Optimization Modeling in the Transportation Industry: The Case of Tanner Valley Transit

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Abstract. Ken Wilson, operations analyst at Tanner Valley Transit Company, wants to determine the best number, location and size of transit centers (bus garages) to serve the company’s route network. He must consider the deadhead cost associated with bringing buses into and out of service, the construction cost of building new transit centers, and the revenue obtained should an existing facility be salvaged. Further, the allocations at all open bus garages need to fall within pre-determined capacity limits. Ken must decide how to model these sets of decisions. As described by transit company officials, the current bus garage and route structure is plagued by overcrowded facilities and inefficient deadheading. This case encourages students to explore the development of a non-trivial optimization model and analyze various “what-if” scenarios.

Keywords: optimization modeling, sensitivity analysis, mass transit systems.

1. Introduction

It had been 45 minutes since the meeting concluded, but Ken Wilson was still jotting down his ideas regarding this newest project. Wilson, a young operations analyst, had been hired eight months previous to systematically analyze various features of the Tanner Valley Transit Company (TVTC). With some success, he had examined such issues as transit routes, fare setting and driver scheduling. However, this latest project appeared to be especially intriguing.

With a sigh of relief, Ken put down his pen and tried to let it all sink in. During this latest meeting, he had met with Paul Green, Vice-President of Capital Projects, and Mary Andrews, Scheduling Supervisor. They indicated that TVTC was at a critical point in its development. One of its transit centers, located in a prime commercial area, was severely overcrowded. Another was at its capacity. Both Paul and Mary wondered if other locations ought to be

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1. Transit centers are particularly large structures that serve as depots or garages where buses are parked overnight or various maintenance activities performed. Besides parking spots for buses, they house offices, conference rooms and lounges for transit staff.
considered as potential transit centers. Mary, in particular, worried about how the current public transit infrastructure could handle future population shifts.

2. Tanner Valley Transit Company Structure

The Tanner Valley Transit Company, owned by the Tanner Valley Economic Authority (TVEA), was responsible for providing efficient, reliable transit service to the 750,000 residents of the Tanner Valley metropolitan area. Without an efficient public transit service, road congestion and pollution would become an increasing problem. With this in mind, Ken knew that successful implementation of this current project could provide substantial benefits to all Tanner Valley residents.

He again glanced at his notes. The transit company currently operated three transit centers. Based on some information gathered by Mary, he observed the total allocation and capacity of each respective garage as reported in Table 1.

Table 1: Current Transit Centers

<table>
<thead>
<tr>
<th>Transit Center</th>
<th>Current Allocation</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>9th Street</td>
<td>121</td>
<td>100</td>
</tr>
<tr>
<td>Lakeridge</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Cotter’s Creek</td>
<td>29</td>
<td>60</td>
</tr>
</tbody>
</table>

The 9th Street location proved a particularly troublesome issue for transit personnel. Besides being severely overcrowded (drivers were forced to park buses with minimal spaces between them), this transit garage was located within a high-priced commercial real estate area. The Lakeridge garage was at its current capacity, while the Cotter’s Creek facility seemed to be underutilized.

Ken then decided to look at the individual routes operated by the transit company. Currently, TVTC operated 12 bus routes. Service was provided on weekdays only, roughly 260 service days annually. (Due to the smaller passenger demands on weekends and holidays, the Tanner Valley Economic Authority had decided to sub-contract this portion of transit service to a private company. This organization provided service with a fleet of smaller vans).

The routes, due to specific passenger demand and route length, did not all require the same number of buses per day. Ken was able to obtain the information provided in Table 2. The first seven routes were considered “urban” routes (they operated solely within Tanner Valley proper), while the remaining five routes were “suburban” (service extended into Tanner Valley’s metropolitan areas).
In order to understand the particular nature of transit operations, Ken reviewed some of the material he had received from Mary’s scheduling group. Undoubtedly the largest cost associated with transit center location involved the cost of “deadheading” buses to and from their assigned routes. Buses do not begin revenue service from the moment of departure from their transit center. Likewise, buses do not undertake revenue service to the garage at the end of the service period. A certain amount of time is required to travel “not-in-service” between the garage and route (“initiation of service”) and the route and garage (“termination of service”). This time is referred to as deadhead time. Since such travel earned no revenue but still consumed resources (driver wages, fuel costs, etc.), it was the desire of transit planners to reduce this deadhead cost as much as possible.

Obviously, deadhead costs could be reduced by simply building several bus garages and locating them relatively close to specific routes. However, the construction of these facilities incurred substantial expense. Deadhead and construction costs epitomized the tradeoffs that transit planners were required to make.

Paul’s Capital Projects group had determined three potential locations for future transit centers. These locations offered sufficient land area for bus garage construction, and also permitted suitable roadway access. The respective locations were in the subdivisions of Bridgepoint, Montgomery and Clearwater.

Mary’s staff provided the data depicted in Table 3. This matrix shows the number of hours required to deadhead one bus of a specific route from a given

<table>
<thead>
<tr>
<th>Route Number</th>
<th>Route Name</th>
<th>Garage</th>
<th>Number of Buses Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4th Avenue</td>
<td>9th Street</td>
<td>11</td>
</tr>
<tr>
<td>2</td>
<td>South Industrial</td>
<td>Cotter’s Creek</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Westview</td>
<td>9th Street</td>
<td>14</td>
</tr>
<tr>
<td>4</td>
<td>Baker Street</td>
<td>9th Street</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>North Heights</td>
<td>Lakeridge</td>
<td>25</td>
</tr>
<tr>
<td>6</td>
<td>Bailey Place</td>
<td>9th Street</td>
<td>30</td>
</tr>
<tr>
<td>7</td>
<td>Hillcrest</td>
<td>Lakeridge</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>Millwood</td>
<td>Cotter’s Creek</td>
<td>5</td>
</tr>
<tr>
<td>9</td>
<td>Richfield</td>
<td>9th Street</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>Brocktown</td>
<td>9th Street</td>
<td>22</td>
</tr>
<tr>
<td>11</td>
<td>Cedar Junction</td>
<td>9th Street</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>White River</td>
<td>Cotter’s Creek</td>
<td>16</td>
</tr>
</tbody>
</table>
transit center per day. Much of this data, particularly for the combination of routes and existing transit centers was already available. Consequently, the bulk of the work required by Mary’s group focused on accurately estimating the deadhead times associated with the new bus garages.

Both Mary and Paul indicated that the data in Table 3 provided accurate deadhead times. Current transit policy was to cost the deadhead time at a rate of $70 per hour. This amount was felt to be sufficient to cover the principal components of deadhead cost; namely, driver salary and vehicle operating expenses.

**Table 3: Deadhead Times (Hours)**

<table>
<thead>
<tr>
<th>Garage</th>
<th>Route</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>9th Street</td>
<td></td>
<td>0.25</td>
<td>0.75</td>
<td>0.50</td>
<td>0.50</td>
<td>0.65</td>
<td>0.80</td>
<td>1.25</td>
<td>0.80</td>
<td>0.60</td>
<td>0.50</td>
<td>0.60</td>
<td>1.50</td>
</tr>
<tr>
<td>Lakeridge</td>
<td></td>
<td>2.00</td>
<td>1.25</td>
<td>1.00</td>
<td>0.60</td>
<td>0.15</td>
<td>1.50</td>
<td>0.20</td>
<td>0.30</td>
<td>1.25</td>
<td>0.55</td>
<td>0.70</td>
<td>0.80</td>
</tr>
<tr>
<td>Cotter’s Creek</td>
<td></td>
<td>1.25</td>
<td>0.60</td>
<td>1.25</td>
<td>1.00</td>
<td>2.00</td>
<td>0.90</td>
<td>1.00</td>
<td>0.75</td>
<td>0.60</td>
<td>2.50</td>
<td>0.90</td>
<td>0.50</td>
</tr>
<tr>
<td>Bridgepoint</td>
<td></td>
<td>0.50</td>
<td>1.00</td>
<td>0.75</td>
<td>0.50</td>
<td>0.30</td>
<td>1.25</td>
<td>0.60</td>
<td>1.25</td>
<td>2.00</td>
<td>0.15</td>
<td>1.00</td>
<td>1.25</td>
</tr>
<tr>
<td>Montgomery</td>
<td></td>
<td>0.60</td>
<td>0.20</td>
<td>1.00</td>
<td>0.75</td>
<td>0.75</td>
<td>0.60</td>
<td>0.30</td>
<td>0.75</td>
<td>0.90</td>
<td>2.00</td>
<td>0.10</td>
<td>0.40</td>
</tr>
<tr>
<td>Clearwater</td>
<td></td>
<td>2.25</td>
<td>1.25</td>
<td>1.75</td>
<td>1.25</td>
<td>1.00</td>
<td>0.75</td>
<td>0.45</td>
<td>0.50</td>
<td>0.40</td>
<td>2.25</td>
<td>0.40</td>
<td>0.10</td>
</tr>
</tbody>
</table>

The three sites selected for potential transit center locations varied in terms of their construction costs. In particular, land values at the different sites meant that some sites would be more affordable than others. Paul’s Capital Projects staff felt that these construction costs could be denoted as a (linear) “per bus” cost over a specific range of transit center size—specifically, between 25 and 100 buses. These minimum and maximum values corresponded to the generally acceptable sizes of bus garages. Transit officials felt that it would be extremely inefficient to build a bus garage with a size less than 25 buses (this minimum size also applied to existing transit centers). Moreover, an allocation of 100 buses was considered to be the highest capacity one would ever devote to such a facility. This linearization of construction costs removed the necessity of incorporating fixed costs into the construction cost expressions.

Based on different land values, the following (“per bus”) capital costs of transit center construction were:

- Bridgepoint: $60,000
- Montgomery: $55,000
- Clearwater: $47,500
During the recent meeting, Ken had learned that these construction costs would not be paid “up-front”. Rather, TVEA would “annualize” the construction costs over a 25-year period, at an annual interest rate of 7%. This, as explained by Paul, was similar to a consumer taking out a mortgage on a piece of personal property. The entire cost was not paid at the outset of the agreement; instead, the consumer would make periodic payments throughout the life of the mortgage. Based on the given term and interest rate, the Bridgepoint location, for example, featured an annualized per bus capital cost of $5,149.

The closure of existing transit centers and concomitant sale of the land (thereby earning some revenue) were indeed vital issues. The 9th Street location, in particular, appeared to offer some benefits in terms of its relatively large size and high-priced land value. Paul and Mary informed Ken that this site occupied 4.0 acres with a land value of $13 per square foot. The Lakeridge site consisted of 2.0 acres priced at $5 per square foot, while the Cotters’ Creek transit center sat on 2.4 acres of land valued at $6 per square foot.

As with the construction costs of new bus garages, Ken learned that TVEA would annualize the salvage revenue obtained from the sale of any existing transit center facility. The term and interest rate would be the same as those used for the construction calculations.

4. Additional Modeling Scenarios

It was during this most recent meeting that Paul and Mary had suggested other scenarios that they would like Ken to consider. Paul wondered what would be the effect if one forced the closure of the 9th Street facility. Mary, concerned about the impact of future development, suggested that the number of allocated buses on suburban routes could soon double. This doubling of demand could alter the attractiveness of certain facilities. Both Paul and Mary knew that certain parts of their transit system were inefficient. They indicated that it would be interesting to know the best decisions if one had a “clean slate” before them. In other words, suppose that one could place the routes in any of the six possible transit centers. Suppose further that this decision was made solely on deadhead costs alone—that is, construction costs and salvage revenues were ignored. If one only limited the problem by garage capacity restrictions (minimum and maximum of 25 and 100 buses, respectively, at each facility), what would be the resulting effects?

Ken looked up from his notes. Rubbing his eyes, he glanced at the transit network map shown above his office desk. This was by no means a trivial project. Paul wanted a completed report in eight days. He knew he had better get to work.
Teaching Note

“Optimization Modeling in the Transportation Industry: The Case of Tanner Valley Transit”

The purpose of this teaching note is to explore the general objectives, classroom format and analysis of the Tanner Valley Transit case.

1. Identification of the audience and appropriate courses, list of the topics covered, and specific teaching objectives:

This case was developed primarily for use by second or third year undergraduate students in an introductory course in Operations Management, Business Analytics, Operations Research or Management Science. The case’s fundamental issue concerns the development of an optimization model to determine the best number, size and location of bus garages to serve the route network of the Tanner Valley Transit Company (TVTC). Ken Wilson, an operations analyst at TVTC, is the case’s main character. Other players include Paul Green, Vice-President of Capital Projects, and Mary Andrews, Scheduling Supervisor.

Although the case does not explicitly tell students to formulate and solve an optimization model, it is expected that they will eventually come to this conclusion. Some students may resort to trial-and-error approaches before realizing that an optimization model will allow them to efficiently investigate the issues posed in the assignment questions.

Through model development and subsequent sensitivity analysis, this case permits students to expand their analytical capabilities. Although there are some similarities between this problem and the more general facility location-allocation model, there seem to be enough differences to make the TVTC case non-trivial. Students should obtain an appreciation of the value of “what-if” analysis in decision-making. Further, they should become familiar with the use of specialized software packages (for example, Microsoft Excel Solver) to solve optimization problems. Indeed, the optimal solution features considerable implications for transit company operations. Extensive in-class discussion can be generated surrounding the appropriate set of decisions to be made.
2. Identification of associated readings or material that instructors might draw on:

Instructors may find it valuable to reference the following textbooks:


Moreover, the following journal article may offer key insights:


3. Brief synopsis of the case:

Ken Wilson, operations analyst at Tanner Valley Transit Company, wants to determine the best number, location and size of transit centers (bus garages) to serve the company’s route network. He must consider the deadhead cost associated with bringing buses into and out of service, the construction cost of building new transit centers, and the revenue obtained should an existing facility be salvaged. Further, the allocations at all open bus garages need to fall with pre-determined limits.

Ken must decide how to model these sets of decisions. According to information obtained from officials at the transit company, the current bus garage and route structure is plagued by overcrowded facilities and inefficient deadheading. The company officials also stress a number of future scenarios that ought to be examined as part of the modeling effort. This case encourages students to explore the development of a non-trivial mathematical optimization model in the context of a real-world problem. Students are permitted to analyze various “what-if” scenarios. Such a modeling effort showcases the power of spreadsheet packages (such as Microsoft Excel Solver) in setting up and solving mixed integer optimization problems.

4. Assignment questions for student preparation:

1. Determine the optimal number, location and size (bus allocation) of the transit centers. What annual savings are obtained by your optimal solution?
2. What implications does the optimal plan have on TVTC? What recommendations would you make to Paul and Mary?

3. Could TVTC alleviate the problem of over-crowding within the current network of transit garages? Why or why not?

4. Determine the effects of Paul and Mary’s suggested (but separate) scenarios:
   - Doubling the number of suburban buses.
   - Closing the 9th Street bus garage.
   - The “clean-slate” approach.

   Do these additional scenarios support or modify your recommendations provided in question 3?

5. Full analysis of each question:

   1. **Determine the optimal number, location and size (bus allocation) of the transit centers. What annual savings are obtained by your optimal solution?**

   Answering this question will require the development of an optimization model. We begin with the decision variables:

   \[ X_{rs} = \text{the number of buses from route } r \text{ assigned to transit center } s \]

   \[ Y_s = 1 \text{ if new garage } s \text{ is opened} \quad 0 \text{ otherwise} \]

   \[ Z_s = 1 \text{ if current garage } s \text{ is closed} \quad 0 \text{ otherwise} \]

   This provides a total of 78 decision variables. We have 72 \( X_{rs} \) decision variables (12 routes \( \times \) 6 garages) plus 3 possible locations for new garages and 3 current transit center locations.

   There may be some questions regarding the \( X_{rs} \) decision variables. At worst, we have seen some student groups attempt to use 72 binary integer decision variables to represent the assignment of a bus to a garage. In this case, they would have \( X_{irs} = 1 \) if a particular bus \( i \) from route \( r \) was assigned to transit center \( s \); 0 otherwise. This serves to increase the number of binary integer
decision variables (although a software package such as Solver could handle the augmentation in binary decision variables). However, such a formulation provides difficulties in the eventual interpretation of computer output (the assignment of specific buses to garages is then obtained by reading a matrix of 0’s and 1’s).

Other student groups have forced $X_{rs}$ to be a general integer decision variable. In other words, the total number of buses of a particular route assigned to a specific garage must be a whole number. Although this is conceptually correct, we inform them that such an approach is not really warranted. Due to the unimodularity of the problem (the right-hand side values and coefficients of the particular constraints are all integer values), the resulting optimal solution will naturally have integer variables. Here, we admit that we make a bit of a tradeoff. The audience in our classes, although second or third year undergraduate students, is taking their introductory course in Operations Management, Business Analytics or Management Science. To a certain extent, we do a bit of “hand-waving” with the integer issue. If they force the $X_{rs}$ decision variables to have general integer values, that’s OK. The same optimal solution will be obtained with or without this integer restriction.

The objective function is given as follows:

$$\text{MIN} \sum_{r=1}^{12} \sum_{s=1}^{6} C_{rs} X_{rs} + \sum_{s=\text{new}} F_{s} N_{s} - \sum_{s=\text{existing}} R_{s} Z_{s}$$

where:

$C_{rs} =$ annual cost of deadheading one bus to route $r$ from garage $s$
(this cost is computed by taking the deadhead times in Table 3 of the case and multiplying these by the hourly deadhead cost ($70) and the number of operating days per year (260)

$F_{s} =$ annualized per bus capital cost of constructing a particular new garage, $s$

$N_{s} =$ total number of buses assigned to a particular garage, $s$

$R_{s} =$ annualized salvage revenue obtained from eliminating a particular current garage, $s$

It is important for the student groups to realize that the construction costs, $F_{s}$, are given in per bus amounts. Frequently, student groups want to multiply the construction cost expression, $F_{s} N_{s}$, by $Y_{s}$ (the binary integer decision variable for constructing a new garage). Such a formulation is essentially non-
linear (the multiplication of two decision variables, \( N_s \) and \( Y_s \)). It is more suitable to include \( Y_s \) in the set of constraints (as we shall show later).

The closure of current bus garages (and concomitant sale of land) represents revenue for TVTC; hence, this cost must be subtracted in the objective function expression.

The constraints are described as follows:

\[
\sum_{s} X_{rs} = D_r
\]

where:

\( D_r \) = total number of buses required on a particular route \( r \)

This constraint forces the total number of buses assigned from a particular route to be equal to the number of buses required on that route. Essentially, this is a “demand” constraint. This constraint would be repeated for each of the 12 routes in the problem.

Our next constraint is:

\[
\sum_{r} X_{rs} - N_s = 0
\]

This constraint is much like a “supply” constraint, repeated for each of the six garages in the case. It adds up the number of buses assigned to a particular garage. I have included the \( N_s \) notation in this constraint to allow an easier representation of the total allotment at each of the garages.

The minimum and maximum restrictions for the sizes of the new bus garages are given as follows:

\( N_s \geq 25 \ Y_s \) and \( N_s \leq 100 \ Y_s \)

If a new bus garage is built (ie. \( Y_s = 1 \)), then the total allocation at this facility cannot be less than 25, nor more than 100 buses. If we choose to not construct the new garage (ie. \( Y_s = 0 \)), then no buses can be allocated from the garage. This ensures that we can assign buses from a new transit center if and only if it is built (and, consequently, the construction costs are incurred).

The next set of constraints forces the total allocation at current bus garages to fall within their minimum and maximum limits. From our experience, this set of constraints presents the students the most difficulty.
N_s ≥ 25(1 - Z_s) and N_s ≤ cap_s(1 - Z_s)

The notation cap_s indicates the capacity at a particular current bus garage. Recall from Table 1 of the case that each current bus garage does not necessarily have the same capacity. This set of constraints forces us to obey the minimum and maximum size limits if the facility is retained. If a particular facility is closed (Z_s = 1), then the salvage revenue will be obtained and the allocation of buses from this garage will be zero.

Student groups have difficulty since they fail to see the need to incorporate (1 - Z_s) in the constraint. Many groups “copy” the formulation used with the new bus garages (i.e. they would simply multiply 25 or cap_s by Z_s). By doing so, however, this permits a closed transit center (Z_s = 1) to have an allocation of buses.

Solving such a mixed integer optimization problem (78 decision variables, 30 constraints) requires the use of an optimization software package. Given the fact that many Operations Management or Management Science textbooks now feature extensive illustrations involving Microsoft Excel, it seems worthwhile to use Solver to analyze such a problem.

The “target cell” in Solver (the cell containing the objective function value) is simply the sum of the total deadhead costs, construction costs and salvage revenue. This target cell is minimized by finding the best values for the various decision variables. In terms of Solver’s syntax, these decision variables are termed “changing cells”.

It is useful in the spreadsheet to set up a matrix containing rows for the particular garages and columns for each of the routes. In all, this will be a 6 row × 12 column matrix. The sum of each row represents the total allocation of buses at a specific transit center. This sum must be forced to be no more than the garage’s capacity, or at least 25, if the garage is retained. For any new bus garages that are constructed, their total allocation must be at least 25, but no more than 100.

The sum of each column represents the total number of buses assigned to each particular route. This sum must equal the total number of buses required per route (given in Table 2 of the case).

Table TN – 1 provides a partial illustration of a typical spreadsheet used to solve the TVTC problem. Note the columns used to represent the particular routes (in this case, we have only shown 2 routes, #11 and #12). The rows are the garages (A represents 9th Street, B is Lakeridge, C is Cotter’s Creek, D is Bridgepoint, E is Montgomery and F represents Clearwater).

The total allocation column represents the total number of buses (if any) assigned to each garage. The various minimum and maximum sizes are illustrated. The binary decision variables represent that each new garage is built and the Cotter’s Creek facility is shut down. The total construction costs and total salvage revenue columns are rather self-explanatory. We note that
this solution calls for $372,203 of annualized construction costs and $53,826 of annualized salvage revenue.

Table TN – 1: Partial Spreadsheet for TVTC Problem

<table>
<thead>
<tr>
<th>Garage</th>
<th>Route</th>
<th>Total Allocation</th>
<th>Binary Variables</th>
<th>Binary Variables</th>
<th>Total Construction Costs</th>
<th>Total Salvage Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>70</td>
<td>25</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>50</td>
<td>25</td>
<td>50</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0</td>
<td>25</td>
<td>60</td>
<td>1</td>
<td>-53826</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>25</td>
<td>25</td>
<td>100</td>
<td>1</td>
<td>128716</td>
</tr>
<tr>
<td>E</td>
<td>20</td>
<td>30</td>
<td>25</td>
<td>100</td>
<td>1</td>
<td>141587</td>
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<tr>
<td>F</td>
<td>0</td>
<td>25</td>
<td>25</td>
<td>100</td>
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<td>101900</td>
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<td>200</td>
<td></td>
<td></td>
<td>372203</td>
<td>-53826</td>
</tr>
</tbody>
</table>

The individual constraints can be denoted in the “Add Constraints” box, a dialog box that appears once we select Data | Solver in Excel.

The following table provides the optimal number, location and size of each transit center.

Table TN – 2: TVTC Optimal Solution

<table>
<thead>
<tr>
<th>Garages</th>
<th>Route</th>
<th>Buses per Route</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>11 14 12 0 30 0 3 0 0 0 70</td>
</tr>
<tr>
<td>B</td>
<td>0</td>
<td>0 0 0 22 0 23 5 0 0 0 0 50</td>
</tr>
<tr>
<td>C</td>
<td>0</td>
<td>0 0 0 0 0 0 0 0 0 0 0 0 0</td>
</tr>
<tr>
<td>D</td>
<td>0</td>
<td>0 0 0 3 0 0 0 0 22 0 0 25</td>
</tr>
<tr>
<td>E</td>
<td>0</td>
<td>8 0 0 0 0 2 0 0 0 20 0 30</td>
</tr>
<tr>
<td>F</td>
<td>0</td>
<td>0 0 0 0 0 0 0 0 9 0 0 16 25</td>
</tr>
</tbody>
</table>

Garage C (the Cotter’s Creek facility) is closed. The three new bus garages are opened, with total allocations of 25 buses each (except for Garage E (Montgomery) which receives an allocation of 30 buses). The annual costs of the optimal solution are easily tabulated in a spreadsheet model. We obtain a total deadhead cost of $1,174,810, a total construction cost of $372,203 and annualized salvage revenue of $53,826. This provides an overall yearly cost of $1,493,187.

How much do current transit center operations cost? This information was not provided in the case. However, it can be quickly computed. The lone cost
that we need to calculate is the current deadheading cost. Since we know the current allocation of buses to garages, we can simply multiply the deadhead times (as provided in Table 3 of the case) by the total route allocations (as illustrated in Table 2). Multiplying this by the deadhead cost per hour ($70) then by the number of operating days per year (260) will provide the total annual current deadheading costs. These calculations yield a total cost of $1,733,550. Thus, our optimal solution generates yearly savings of $240,363 (or 13.87% of total current costs).

2. **What implications does the optimal plan have on TVTC? What recommendations would you make to Paul and Mary?**

The optimal strategy has some rather substantial implications on TVTC’s operations. If the least-cost plan is followed, then this will lead to the construction of three new bus garages and the closure of one current transit center. Moreover, we note that the 9th Street facility remains open (although its total allocation is almost cut in half). This would appear to suggest that, despite the highly-valued land upon which the garage sits, there are some rather significant disadvantages associated with completely closing it. Perhaps the fact that closing this facility would necessitate finding “homes” for 121 buses (previously dispatched from the 9th Street garage) precludes one from opting to close the transit center.

A potential difficulty with the optimal solution concerns the issue of splitting. We note that routes 5, 7 and 9 are split between alternative bus garages. Garage B (Lakeridge) receives 22 buses from route 5, while the Garage D (Bridgepoint) transit center receives the remaining three buses. With respect to route 7, we have 23 buses from Garage B (Lakeridge) and 2 buses from Garage E (Montgomery). For route 9, a total of 9 buses are allocated from Garage F (Clearwater) and 3 are dispatched from the Garage A (9th Street) facility.

Considerable discussion is usually generated regarding this issue. Does it really present a difficulty for TVTC personnel? If one considers the lower number of buses in each split-route situation, then (in totality) only 8 buses (or 4% of its current fleet) are affected. Splitting only occurs for 3 buses (route 5), 2 buses (route 7) and 3 buses (route 9). Further, “a bus is a bus is a bus”. From the perspective of bus maintenance personnel, it really does not matter whether a certain bus in a particular garage is from route 5, 7, 9 or any other route. Passengers are wholly oblivious to the fact that a specific bus is allocated from one garage or another.

Nonetheless, splitting could affect the bus operators themselves. Take a particular driver who is scheduled to operate a bus on, say, route 5. Confusion could results among the bus operators if some buses are dispatched from one
garage while others are housed at another facility. Quite simply, the driver may have signed up for a particular route that was dispatched from a garage relatively close to his or her residence. Allocating buses from different garages could create scheduling difficulty and driver apprehension.

As a wrap-up to this part of the analysis, the students should be questioned as to the appropriate recommendations they would make to the Tanner Valley Transit Company. It should be stressed during the discussion that this organization - if it follows the strategy suggested by the optimization model - will face a number of key decisions.

The Cotter’s Creek facility ought to be shut down since it was “disposed” in the model’s optimal solution. Recall that all three candidate locations were selected for construction. Should they all be built with a “phased-in” program whereby one facility is constructed at a time? On the other hand, would it be preferable to have one big building campaign so that construction, procurement and negotiation hassles are not unnecessarily drawn out? Or, would such an approach place undue strain on transit planners and capital projects staff?

3. Could TVTC alleviate the problem of over-crowding within the current network of transit garages? Why or why not?

Yes, it is possible for the transit company to alleviate the over-crowding problem by using the current network of bus garages. This is simply obtained by determining the total number of buses in the transit system (200 buses) and comparing this to the total capacity of the three current transit centers (210 buses, as provided in Table 1 of the case). Obviously, with a total capacity in excess of the total number of buses in the system, TVTC should be able to mitigate the effects of over-crowding.

The vital question, however, is to determine the best way for this to be done. This may be quickly determined by returning to the original optimization model we developed. All we need to do is set each of the $Y_i$ binary integer decision variables (referring to the construction of a new garage) equal to zero. By so doing, Solver will search for a solution that obeys capacity restriction involving the three current transit centers. This approach provides a solution in which total costs are $1,749,930. Bus allocations are as follows: 9th Street (100 buses), Lakeridge (50) and Cotters’ Creek (50). Remarkably, the total costs of this solution are only $16,380 more than the current transit system costs! In the case, both Paul Green and Mary Andrews indicated problems inherent to severe overcrowding with at least one of their bus garages. As it turns out, over-crowding is not the major factor in determining TVTC’s overall performance. Rather, it is the inefficiencies generated by poor location-
allocation decisions! Overcrowding could be alleviated simply (and inexpensively).

4. **Determine the effects of Paul and Mary’s suggested (but separate) scenarios:**

   - Doubling the number of suburban buses.
   - Closing the 9th Street bus garage.
   - The “clean-slate” approach.

Do these additional scenarios support or modify your recommendations provided in question 3?

We shall indicate how the optimization model can be reformulated to address each of these suggested scenarios. The following table illustrates the transit center allocations in each of the scenarios.

*Table TN – 3: Allocations of Various Scenarios*

<table>
<thead>
<tr>
<th>Garage</th>
<th>Doubling of suburban buses</th>
<th>Closure of 9th Street garage</th>
<th>“Clean-slate” approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>9th Street</td>
<td>91</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>Lakeridge</td>
<td>50</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>Cotter’s Creek</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bridgepoint</td>
<td>44</td>
<td>59</td>
<td>34</td>
</tr>
<tr>
<td>Montgomery</td>
<td>58</td>
<td>63</td>
<td>58</td>
</tr>
<tr>
<td>Clearwater</td>
<td>32</td>
<td>28</td>
<td>28</td>
</tr>
</tbody>
</table>

The “doubling of suburban buses” scenario is achieved by doubling the Dr values for routes 8 – 12. This modification increases the attractiveness of the Montgomery garage (it now receives a total allocation of 58 buses). Cotter’s Creek continues to offer no signs for its retention.

The closure of the 9th Street transit center is performed by setting its Zs variable equal to 1. Such an approach generates salvage revenue, but precludes any buses from being assigned to this facility. Again, the Cotter’s Creek garage is shut down. Further, the Montgomery facility has the highest allocation of any of the three new transit centers.

The total costs of this solution are $1,632,744. Although this would generate savings of just over $100,000 annually (when compared to the current location-allocation strategy), we could save about $240,000 per year by adopting the optimal solution examined earlier (recall that the 9th Street transit
center was left open in that solution). Consequently, the retention of the 9th Street garage appears to be warranted.

Finally, the “clean-slate” approach is obtained by setting the salvage revenues and per bus construction costs equal to zero. By only permitting garages (if they are used) to have minimum and maximum allocations of 25 and 100 buses, respectively, we obtain an indication of the best location for garages if TVTC “could do it all over again”. We observe that the Montgomery garage has the largest allocation of any garage. The 9th Street transit center has its total allocation cut from 121 (current TVTC solution) to just 25. The Cotter’s Creek garage continues to receive no buses. As we remarked earlier, its continued usage is severely questioned.

6. Teaching Plan

This case works best if undergraduate students are combined to form groups of between 3-5 participants per team. From our perspective, there is too much model development and analysis in this case for a single person or two-player team. Having more than five participants in a single team tends to limit the participation of marginal members.

The analysis of the case can be comfortably presented in a single 80-minute class period. The case ought to be distributed to the student teams at least three weeks prior to its in-class presentation. Such a time frame will allow the students to probe the issues evoked in the case and to develop an optimization model.

Instructors should be able to achieve a smooth flow of discussion by sequentially investigating the assignment questions. The overall value of this teaching case would be bolstered by the instructor using a room in which the Solver model could be displayed to the entire class by means of an overhead computer projector. This permits students to efficiently follow and observe key analytical points while the instructor elicits conversation regarding various modeling features.

At a minimum, the dialogue ought to focus on the following important aspects and implications:

a. Determining the best number, location and size of facilities to serve a network can be accomplished through developing a mixed integer optimization model.

b. From the student’s perspective, the model formulation’s most challenging feature may be the constraints surrounding the minimum and maximum size limits of current bus garages. As explained earlier, these constraints used binary integer decision variables ($Z_s$) within the following expressions:
\[ N_s \geq 25(1 - Z_s) \text{ and } N_s \leq \text{cap}_s(1 - Z_s) \]

If \( Z_s = 1 \), then the garage was closed. Else, the facility remained opened.

c. The model’s optimal solution generated more than $240,000 in savings.

d. Despite its large size, current overcrowding and exorbitant land prices, the 9th Street facility offers a suitable location for a transit garage. The overall costs associated with forcing its closure exceeded those costs generated from the optimal solution.

e. Of the existing facilities, the Cotter’s Creek garage may be the most viable candidate for closure. The model’s optimal solution determined that it should be shut down.

f. Of the new facilities, the Montgomery location could offer the most benefit. It received an allocation of 30 buses in the optimal solution. Moreover, it featured the highest number of any buses in the “clean slate” model.

g. The optimal solution called for the construction of three new garages. Nonetheless, transit planners ought to be prudent regarding these projects. Should all three be built immediately, or would a phased construction program be beneficial?

h. The optimal solution called for route splitting on three of the 12 routes. Does this pose operational difficulties and driver hassles, or is its presence merely an inconsequential feature of the least-cost solution?

i. Ken Wilson’s supervisors felt that severe overcrowding presented critical problems for the transit company. Through developing the analytical model and interpreting its optimal solution, one can demonstrate that overcrowding is not a major factor in determining TVTC’s overall performance. Rather, the inefficiencies generated by poor location-allocation decisions contributed to detrimental operations. Overcrowding could be inexpensively alleviated.

7. Field Research Conducted

Although fictional, the Tanner Valley transit company case is based on the author’s personal experiences as a public transit planner with the Vancouver Regional Transit System (Canada). The case write-up is a condensed version
of the location-allocation model developed to guide transit center decision-making for the Vancouver system.

8. What Happened?

In the actual Vancouver Regional Transit System study, the agency eventually followed up on one of the author’s recommendations by constructing a new facility in a Vancouver suburb. The model’s findings were an important piece of evidence in favor of implementing this public transit decision. As demonstrated through the application on which this teaching case is based, optimization modeling represents a powerful approach in analyzing costs, benefits and constraints, and determining appropriate operational recommendations.