Models for Improving Grain Transportation in Western Canada
by James H. Bookbinder and Fusun Ulengin

ABSTRACT
Much has been written on the disadvantages of the Canadian system for grain transportation and handling. Although some high-capacity elevators exist, there are many small elevators located on little-used branch lines. It has been difficult politically to rationalize branch lines and elevators. In this paper, we assume that political difficulties can be overcome to permit conversion to a system more like that of the United States, based on "inland terminals." These would be far fewer in number than the local elevators, but capable of high-capacity throughput and located on the main railway lines. The Canadian procedure for allocating railcars, by which train runs are made up, is retained, but with inland terminals replacing local elevators.

Two linear programming models, each with two or three variations, are presented to minimize the total costs of grain transport, the holding of grain inventories, plus certain other penalty or shortage costs. These models (or variations) differ as to whether they allow interchange of grain traffic between railways; whether the railway can lease additional railcars if necessary; the presence of a penalty cost for grain still unmoved from inland terminals at the end of the planning horizon, vs. whether grain inventory "targets" are set at the inland terminals for each period.

1. Introduction
Policies concerning the transport of western Canadian grain have long been subjects of debate. The "Crows Nest Pass Agreement" of 1897, reaffirmed by an Act of Parliament in 1925, established in perpetuity the rate for export grain moved by rail. This "Crow" rate, only recently abolished, of approximately $1/2/ton-mile would cover only about 20 percent of the railway's costs in current dollars. In this regime, the two major Canadian railways (Canadian National and Canadian Pacific, or CN and CP) omitted all but essential maintenance to rolling stock and the unprofitable branch lines. However, the

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Federal Government generally denied permission to abandon these branch lines, in order that service be available to rural prairie communities.

While the 1983 Western Grain Transportation Act did allow changes in rail freight rates for moving grain, it still committed the Federal government to preserve most financial benefits to producers that the Crow always made possible. These benefits would be paid as direct transfers to the railways (Coffin 1984, Tychniewicz 1984, Report of Committee of Inquiry 1985). Controversy in the past several years has centered on this form of payment, granted a method to properly calculate losses incurred by the railways for grain transport.

The 1983 Act also created the Grain Transportation Agency, among the responsibilities of which are promotion of system efficiency. This is the focus of the present paper: improvement in total cost performance for the storage of grain at proposed inland terminals, movement from there to ports, and the storage at port elevators prior to shipment overseas.

The remainder of this paper is as follows. Section II describes the current system for the physical handling and transport of grain in Canada, and how it compares to the U.S. approach. Some pertinent references are discussed. Section III outlines the Canadian "Block Shipping System" by which grain cars have been allocated and train runs made up. This system is retained in our models. These LP models and the associated input data and parameters are presented in Section IV. The fifth section contains an example problem, its solution by each of the models, and discussion of results. Conclusions and further research are then suggested.

II. The Physical System for Grain Handling and Transportation

A paper of this type can only give a brief description of the present system for grain handling and transportation. Further details are contained in Crawford (1978) and Earl (1983) (see also the next section of this article).

Canadian grain movements generally occur as follows. Grain from each farm is first taken by truck to a small elevator nearby (10-15km.). This extensive network of primary elevators, located on rail branch lines, enables individual grain cars to be loaded. The 1,000 km. trip to export position is eventually carried out by a "solid" train, requiring considerable effort by the railway to collect all grain cars at local country elevators and move them to the main track.

The system in the United States, by way of contrast, long ago abandoned the country elevator approach for one based on large-scale "inland terminals." This system arose because of diseconomies in local elevator operation; inherent cost advantages held by truck over rail for trips of less than, say, 100 km; and the superiority of truck transport in performing a collection function. Thus, the truck mode replaced rail movements over the (short) distances from local elevators on a branch line to a point on the main track where a solid train could be assembled. On the basis of cost savings, a similar system of inland terminals has been suggested for Canada (P.S. Ross & Partners, 1971).

Nevertheless, the introduction of such a system in Canada would face a number of barriers. Maister (1979) found, at that time, the most important of these was the Crow rate itself; the tariff per tonne-mile did not distinguish between grain originating at a country elevator on a branch line, and grain that was already on the main track (at a proposed inland terminal). Indeed, to truck grain the further distance to an inland terminal, a farmer would probably have to hire a common carrier. There was little incentive to do so, nor was there any incentive to stop using the local elevator. Until the early 1970's, it would not have been possible for an elevator operator to offer a discount per bushel for grain brought to the more efficient inland terminal. Rather, the same charge per bushel had to apply at all elevators owned by the firm.

Today, however, elevator operators are permitted variable handling tariffs. Even a railway may offer incentive rates, to entice farmers to bring grain to central points. (The Western Grain Transportation Act only requires that the railway demonstrate to the Canadian Transport Commission where specific efficiencies could be gained). Many local grain elevators would thus be eliminated, but perhaps only in the longer term; Cabinet order prevents the railway from abandoning designated grain-dependent branch lines until the year 2000.

In summary, assuming the political issues can be resolved, the future Canadian system for grain handling and transport may be based less on small country elevators, and instead emphasize inland terminals of high-capacity throughput. The present paper studies some aspects of rail transportation for such an operation, in combination with current Canadian railway practice for grain car allocation (see the next section).

III. The Canadian Block Shipping System

This section briefly describes the Block Shipping System for grain car allocation which as existed in Canada since the early 1970's. Further details can be found in Piper and Clark (1983), Crawford (1978) and Earl (1983).

Now under the direction of the Grain Transportation Authority and the Transport Department of the Canadian Wheat Board, the system of Block Shipping is aimed at overall coordination of grain movements by rail. A shipping block is one of the 48 segments into which the railway network on the prairies is divided. Within each block, train runs are established to serve
various branch lines and local (country) elevators. This system of car allocation was designed to allow the local elevators, around 60 of which operate within each block, some flexibility in satisfying shipping orders. (Note that a single area may have two shipping blocks, if service is offered there by both CN and CP Rail).

Grain movements are based on a joint six-week plan for the key actors: Wheat Board, railway, elevator company. Each is to be kept informed of decisions made by the others. Six weeks is the intended lead time for the transport of grain from local elevator to the coast, to be loaded on a vessel going overseas (see Table 1). Note that the allocation of grain cars is made by the Wheat Board rather than the railway (Earl, 1983 explains how this came about). Note also that, if the railway is to make available empty cars in the number and type assigned to that date and location, there must be a sufficiently high unloading rate at the port elevators and enough storage capacity there.

One sees in Table 1 that individual rail cars are actually involved only in weeks 4 and 5. Under good conditions, these same cars can operate during weeks 4 and 5 of two other planning cycles, where week 1 of the third cycle would correspond respectively to weeks 3 and 5 of the other two. Naturally only a portion of the fleet is allocated during any two-week period. Thus, an n-week season for grain unloading and export will contain about n six-week planning cycles.

This two-week interval of rail-car commitments is retained in the block-shipping feature of our LP models. As mentioned, these models do not involve local elevators. The latter can be thought of as having been replaced in Table 1 by the proposed "inland terminals." Such terminals will of course be far less numerous than local elevators are at present. It is this smaller size of our models that will permit solution even for a realistic case.

IV. The Linear Programming Models

We turn now to the details of these LP models. Each combines the advantages of the car allocation or block shipping cycle (see Table 1) with those of high-capacity inland terminals. Inland terminals would be designed to handle a much larger throughput than local elevators. The latter are thus not considered in our models, which deal solely with inland terminals and ports.

The objective is minimization of total costs. Both Model 1 and Model 2 consider the costs of transport (from inland terminals to ports), inventory storage of grain (both at inland terminals and at port elevators), and a shortage cost for any unsatisfied demand at a port. We also include in the

<table>
<thead>
<tr>
<th>Week</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wheat Board plans that a specific vessel be loaded six weeks later at the coast.</td>
</tr>
<tr>
<td>2</td>
<td>Wheat Board allocates rail cars to each shipping block, based on the supplies of each car type and the degree of congestion.</td>
</tr>
<tr>
<td>3</td>
<td>Elevator companies designate particular local elevators, the grain from which will be loaded onto these cars.</td>
</tr>
<tr>
<td>4</td>
<td>Rail cars are sent to those elevators, loaded, and assembled into train sets.</td>
</tr>
<tr>
<td>5</td>
<td>Cars are hauled to port and unloaded at terminal elevators.</td>
</tr>
<tr>
<td>6</td>
<td>The specific vessel is loaded with the proper type of grain.</td>
</tr>
</tbody>
</table>

*In the block-shipping feature of our LP models, the local elevators are replaced by the proposed inland terminals.

The objective function of Model 1 is a high penalty cost for any stock remaining at an inland terminal at the end of the time horizon. Model 2 then extends this penalty cost concept to stock held in any period, when the inventory level at the inland terminal is above a designated target. Model 2 also allows for leasing additional rail cars as needed; we study three possible levels for the budget on leasing expenses.

Note that our objective function includes costs of both the tangible and intangible varieties. We defer until later in this paper a further discussion of this point, including interpretation of the penalty costs.

In practice, demurrage charges help prevent grain cars from being held too long at (inland) terminals or ports. These charges would be important in a short-term operational model designed to spot cars, a model which also incorporates revisions to forecasts of car demands or supplies. Such a system for the management of "rail-car inventories" has been developed by Bookbinder and Sereda (1987), based upon Distribution Requirements Planning (DRP). Since no forecast revisions have been incorporated in the present paper, our medium-term planning model does not include demurrage charges.

However, to attain more efficient car utilization, we do consider the possibility of an interchange of grain traffic between the railways. Model 1 will be solved both with and without interchange, while Model 2 will always assume such an exchange of grain traffic between rail carriers. Further details will be
given when each model is formulated. It will be seen that as the various cases are solved, the most interesting aspects are carried over to the next model variation. But let us begin by discussing the input data.

Input Data

Among the six major types of prairie grain, wheat and barley are predominant, accounting for 60 and 25 percent of production, respectively (Canadian Wheat Board 1985). Our calculations were performed for these two grain types. Since conclusions of the model are similar in each case, results presented in this paper are limited to those for wheat. We considered in our examples a planning horizon of 5 periods, during which the supply of wheat at each inland terminal is consistent with the seasonality observed for the crop year (Canadian Wheat Board 1985, Crawford 1978). To avoid solving a 52-period problem, we "contracted" the seasonal variations of a crop year to map onto the 5-week planning horizon used in our models.

At present, export grain is handled principally at four Canadian ports: Thunder Bay, Ontario; Vancouver and Prince Rupert, B.C.; and Churchill, Manitoba. (CP Rail serves only the first two of these ports, while CN service is available at all four). In order that the numerical examples we solve not be excessive in their computational requirements, however, we consider only two ports, respectively referred to as the east port (i=1) and the west port (i=2). (These are, in fact, Thunder Bay and Vancouver, respectively). In the same spirit, there are four inland terminals (1 ≤ k ≤ K = 4). Consistent with statistics on the supply of grain, there are two terminals in Saskatchewan (k=2,4). By k=1, we denote the Alberta terminal, while k=3 is the one in Manitoba. All terminals are served by CN; initially, CP is assumed to serve all but k=3.

Table 2 presents the transportation cost per tonne of wheat moved from inland terminal k to port i. These are based on data ($/tonne-km) given in the Wheat Board report. The corresponding distances were set by assuming each inland terminal is at the center of the area it serves. Transport of grain between the four inland terminals and two ports is accomplished by a rail fleet which is a mixture of box cars and hopper cars, whose weighted-average payload is 60 tonnes per car.

With the system of grain transportation presently in existence on the prairies, it can sometimes happen that a farmer will drive to the local grain elevator, discover that it is full, and be forced to take the freshly-harvested wheat back to the farm. We attempted to set various controllable parameters to "encourage" our model to leave less wheat at the inland terminals and move more wheat to the ports (for reasons further explained below). One example of such a parameter is the penalty cost in Model 1 for any grain still remaining at an inland terminal at t=5, the end of the planning horizon. After experimentation, this penalty was set at $7,000/tonne, almost 1,000 times as large as the cost ($8/tonne) for any grain carried in inventory from period (t-1) to period t, for 1 ≤ t ≤ 4.

To add a degree of difficulty to the cases studied, we set the export levels at ports, i.e. the cumulative space available on vessels during the planning horizon, to be only 25% of the total supply of wheat. Each port elevator is far larger than even an inland terminal, so there would be no problem in unloading the hopper cars. Again, consistent with the 1985 Canadian Wheat Board report, the capacities at ports 1 and 2 for storing wheat in any period are, respectively, 35 to 20 percent of total wheat production. (By "total wheat production," we mean the grand sum of all wheat supplied over the five periods by the four inland terminals). Costs for carrying grain inventory at inland terminals ($8/tonne/period) and ports ($5/tonne/period) were extrapolated from this same source. For any unsatisfied demand at a port, there is a shortage cost of $50/tonne/period.

Decision Variables, Constraints and Objective

We now present the details of each model. Table 3 lists the four sets of decision variables for Model 1. Note the first two sets pertain to movements of rail cars, while the second two concern grain inventories at inland terminals and ports.

For each type of grain considered, there will be identical constraints. Since no constraint couples different varieties such as wheat and barley, we will take for granted in our discussion that each constraint is for a given grain. These constraints may be interpreted as follows.

The first (1) relates total capacity of cars allocated to any inland terminal k, to the impact on grain inventory there. The difference between the closing
inventories of periods t and (t-1) equals the grain received from farms in period t at k minus the total shipments outbound from k in that period.

Constraints (2), (3) and (4) are very similar to the supply and demand constraints of the usual transportation model. In our case, the supplies represent rail cars in the total system [constraints (2)] and at each inland terminal (3). Constraints (3) thus relate the empty rail cars, inbound to an inland terminal, to those which leave carrying grain and those cars which remain. The demands in constraints (4) correspond to the export grain required at each port. These demands will either be satisfied exactly or, in a given period, there will be a shortage or an accumulation of stock at the port elevator. In the latter case, constraint (5) prevents the grain inventory from exceeding the storage capacity at that port.

Finally, there is the objective function: the minimization of total cost of grain transportation from inland terminals to ports, and of carrying the grain inventory at inland terminals and ports, with a high penalty cost at the end of horizon (period 5) for any grain remaining at inland terminals. As well, a unit shortage cost is applied to the un-met portion of grain demand at each port.

The reader will observe that no mention is made of real-time decision rules to "trigger" various movements of cars or farm deliveries, etc. Our optimization model is to be used in developing an annual plan. It should not be confused with a simulation model, in which particular rail cars are tracked as they are sent to specific inland terminals and loaded with grain for a certain vessel at a determined date. Such a simulation model would be used for short-term planning over a 1- or 2-month period. These points should be kept in mind in the following discussion of our optimization models.

V. Numerical Results

Model 1

The results of Model 1 for grain inventories are given in Table 4. Several points should be noted. First, in each period, there is a greater total stock of wheat at the ports for case (4b) than (4a). That is, interchange of grain traffic between railways has permitted at least 30% more grain in relative terms [13% vs. 10%] to reach the ports in every single period. As well, the cumulative total wheat moved (the sum of stock at ports plus inland terminals) is greater in every period for case (4b) than case (4a).

One goal of the inland-terminal system is of course to move to port the wheat required to meet sales. Constraint (4) is directed toward this end. However, the model logic encourages transportation of some additional grain to port position. Export grain must ultimately move there anyway, and we have suggested a compromise between a "pull" and a "push" inventory system. The extra 30% of grain moved would represent, in the applied setting, a buffer against early vessel arrivals and late farmer deliveries.

Naturally, interchange of rail cars between CN and CP permits either railway to serve any port and any inland terminal. This leads to a more cost-effective matching of inland terminal supplies with port demands, and in the process creates a greater capacity for grain transportation.

Model 2

Nevertheless, the results of Model 1 are not very satisfactory. Considerable wheat still remains at inland terminals even for case (4b). The results of Model 1 may be understood by recalling that in each period, total grain supplies at inland terminals exceed the total demands at ports. Although there is a saving in inventory carrying cost at port elevators relative to inland terminals of $8 - $5 = $3/tonne, the cost $5 to move wheat to ports (Table 2) exceeds this saving for every (k,l) pair. Consequently, for 1 ≤ t ≤ 4, the model suggests moving only the quantity of wheat required at the ports. True, at the end of the horizon, there is a high penalty cost at inland terminals, but then, the model is limited in how much can be moved by the number of rail cars available.

Thus, in Model 2, the $7,000 penalty will pertain every period at any inland terminal, and will be charged for each tonne of wheat held above that period's target. The target at each inland terminal was set equal to the maximum amount of wheat delivered there during any single period of the planning horizon. This may permit grain inventories to build up slightly if there are a few successive periods with small inbound shipments, but the high penalty cost once the target is exceeded will ensure that considerable wheat will be moved to ports in each period that the inland terminal receives a large
TABLE 4
OPTIMAL STOCK LEVELS FROM MODEL 1

Grain inventories at inland terminals and ports (penalty cost at inland terminals for the last period only). Each entry for period t is a percentage, relative to cumulative inbound wheat shipments received at inland terminals through period t.

(4a) No Interchange of Grain Traffic Between Railways

<table>
<thead>
<tr>
<th>Period</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total at Inland Terminals</td>
<td>37</td>
<td>64</td>
<td>72</td>
<td>68</td>
<td>63</td>
</tr>
<tr>
<td>Total at Ports</td>
<td>0</td>
<td>11</td>
<td>7</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Overall Sum</td>
<td>37</td>
<td>75</td>
<td>79</td>
<td>78</td>
<td>73</td>
</tr>
</tbody>
</table>

(4b) Interchange Between Rail Carriers

<table>
<thead>
<tr>
<th>Period</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total at Inland Terminals</td>
<td>0</td>
<td>67</td>
<td>67</td>
<td>69</td>
<td>59</td>
</tr>
<tr>
<td>Total at Ports</td>
<td>75</td>
<td>16</td>
<td>17</td>
<td>13</td>
<td>19</td>
</tr>
<tr>
<td>Overall Sum</td>
<td>75</td>
<td>83</td>
<td>84</td>
<td>82</td>
<td>78</td>
</tr>
</tbody>
</table>

Also, Model 2 will allow interchange of grain cars between railways, since that was the best case above. Table 5 presents the results of Model 2. Cases (5a), (5b), (5c) allow additional rail cars to be leased as required, in which the budgets for leasing are set respectively at $150 million, $300 million and $600 million.

Consider in Table 5 the total grain inventories at inland terminals plus ports. It will be noted that these sums are essentially the same in each period for cases (5a), (5b), (5c) and these in turn agree with Table (4b). However, each increment in budget for leasing allows more wheat to be moved sooner to ports, for a greater supply there in a given period. One observes in Tables 5 and 4b, for total grain stocks at ports, that 5c > 5b > 5a > 4b, where the notation has the obvious meaning.

Another aspect of Tables 4 and 5 occurs as expected. Since the total grain supply is the same in each case, the stocks available at inland terminals follow

<table>
<thead>
<tr>
<th>Period</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total at Inland Terminals</td>
<td>0</td>
<td>51</td>
<td>58</td>
<td>62</td>
<td>51</td>
</tr>
<tr>
<td>Total at Ports</td>
<td>75</td>
<td>32</td>
<td>28</td>
<td>20</td>
<td>28</td>
</tr>
<tr>
<td>Overall Sum</td>
<td>75</td>
<td>83</td>
<td>84</td>
<td>82</td>
<td>77</td>
</tr>
</tbody>
</table>

(5b) Budget of $300 million for leasing cars

<table>
<thead>
<tr>
<th>Period</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total at Inland Terminals</td>
<td>0</td>
<td>35</td>
<td>49</td>
<td>54</td>
<td>44</td>
</tr>
<tr>
<td>Total at Ports</td>
<td>75</td>
<td>48</td>
<td>36</td>
<td>28</td>
<td>34</td>
</tr>
<tr>
<td>Overall Sum</td>
<td>75</td>
<td>83</td>
<td>85</td>
<td>82</td>
<td>78</td>
</tr>
</tbody>
</table>

(5c) Budget of $600 Million for Leasing Cars

<table>
<thead>
<tr>
<th>Period</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total at Inland Terminals</td>
<td>0</td>
<td>29</td>
<td>45</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Total at Ports</td>
<td>75</td>
<td>55</td>
<td>39</td>
<td>45</td>
<td>42</td>
</tr>
<tr>
<td>Overall Sum</td>
<td>75</td>
<td>84</td>
<td>84</td>
<td>82</td>
<td>79</td>
</tr>
</tbody>
</table>

a reverse inequality: 4b > 5a > 5b > 5c. This latter sequence of inequalities is naturally reflected in the cost performance (see Table 7). Greater amounts of wheat moved earlier to ports mean lower penalty costs need be incurred at inland terminals.
Comparison of Cases

In this section, we contrast the effects on grain movements of the models or assumptions considered. The various cases are compared in terms of transport flows and on the basis of total cost.

Typical of the results on transportation patterns are those given in Table 6. The entries are the number of unit trains carrying wheat in each period from inland terminal k=4 (Saskatchewan II) to the West port (i=2). The total quantity of wheat (proportional to the extreme right column) is strictly increasing as we move down through the various scenarios. Moreover, in proceeding from a given row to the one below, there is either more wheat carried in the same period (e.g. period 3, row 2 to row 3), or an equal or greater amount is carried in an earlier period (cf. period 3, row 3 with period 2, row 4; or period 5, row 3 vs period 4, row 4).

One would normally prefer smooth flows of grain from inland terminals to ports. In Table 6, however, each case has at least two periods in which zero unit-trains of wheat are dispatched to the West Port. The explanation is that in some of those periods, wheat is moving from Saskatchewan II to the East Port. In others, there is in addition a flow of barley to either port.

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**TABLE 6**

**THE TRANSPORT FLOWS**

<table>
<thead>
<tr>
<th>Case</th>
<th>Period</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>4b</td>
<td>53</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>53</td>
</tr>
<tr>
<td>5a</td>
<td>53</td>
<td>0</td>
<td>133</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>186</td>
</tr>
<tr>
<td>5b</td>
<td>53</td>
<td>0</td>
<td>267</td>
<td>0</td>
<td>92</td>
<td>0</td>
<td>412</td>
</tr>
<tr>
<td>5c</td>
<td>53</td>
<td>287</td>
<td>0</td>
<td>179</td>
<td>0</td>
<td>0</td>
<td>499</td>
</tr>
</tbody>
</table>

In fairness, it should also be mentioned that not all unit trains in Table 6 had the same number of grain cars. Rather, in that table and throughout our calculations, this number typically came out between 120 and 130 cars per unit train. (Such a variation also occurs in practice. The availability of hopper cars is usually above or below the number required, and the supply of wheat to be moved may not be precisely as forecast). Nevertheless, results of Table, and similar calculations for other (k,i) combinations, show that transport flows obtained by our model are as desired. As one progresses from each scenario down to the next, more wheat is moved to the ports, and sooner.

Naturally, one must consider the cost implications of each scenario. Table 7 presents results for the overall system (5 periods, 4 inland terminals and 2 ports) in terms of relative cost. Here, a value of 100 is given to the base case (4a) for Model 1: no interchange between carriers; penalty cost at last period only; and no leasing. For scenarios which permit additional rail cars to be leased, that cost is added to those of transportation, of carrying grain inventories and of penalties. Thus, even as one doubles the leasing budget (and then doubles it again), and includes this cost with those of grain movements and storage, the objective function in each case improves considerably.

It could be argued, of course, that such results are dependent on the particular values chosen for the costs of leasing ($10,000 per railcar leased for the 5-period horizon), and on the costs of transportation (Table 2), inventory carrying and penalties or shortages. To this we answer, "guilty." Other reason-
Table values for these parameters, however, do produce similar outcomes.

Again playing the Devil's advocate, Table 7 might just be the natural effect of an ever-increasing supply of rail cars, sensibly managed. This is partially true. Nevertheless, the appropriate number of additional cars to obtain is determined by our model, consistent with the budget available for leasing those cars. Moreover, the model's decisions on the optimal uses for these cars (e.g. Table 6) correspond to outcomes desired by the participants: Wheat Board, railways, terminal operators, grain producers.

VI. Conclusions

This paper presented two linear programming models with several variations concerning the storage of grain and its transportation to ports. We began with Model 1, whose decision variables are given in Table 3. Successive cases differ slightly in their details (see Table 7). All are based on the car allocation of "Block Shipping" system (Table 1), applied not to country grain elevators on railway branch lines, but rather to a system of high throughput "inland terminals" located on the main railway lines.

Results concerning grain stocks at ports and inland terminals (Tables 4 and 5) appear encouraging: As one progresses through our sequence of models, more grain is moved to ports, and sooner. These findings on grain inventories, and those of Table 6 on the flows of unit trains, are based on the transport costs of Table 2 and on previously mentioned parameters for the carrying of grain, the "target" stock levels at inland terminals, the penalty costs for exceeding these targets and the shortage costs for any demand unsatisfied at the ports. These data, and the "seasonality" of the quantities of wheat to be moved, are consistent with available statistics (Canadian Wheat Board 1985).

Rationale for Inventory Targets and Penalties

It is important to explain our reason for a penalty cost on grain inventories exceeding the target at inland terminals. The argument is the same here as one would use in deciding that some safety stocks of finished goods should be located nearer the ultimate consumer in a multi-echelon distribution system. As pointed out by Earl (1983), the dates of vessel arrivals often are not well forecast, and their requirements for grain may be underestimated. Naturally, there is also greater storage capacity at the ports. The rationale for a penalty is thus increased flexibility. These penalties are quite realistic, provided targets are not set too low and that neither port receives too high a percentage of total system safety stock. The ports, after all, are the ultimate destinations.

In an actual implementation of our model, one could thus protect against contingencies by moving more safety stock forward. However, in the present paper, we have not treated the case of uncertainties in supplies or demands of grain and/or rail cars. A good forecasting method will be unbiased on average over a 52-week horizon, hence the forecast errors should cancel. Revisions to forecasts were thus not carried out in conjunction with our model for planning over a static medium-term horizon. Revisions in response to randomness would be important in a dynamic model covering a shorter time horizon (Bookbinder and Sereda, 1987).

Our objective function has minimized costs and hence has avoided the problem of "cross-haul." This concerns movement of Manitoba grain to Vancouver while simultaneously transporting Alberta grain to Thunder Bay. In practice, a user of the model must also guard against always shipping grain from inland terminals nearest the ports, and leaving Saskatchewan terminals too full until forced by restricted grain supply to draw from them. Such a difficulty can be lessened by careful choice of lower target stock levels at Saskatchewan I and II. This indicates one of the benefits derived from our model's use of penalty costs.

However, inclusion of these penalty costs in the objective function raises another issue. The objective function also accounts for the "real" costs of the system, which are obviously transportation (costs of shipping and leasing cars) and handling (costs of carrying grain inventories). Thus, although they are related, our objective function value cannot be expected to equal the system costs on an income statement prepared for financial accounting purposes. (As well, an LP does not include any allocation of fixed costs or amortizations, etc.) The penalty costs are a device to aid management decision making.

We are not suggesting in Table 7 that "real costs" have been lowered by such a great percentage simply by incorporating penalties in the model. Transportation and handling costs have decreased, but the penalties have also encouraged the model to behave as desired. If a user of the model wishes that less grain be shipped sooner to port, this can be accomplished by a fine-tuning of model parameters such as these penalty costs.

The results of Table 7 indicate that the increased grain movements and the decreased stock at inland terminals would thus also be accompanied by improved cost performance in the sense of our objective function. Even so, the farmers and Provincial Wheat Pools have a stake in the continued operation of local elevators. Their replacement by a system of larger inland terminals which are fewer in number, hence a greater distance from most farms, would require resolution of several political issues (Maister 1979, Report of Committee of Inquiry 1985).
Actual Problem Size

The above issues are non-trivial. Assuming they can be circumvented, however, we feel the numerical results show our models have promise, and can assist in planning the operations of the proposed system of inland terminals. Our numerical examples considered a small problem: 5 periods, 4 inland terminals, 2 ports. If this approach is to be used in the real setting, it is appropriate to ask about the size of the actual problem.

There are 52 periods in a crop year (although grain deliveries to inland terminals would be made over clearly a much smaller number of weeks); possibly 48 inland terminals (one for each of the present shipping blocks); and 4 ports. The final case of our model, i.e. containing target stock levels in each period plus the leasing of rail cars, can be shown to have approximately 13,000 constraints and 23,000 decision variables. (This is for a single variety of grain, but as mentioned earlier, there are no constraints which couple various grain types). Our preliminary analysis of the model has not yielded a simple decomposition which would reduce the problem size, although some groups of constraints have a staircase structure and others are of the generalized-upper-bound type.

The actual problem is thus not of "classroom" scope. It is nevertheless straightforward, relative to the size of LP's routinely solved in industrial applications (e.g. by an oil company) using commercially available mathematical programming software and data base management systems. Naturally, at the time the proposed system of inland terminals is adopted, the input parameters of this model can be more carefully estimated.

It should be noted that even though the transport flows of Table 6 are presented as numbers of unit trains, our computer formulation was in terms of individual rail cars. As indicated, we solved in each case an LP rather than a problem in integer programming (IP). Because of the large numbers of rail cars involved in Table 6 (and other results not presented here), it was easy to show that a rounding of the LP solution would differ little, if any, from the IP optimum.

However, this same large number of cars presents a potential complication. In the actual setting with 13,000 constraints and 23,000 variables, could the number of unit trains be so large as to exceed the capacity of a single track? Yes indeed (Piper and Clark 1983), for certain periods in the crop year. In practice, this would be handled not by incorporating extra constraints in the model, but rather via an interactive "post processor." This would permit modification of the demand constraints at the ports, perhaps shifting some requirements in time, until achieving feasibility with respect to track capacity.

Further Research

Our calculations were performed for both wheat and barley (although results presented in this paper were only for wheat), within a modeling framework limited to the so-called "Board" grains (Crawford, 1978; Earl, 1983). These include wheat, oats and barley, for export and for domestic human consumption. "Non-Board" grains are those not marketed by the Canadian Wheat Board. Rather, individual private-sector firms are concerned with the marketing of rye, flax and rapeseed (for any end use), plus wheat, oats and barley for domestic feed. Real difficulties in logistics management arise in allocating, between Board and Non-Board grains, the limited physical resources of a common network for storage, transport and materials handling. Recognizing the different grades of a particular grain type further complicates the logistics system. Study of these conflicts and development of a model to help resolve them, would be an interesting area for future research.

We note as well that the present article does not at all address the question of "equity": drawing grain in as regular a manner from each farm location (and each inland terminal). As mentioned earlier, this would require introduction of real-time decision rules in the framework of a simulation rather than an optimization model. The importance of equity merits additional research.

Indeed, we have treated only the car allocation/block shipping system. We did not incorporate "delivery quotas" for the farm inland terminal interface, nor did we discuss the "car-pooling" system which governs grain-car movements around the ports of Thunder Bay and Vancouver. Further research might extend the present model to include each of these aspects. Such an enhanced model would be used to modify the longer-term plan as shorter-term operating results become known.
1. The term "solid" train is sometimes used rather than the term "unit" train. The latter refers to trains which remain intact throughout the round trip, as in unit coal trains. At present, the grain cars must be assembled to form a "solid" train of grain. However, with only a few large inland terminals, something closer to a true unit train operation can be achieved.

2. Other pertinent references concerning Canadian grain transportation include Ash and Yagar (1977) who considered how grain movements might be improved in the context of the system of local elevators as it then existed in Western Canada. Tychniewicz (1973) discussed possible improvements in Canadian grain movements, but based less on a mathematical model than was the treatment of Chow et al. (1985) for the US midwest. Recent issues relevant to rail transport in Canada are discussed in Meyer and Maister (1980) for Canadian Pacific Railway, and in Piper and Clark (1983) for rail freight in general.

Also, even though the "Crow" has been so pervasive in Canada, it should not be forgotten that in the United States and other countries, the rates for grain transport are determined by competitive forces. There are studies concerned with demands for alternative grains moved by the same mode (Fitzsimmons 1981, Hauser et al 1985), as well as transport of the same grain by alternative modes (Hauser 1986).

3. One important simplification concerns the degree of homogeneity of grains. The models can distinguish between major grain types (wheat, barley, etc.). In practice there are many grades of each grain type which must be distinguished, and this complicates the prairie assembly and port storage problems.

REFERENCES


13. Piper, C.J. and D. Clark (1983), "Railway Freight Transportation in Canada," Industry Note 9-83-D008, School of Business, University of Western Ontario (London, Ont.).


