving an empty car this distance is saved by having the loaded movement. To calculate the cost of the shipment from New York to Chicago requires that this saving in empty car miles be deducted.

Likewise, a shipment from Chicago to New York would increase the number of empty car miles required by the system by 460 miles (740 km). The cost of a carload from Chicago to New York should include the cost of these 460 added empty car miles. (In addition there will be the empty car miles needed to take the cars to and from central areas in each zone to the actual point of shipment.)

If in the optimal solution empty cars are actually sent from one area to another, the difference in shadow prices will be equal to the distance between the zones. If there are no flows between the zones, the difference in shadow prices may be less than the actual distance between the zones.

PATTERN OF SHADOW PRICES

The map of shadow prices falls into two zones. In the western United States shadow prices increase in all directions away from central Oregon. The rate of increase decreases, however, in the vicinity of the Mississippi River. In the East and South the variation of shadow prices is less, and between major metropolitan centers it is often small. This is especially obvious when the major ports are compared. For instance, some typical shadow prices are as follows:

Port	Shadow Price	Port	Shadow Price
New Orleans	2,504	Baltimore	2,465
Mobile	2,347	Philadelphia	2,571
Jacksonville	2,576	New York	2,661
Wilmington	2,596	Boston	2,926
Norfolk	2,503	Buffalo	2,518

Aside from Boston and Mobile, the differences between cities are small. Shipments from one of these cities to another have little effect on the total cost of getting cars where they are needed. Reasonably accurate cost computations can be made by assuming that car flows do not have pronounced directionality and that a movement from one city to another does not appreciably change empty car miles. Thus, an allowance for such miles is not needed in the costing (other than for local movements). In traditional costing terminology, the percentage empty is zero.

What is happening is that the car flows are to and from the interior (and notably to and from the coalfields) and the movements between the port cities are at right angles to these flows. Thus, as shown in Figure 1 the overall situation is little affected by shifting cars between these cities.

The loading and unloading of ships are probably the industry most sensitive to inland transportation costs. However, if the data given here are applicable for all types of cars, there is not much difference between the eastern ports in the number of empty car miles that result from using them. The situation is different on the West Coast, where there is a flow of empties parallel to the coast. For instance, the shadow price for cars at Portland is 233 miles (375 km), 940 miles (151 km) at Los Angeles, and 1,183.5 miles (1904.6 km) at San Diego. As a result east coast exports through Portland have the lowest cost, and routing imports through San Diego or Los Angeles has the lowest cost. The difference in costs between Portland and Los Angeles is equivalent to the cost of hauling an empty car 707 miles (1138 km).

There is an even larger difference between the two coasts in shadow prices. The minimum difference is between San Diego (1,048 miles or 1686 km) and Galveston (2,222.5 miles or 3576 km). This is still a difference of almost 1,200 miles (1900 km) of empty haul saved by exporting through San Diego and importing through Galveston. In most cases the saving in exporting through the West Coast and importing through the East Coast is even greater.

LOCOMOTIVE AND CREW USE

The work has been devoted to showing that it is possible to calculate shadow prices for cars, which can be used for costing purposes. To do this it was required that all types of cars be considered together. Thus it is possible that the shadow price pattern for the different types of cars would be substantially different from the composite pattern described here; therefore, the above conclusions should be checked by using separate models for different kinds of cars.

As discussed earlier, there is usually excess capacity in locomotive engines and crews in the direction of flow for empty cars. Even for goods carried in cars different from the empties being returned, there are economies in using the excess capacity in the engines or crews for hauling the cars. The results of this model should give reasonably good indications of where such economies are.

CONCLUSIONS

Several conclusions emerge from this work. One is that the use of linear programming for determining efficient routing of empty cars is computationally possible. It may have application for operational problems in which it is necessary to determine where cars should be sent after unloading. Such models might be especially useful if some type of national car pool is ever established.

Another conclusion is that, even with efficient car routing, there are substantial numbers of empty cars being moved over long distances in this country. It should be recalled that the model indicates minimum volumes of empty flows since the objective function used was to minimize the number of empty ton miles. In the real world, the disposition of empty cars is determined by a host of institutional factors. A railroad typically retains empty cars on its own lines, even though another railroad in the vicinity might need such cars for loading. When cars are off line, they are normally returned to the owning line by the most direct route. This need not be the most efficient procedure for the rail system as a whole. For instance, a railroad may have a steady flow of traffic from Seattle to Chicago and a steady flow of empties from Chicago to Seattle. Suppose this railroad loads one of its cars for shipment by a different railroad from Chicago to New Orleans. The empty car would normally be returned by that railroad to Chicago, from whence it would be sent to Seattle. The linear programming model would probably send the car by the direct route from New Orleans to Seattle, greatly reducing the total empty car miles. Finally, cars are of different types and are not completely interchangeable as is assumed in this model. For these reasons the actual capacity of empty car movements is greater than indicated by the model and perhaps in somewhat different locations.

Wherever there is an imbalanced movement of cars, there is an opportunity for carrying freight in the empty cars at a very low marginal cost. Conversely, when goods are carried in the predominant direction of movement, the marginal costs are high because every additional carload of freight implies the return of an additional empty car. Notice that this differs from standard ICC railroad costing, which uses a single empty return rate for each type of car regardless of the direction of the movement or the commodity carried. To induce shippers to use the excess capacity represented by empty cars probably requires that rates reflect the true marginal costs by being lower where empty backhauls can be used. Such directional rates have traditionally been opposed by the Interstate Commerce Commission as involving undue discrimination.

In most cases, giving low rates for backhauls merely permits the railroad system to capture some traffic from other modes or results in a small expansion in the capacity of shipments in certain directions. However, in certain cases more interesting effects on the location of industry may be anticipated. Unfortunately, only brief summaries of the results were presented because the full tabulation of flows is voluminous, and even when plotted the map is 5 by 7½ ft (1.5 by 12 m).

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