An Optimization Model for Roadway Pricing on Rural Freeways

Stephen D. Boyles
Promothes Saha

University of Wyoming
Laramie, Wyoming

February 2012

Disclaimer

ABSTRACT

The main objective of rural roadway pricing is revenue generation, rather than elimination of congestion externalities. This report presents a model that provides optimum tolls accounting for pavement deterioration and economic impacts. This model contains multiple components, because imposing tolls creates “ripple effects” on traffic flow: changing traffic movements, which changes pavement deterioration rates, maintenance schedules, and spending in local economies. The model described here also allows differential pricing for different types of vehicle. Due to the discontinuity of the formulation, simulated annealing is used to find tolls on selected roadway arcs. This model is demonstrated on a network representing the state of Wyoming, along with some discussion of the issues raised by the model’s recommendations.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

The issues involved in implementing roadway tolls in rural areas differ largely from those involved in tolling urban areas, where the greatest research attention has been focused. In particular, the economic theory of urban tolling suggests pricing the congestion externality due to a vehicle's impact on the delay experienced by others. Such impacts are mostly negligible in rural settings, and the need for pricing arises from a separate externality associated with pavement deterioration and repair. This report describes a model that aims to maximize societal welfare through the implementation of tolling, focused primarily on the impacts related to pavement deterioration and maintenance.

In particular, the impacts of a tolling policy are represented in the following ways: tolls will divert traffic (possibly out of state), which changes the loading rates on pavement facilities throughout the network, and also changes the amount of money spent in local economies – for instance, many small towns located along highways rely heavily on pass-through traffic for their economic base, and may be affected by tolls that divert traffic to different routes. At the same time, tolls generate additional revenue, which in this model is assumed to be spent only on pavement repair projects. This assumption follows primarily from political considerations; if the justification for tolling is to offset pavement repair, it is not unreasonable to require the funds to be spent in this way. Finally, the cost of the tolls is reflected in terms of additional travel time, which may be imposed as people divert routes. These components are shown schematically in Figure 1, classified either as a revenue-based effect or a diversion-based effect.

Building on this framework, a set of models is applied to predict the impact of a given toll policy. Briefly, we perform the following steps:

1. Find the least generalized-cost path from each origin to each destination, taking into account the tolls and the travel times (which may vary by vehicle class) and determine the traffic flow pattern arising from loading each traveler on his or her least generalized-cost path.
2. Determine the equivalent single-axle loading (ESAL) on each roadway segment based on the pattern derived in the previous step.
3. Calculate gross toll revenue based on this pattern.
4. Calculate net toll revenue by subtracting administrative costs associated with toll collection.
5. Calculate the effects of shifting traffic toward the new pattern on long-run maintenance costs.
6. Identify a set of candidate maintenance projects that can be funded with the toll revenue.
7. Identify the subset of maintenance projects with the highest total benefits, which fit within the available budget and calculate their value.
8. Calculate the total generalized cost of all trips in the network.
9. Calculate the benefits to local economies based on pass-through traffic spending, using the post-toll flow pattern.
10. Add the results of steps 5, 7, and 9, and subtract the result of step 8, to obtain the total impacts of tolls.

The resulting value is taken as the objective function in an optimization approach, which we seek to maximize by choosing (a) the locations where tolls will be levied and (b) the amount to charge. These values can vary by vehicle class (e.g., passenger cars and semi-trailer trucks can be charged differently.) Applying the usual tools of nonlinear optimization was found to be impossible due to the complexity of the embedded models – the formulation described above is nonconvex, discontinuous, and nondifferentiable.

For this reason, simulated annealing was applied as a heuristic solution method. To adapt this general technique for the rural pricing problem, a search strategy was adopted with the goal of tolling as few roadway links as possible. Such strategies are seen as more implementable, and reduce the number of feasible solutions to evaluate. Once a set of tolling locations was determined, approximately optimal tolls were found by a neighborhood-based search.

This model and solution method are demonstrated using a sketch network representing the state of Wyoming, seen in Figure 2. The toll values and locations found by the model are shown in the figure (the lesser value is for passenger cars; the higher toll is for heavy vehicles). These values are of the same order of magnitude as those suggested in a feasibility report produced by the Wyoming Department of Transportation.

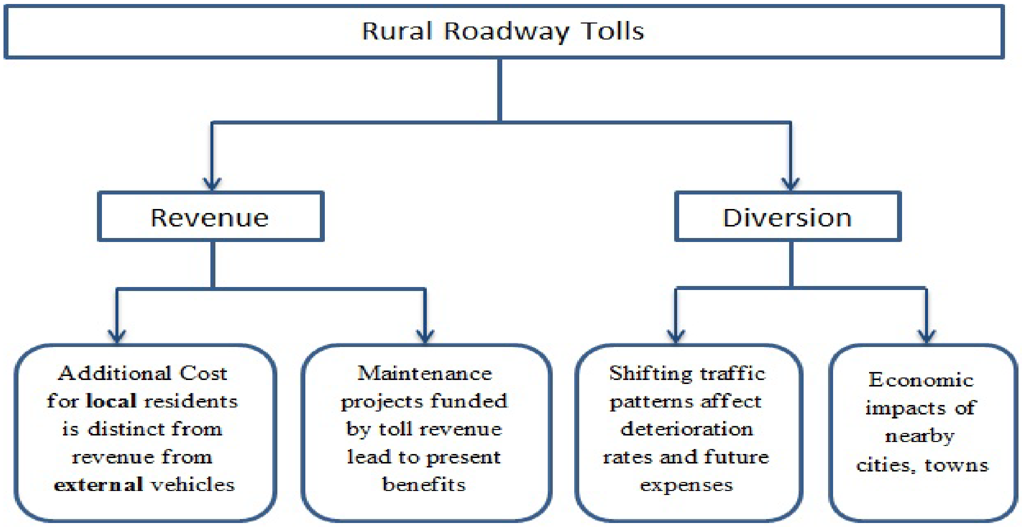

Figure 1. Schematic of Model Components

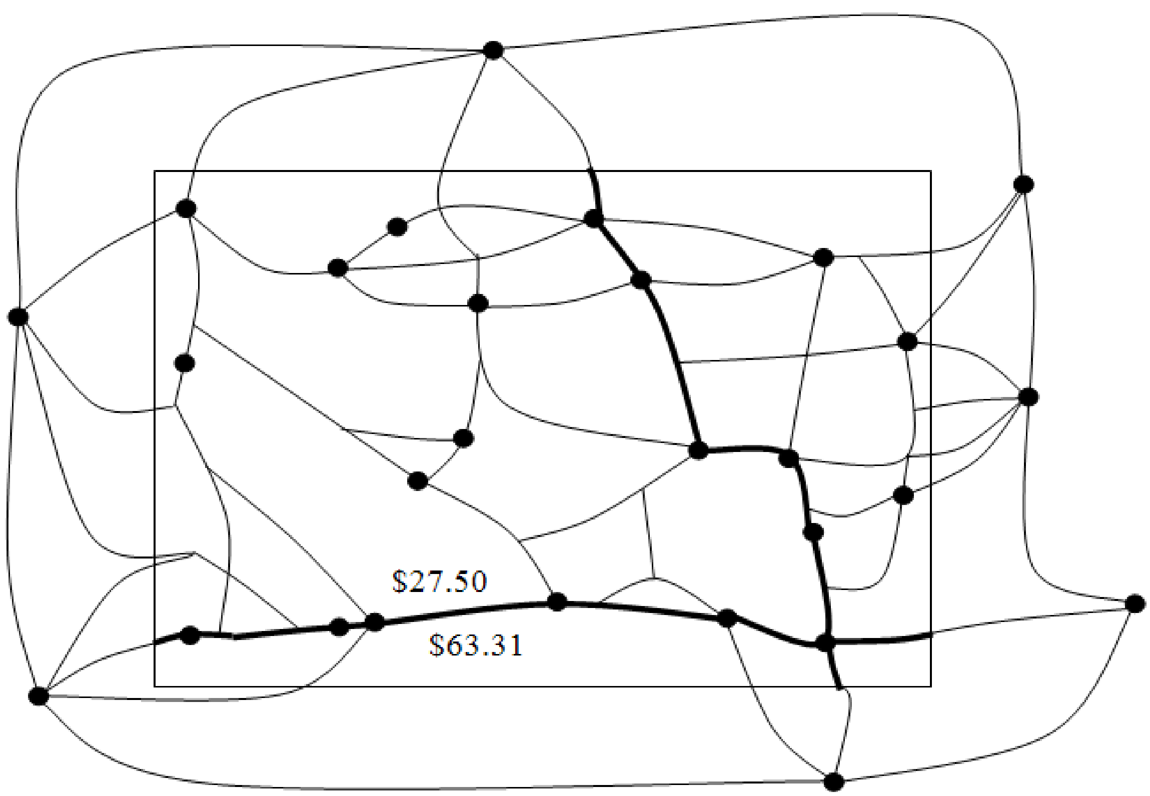

Figure 2. Wyoming Network and Tolls Found by the Model

1. INTRODUCTION

1.1 Background

Since the 1920s, automobile ownership has grown consistently, leading to steady growth in vehicle-miles traveled. In 2000, there were a total of 2.46 trillion vehicle-miles in travel in the United States alone. If this trend continues, 3 trillion vehicle miles are not far in the future. With the growing number of vehicle-miles traveled in limited lane miles, roadway pricing is growing in importance as a strategic tool for roadway management. This consistent growth of traffic creates a fundamental problem for engineers, such as maintaining mobility and safety, or generating sufficient revenue for maintenance and new construction.

In rural areas, adding system capacity is not as difficult as in urban areas because right-of-way is typically less expensive. Transportation engineering issues are also different, due to the high percentage of freight traffic, the presence of recreational trips, the freedom out-of-state drivers have to switch routes away from tolled facilities, the lack of congestion, a different funding situation, and the importance of pavement deterioration relative to traffic operations. Economists suggest that roadway pricing is an effective strategy for improving urban traffic operations and generating revenue by eliminating congestion externalities and aligning user and system optimal assignments of a roadway. This concept dates to Pigou (1920) and forms the basis for vast majority of research on optimal roadway pricing. This report studies roadway pricing on rural contexts, where the main concern is revenue generation and efficient allocation of money to maintenance and pavement deterioration, rather than eliminating congestion externalities.

Effective rural pricing should reflect the impacts on pavement deterioration due to the large percentage of heavy vehicles, optimum maintenance actions based on revenue generated, and local economic impacts of traffic on nearby cities and towns. The main contribution of this report is a pricing model that can help policymakers make decisions regarding rural tolling, including the locations tolled and the toll amounts.

1.2 Motivation

Heavy vehicles comprise nearly 60% of the total volume on certain segments of Interstate 80 in (Brinckerhoff 2008). The effect of such vehicles is larger than that of passenger cars and maintenance expenses are rising at a rate much faster than anticipated. At the same time, federal funding in the United States is partially determined by state population, so rural states face a combination of growing maintenance expenditures alongside limited federal assistance. In this situation, Wyoming and other rural states are considering implementing tolls to keep roadway facilities in good condition.

Even though congestion is not apparent in rural areas, growth in vehicle miles traveled still causes problems: expansion of trade has caused heavy vehicle volumes to grow at a far faster rate than passenger car volumes. Congestion externalities are not the problem, but externalities represented by pavement deterioration and maintenance is the major concern. Aggregate approaches to quantifying this externality (e.g., “each truck causes X dollars in damage”) fail to represent differences in existing pavement quality between and within regions, the maintenance options available to a particular agency, and the effects of diversion within the network onto facilities of varying quality.

Instead, a broader perspective is needed where the connection between tolls, traffic diversion, and future damage on specific facilities is explicitly modeled. The necessary components of this model are specified in the following section.

1.3 Problem Statement

The effects of tolls are accounted for in several ways. First, the primary societal benefits from rural pricing accrue from securing funding for maintenance and construction projects, and the benefits that these projects provide, rather than congestion reduction. Second, a substantial component of rural freeway traffic consists of long-distance freight or recreational trips, which may have more freedom to switch routes away from tolled facilities. Third, this re-routing may shift trips entirely out of a state, due to its regional nature, which carries additional economic consequences. This research will construct pricing models accounting for these factors, in order to aid rural states in generating and evaluating pricing policies that provide maximum benefits to their citizens.

This report develops a pricing strategy of rural highways considering four primary components. Figure 1.1 shows the schematic diagram of the model. The first component includes the benefits of currently available maintenance projects, which includes administrative costs due to operation and management of tolling systems depending on toll and arc flows. The second accounts for the effect of traffic diversion on pavement deterioration and future maintenance needs induced by pricing, which can potentially be beneficial (e.g., if external vehicles divert out of the network entirely) or harmful (e.g., if vehicles divert within the network onto lower-quality facilities). The third component represents the economic impact on cities and towns because of diversion of traffic or re-routing. The last category includes the generalized travel costs of travelers residing within the study area. The distinction between in-state and out-of-state travelers is important, considering the large number of external vehicles passing through rural areas – funds obtained from pass-through traffic are essentially "free" to the network manager, while funds obtained from local residents represent a transfer payment that is only beneficial if the welfare gains from pricing (i.e., from maintenance projects or traffic diversion) exceed the costs to local users.

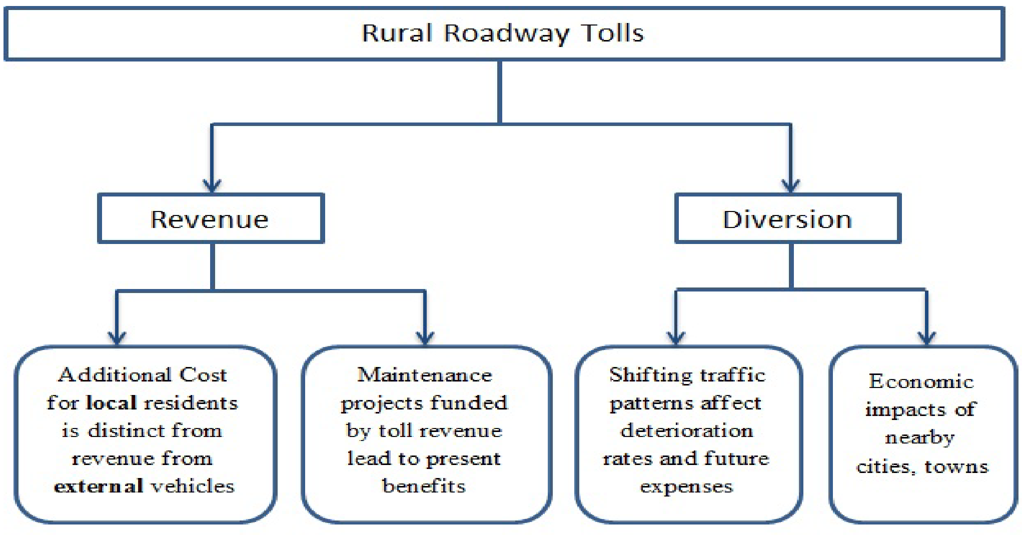

Figure 1.1 Schematic for Rural Pricing Model

A necessary component of this model is a route choice or diversion model that predicts how travelers will respond to tolls. Two major equilibrium concepts, user equilibrium (UE) and system optimal (SO), have been proposed for urban systems (Y. 1985). The UE principle states that every used path connecting the same origin to the same destination will have the minimal and equal travel time, which will occur if each user is trying to minimize their travel time to get an equilibrium state. If travelers are used to minimizing
the average cost of all users instead of their individual costs; that is said to be an SO state. However, in rural areas, assuming negligible congestion, the UE and SO states coincide and can be found by assignment to least-generalized cost routes, greatly simplifying the assignment process.

The algorithm was derived for a multiple-zone network. It assumes constant travel time for a specific link based on free-flow condition. Multiple vehicle classes are considered, and each may have its own value of travel time and damage caused to pavement. Due to the discontinuity and nonconvexity of the resulting formulation, simulated annealing is used to find tolls on selected arcs. A bi-level programming model was created where the leader represents an agency wanting to find the optimal solution for maximizing societal welfare, including current pavement condition and future maintenance expenses, and the follower represents individual travelers seeking to minimize their costs of travel.

1.4 Contribution

To our knowledge, this research is the first attempt to explore the integration of pavement deterioration and maintenance models into rural roadway pricing, which leads to a more disaggregate and precise estimation of the benefits of roadway tolling. It was expected that this model can represent a special case of rural pricing strategy by accounting for a wide range of behavior, such as involvement of different vehicle classes, in-state and out-of-state origin destinations, bi-level optimization where policymakers optimize tolls considering road user benefits, pavement maintenance and deterioration, and economic impacts due to diversion of traffic. None of the research incorporates all of above factors together. Finally, this work may motivate additional research in this area, as described more fully in Section 5.2.

1.5 Report Organization

Section 2 discusses relevant literature, including approaches to roadway pricing, optimization techniques, types of traffic assignment models, bi-level optimization, and simulated annealing. This section also reviews the general roadway pricing problem and identifies specific characteristics of rural pricing problems which distinguish them from urban ones. Section 3 develops a model and algorithm to find optimal prices for rural highways. Here each component of the model and their relationships with each other will be discussed. Assumptions, limitations, and specific implementations are also discussed. Section 4 applies this model to a representative roadway network in the state of Wyoming and discusses the results. Section 5 summarizes the contributions of this work and key findings, and points to future research directions.

2. LITERATURE REVIEW

2.1 Introduction

This section summarizes some important results from previous research that is relevant to the rural pricing problem, including optimization techniques, routing problems, equilibrium solution methods, pavement deterioration and maintenance, traffic assignment model, and economic impacts on local business due to traffic diversion. All the relevant literature mentioned above, which will be described concisely in the following subsections, will help to understand the specific pricing model for this research.

2.2 Pricing in Traffic Assignment

Pricing in traffic assignment can be classified into *first best pricing* and *second best pricing.* First best pricing, which dates to Pigou (1920), achieves the optimal utilization of transportation system by changing the UE flow pattern to SO, given the unrestricted ability to price. Secondary objectives may include minimizing the revenue generation from toll and minimizing the administrative cost, as in Dial (1999a) or Hearn and Ramana (1998). Second best pricing frameworks, on the other hand, enforce constraints such as tolls only on pre-specified subset of links, or within certain limits. Ferrari (1999) studied a second best pricing problem that includes minimizing total system travel time and maximizing toll collected. Parry (2001) proposed an interaction model between congestion pricing and impacts of congestion pricing. This model tries to create a balance between how much labor is being affected and revenue from road pricing. Dial (1999b, 1999c) developed a stochastic optimization model and algorithm, respectively, determining optimal tolls considering heterogeneity in value of time. Yang and Bell (1997) showed how toll patterns could be optimized to reduce traffic demand to a desired level. Yang and Huang (1997) made a theoretical investigation into roadway pricing by economic principle describing marginal cost pricing. May and Milne (1999) analyze how network speed could be controlled using traditional pricing strategy such as cordon, distance, and time-based pricing. Boyles et al. (2010) studied pricing in the context of uncertain demand in static transportation networks, using day-to-day variation of capacity instead of real time variation of traffic parameters. Due to limitations of static traffic assignment in capturing time-varying flows, Henderson (1974) studied the problem of determining time-varying tolls in the context of single bottleneck models.

The model developed in this report only allows tolls on certain links (such as freeways), and thus can be described as a second best pricing model. It is also a bi-level model in that there are multiple agents with different objectives. Labbé et al. (1998) considered a bi-level model where the leader wants to maximize revenues from a pricing strategy, while the followers want to minimize their spending. Our model is similar in structure, although the leader's objective function accounts for pavement deterioration and maintenance, and is therefore much more complicated.

2.3 Pavement Deterioration and Maintenance

A substantial research has been developed in the area of Maintenance and Rehabilitation (M & R) models with differing assumptions and modeling scope. One important distinction is between facility models and network models. Facility-level models focus only on a single facility like a bridge, section of pavement, etc. Network-level models consider a large system of facilities linked in a way that prevents a simple decomposition by facility (as with a total budget constraint). Facility-level models can be found in Carnahan et al. (1987) and Madanat (1994) and network-level models in Kong et al.

(2001). Robelin and Madanat (2007) describe a network-level model in which each facility's individual response to spending is considered. Prozzi and Madanat (2004) developed a pavement performance model based on experimental and field data using ordinary least squares. This model can be used to predict the pavement performance of in-service sections. Martin et al. (2004) proposed a road deterioration model for Australia's sealed granular pavements. This model can predict the impact of environment and surface maintenance treatment, time, and traffic on pavement deterioration. Multiple, independent facility-level M & R models are used in this report to represent deterioration.

The simplistic pavement deterioration model is needed for reducing the number of iterations for the evaluation of the objective function. The following equation shows how pavement condition in terms of Pavement Condition Rating (PCR) varies with life of pavement. The relationship between PCR and life of pavement illustrates, that in the early age of pavement's life, the deterioration rate is fairly slow compared with the rest of the design life. A simple relationship suggested by the Federal Highway Administration (1990) is:

$$PCR = 100 - 0.76\tau^{1.75}$$

In the following section, discussions focus on how this equation is adapted for our purposes. Finding an efficient way to incorporate more sophisticated deterioration and maintenance models is an important task for future research. More sophisticated relationships could be substituted without any methodological difficulty, but would potentially increase the computational burden and would not shed additional light on the fundamental pricing model itself, which is the primary contribution of this report.

2.4 Shortest Path Algorithms

The shortest path problem is one of the most fundamental problems in network optimization. In transportation logistics problems, it can be used to find the cheapest paths connecting each OD pair. The two most common approaches for solving shortest paths are label setting and label correcting. Dijkstra's algorithm (Dijkstra 1959) and the Bellman-Ford algorithm (Bellman 1958; Ford 1962) are representative label setting and label correcting algorithms, respectively. The following discussions about them would be about their differences and approaches.

Dijkstra's algorithm can solve a one-to-all shortest path problem when every link has a nonnegative cost. By the way, negative arc cost creates negative cost cycles. The efficient solution of this problem relies on the additivity of arc costs. At each step it finds the shortest path for each OD pair considering one additional node. It uses the concept of finalized nodes, that is, nodes to which the shortest path has already been found, as well as labels L_i denoting the cost of the shortest path from the origin to node i and a path vector q indicating the shortest paths themselves. This approach cannot be applied when arc costs may be negative, in which cases a label-correcting approach is needed

Dijkstra's algorithm can be stated as follows.

1. Initialize every label L_i to ∞ except for the origin, where $L_r \leftarrow 0$.
2. Initialize the set of finalized nodes $F = \{r\}$, and the path vector $q \leftarrow -1$.
3. Find the set of eligible arcs $E = \{(i,j) \in A: i \in F, j \notin F\}$, where A is the set of arcs
4. For each arc in E, calculate the temporary labels $L_{ij}^{temp} = L_i + c_{ij}$
5. Find the arc $(i^*, j^*)$for which L_{ij}^{temp} is minimal.

6. Update $L_i = L_{ij}^{temp}$ add j^* to F, and set $q_j^* = t^*$
7. If all nodes have been finalized *(F = N)* terminate. Otherwise, return to step 3, where *N* is the set of nodes.

Two potential problems of label setting algorithms are 1) they only work when arc costs are nonnegative and 2) finding the minimum temporary label can be time consuming. For these reasons, an alternative "label-correcting" approach to find the shortest path has been developed. This approach requires more iterations than label setting but each iteration is faster. Bellman-Ford Algorithm can be stated as follows (Bellman 1958).

1. Initialize every label L_i to ∞ except for the origin, where $L_r \leftarrow 0$.
2. Initialize the scan of eligible list $SEL \leftarrow \{r\}$ and the path vector $q \leftarrow -1$.
3. Choose a node $i \in SEL$ and remove it from the list.
4. Scan node *i* as follows: for each arc $(i, j) \in A$ compare $L_{ij} = L_i + c_{ij.}$ If $L_i + c_{ij.} < L_j$ update $L_i + c_{ij,}, q_j = i$ and add j to SEL .
5. If *SEL* is empty, then terminate. Otherwise, return to step 3.

In this model, Bellman-Ford algorithm was used to find the shortest path network because of having two advantages over Dijkstra's algorithm: a faster approach and it works when arc costs are negative.

2.5 Network Representation Techniques

In transportation network analysis, the performance of a model depends greatly on the algorithm used to represent the network within a computer. In representing a transportation roadway network, two types of data are needed to store the network configuration that is node and arc structure, and the link data such as cost, flow, and capacity.

The following techniques are very common:

- Node-Arc Incidence Matrix
- Node-Node Adjacency Matrix
- Adjacency Lists
- Forward and Reverse Star Representations
- Compact Forward and Reverse Star Representation

The representation is vital on the basis of performance of the model or network analysis (Ahuja 1993). The tradeoff of choosing network representation method lies in between program running speed, storage space, and programming ease. The forward and reverse star representations of a network is the most efficient technique in terms of the performance of the algorithm, and was chosen for the implementation of the models in this report (Ahuja 1993).

The forward star representation of data structure stores the arcs in a single array and can identify all the nodes that are outgoing from them. Properties defining the forward star representation are:

- Each arc is numbered in a sequence, thus defining an ordering of the arc list.
- All the arcs emanating from node 1 are consecutively listed, followed by those emanating from node 2, node 3, and so on.
- The arcs emanating from the same node can be ordered arbitrarily.

Relevant data for each arc can be stored in additional arrays with the same numbering. The reverse star representation is the opposite of forward star representation. Here all the arcs are sorted according to their incident node, rather than the emanating node. A *trace* array can be used to efficiently store both the forward and reverse star representations simultaneously.

The forward and reverse star representation of network still duplicates some information by storing arc numbers instead of the tails, heads, costs, and capacities of the arcs. Once the arc numbers are known, they can always retrieve the associated information from the forward star representation. More details on this format can be found in Ahuja et al. (1993).

Because of having more advantages of forward and reverse start representation technique in terms of running speed of the model and storage capacity over other approaches, this network representation technique was applied in this research.

2.6 Knapsack Problem

The knapsack problem is a combinatorial optimization problem where one must select a collection of objects of maximum value while satisfying some "weight" constraint. More formally, the problem can be written

$$\text{Maximize } \sum_{j=1}^{n} v_j x_j$$

$$\text{subject to } \sum_{j=1}^{n} w_j x_j \le W$$

$$x_j \in \{0, 1\}$$

where x_j is an integer equal to one if object j is selected and zero otherwise; v_j and w_j are the value and weight of object j, and W is the weight limit. Small knapsack problems are often solved by dynamic programming (Silvano and Toth 1990). Dynamic programming, developed by Bellman (1957), is a solution method for solving complex problems by breaking them down into smaller problems and combining their solutions to reach an overall solution. In this report, the selection of optimal maintenance projects given a budget constraint is modeled as a knapsack problem.

For a roadway pricing problem, the engineers need to find the appropriate set of links satisfying total revenue and minimizing the number of tolled links. For example, engineers need to get a minimum of $3,000 per hour; there are four links to be toll-able. The total amount of toll will be given for each link. What is the minimum valued combination of links that would be toll-able?

Links	Toll/hour
(1,2)	$2,000
(2,3)	$1,500
(1,4)	$500
(2,4)	$1,000

On the other hand, if there is one of links then the optimal knapsack contains link (1, 2) and link (2, 4) (total $ 3,000) using minimum number of links in a combination.

2.7 Simulated Annealing

Simulated annealing is a probabilistic heuristic method for finding global optima in a large search space that may possess many local minimums proposed by Kirkpatrick, Gelett, and Vecchi (1983). This process is based on an analogy to metallurgical annealing, and a key parameter is the "temperature" of the system. In annealing, a molten metal is slowly cooled to reached a stable condition. If the initial temperature is too low or the cooling process is too rapid, the system might reach a meta-stable state rather than the most stable one.

In simulated annealing, the solution, the cost of a solution, and the optimum solution correspond to the states of the physical system, the energy of the state and minimum energy, respectively. Given a solution to an optimization problem, a "neighboring" solution is obtained by perturbing the original one. If it improves the objective function, the neighbor is chosen as the new solution and the process is repeated. If the neighbor worsens the objective function, it is chosen as the new solution only with some probability depending on the temperature and how much worse it is. This last step is needed to avoid local optima (Figure 2.1). As the temperature decreases, the probability of accepting a worsening move shrinks to zero. An important component of a simulated annealing algorithm is the "cooling schedule" by which the temperature is slowly but surely reduced.

The steps for simulated annealing can be stated as follows:

1. Get the initial solution *S* and choose the initial temperature *T*.
2. Randomly generate a neighbor *S*'.
3. Find the change in the objective function *f*. ($\Delta = f(S') - f(S)$)
4. If $\Delta \leq 0$, set *S*=*S*'. otherwise *S*=*S*' with probability $e^{-\Delta/T}$
5. Consult the cooling schedule to see if the temperature needs to be reduced.
6. If convergence criterion is satisfied, stop and return *S*. Otherwise go to step 2.

Simulated annealing is thus an iterative procedure. It gives better solutions than greedy algorithms because it can escape local optima. It does not provide the probably best solution, but provides a solution technique that does not require a continuous objective function (let alone a differentiable or convex one). In this research, because of having discontinuous function and for getting the best solution quickly, simulated annealing was used.

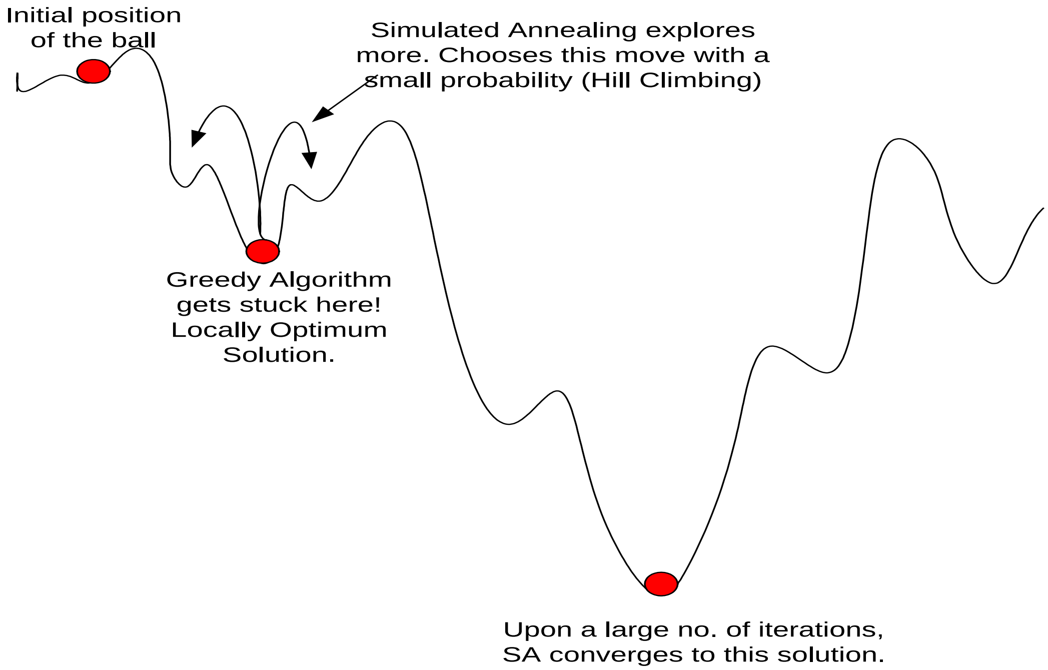

Figure 2.1 The generalized simulated annealing algorithm.
(http://www.bioinf.uni-leipzig.de/~steigele/Combinatorial_Optimization2.pdf)

2.8 Bi-Level Optimization

A general pricing model usually considers two levels of decision making. The first level of decision making belongs to the leader who imposes taxes to optimize their own objective while the second level represents followers who optimize their own objectives in response to the leader's decision. In mathematical programming, this kind of problem is known as a bi-level optimization problem where two objective formulations (leaders and followers) are merged into one formulation (Labbe 1998).

In the context of a road pricing problem, the leaders are the decision makers who will set toll rates and followers are the road users who will make decisions to minimize their travel cost as much as possible. The leader's objective function is to maximize the system benefit. Let F and f be the leader's and followers' objective functions, respectively, where the leader's objective is to maximize the benefit and the followers' is to minimize their individual operating cost. The variables in this general problem are shown in Table 2.1. Taxes are in control of the leader so that they optimize the system. This situation can be expressed as the bi-level model of taxation (Labbe 1998).

Table 2.1 Notation of the toll setting problem

N	Set of nodes of the network
A	Set of arcs of the network
Z	Set of origin/destination of the network
Ω	Set of origins of the network
Δ	Set of destination of network
T	Toll on arc, a ϵ A
T_a	Toll on arc, aϵ A, exclusive of tell fee
B	Net benefit of the network
$a\ (i, j)$	An element of A
C	Travel cost for each arc
Θ	Set of constraints on benefit
Ξ	Set of constraints on taxes
Π	Set of constraints on cost

The leader's objective function is as follows:

$$\max_{B,T,c} \quad F\,(B, T, c)$$
$$\text{Subject to} \quad B \in \Theta, \quad T \in \Xi, \quad c \in \Pi,$$

The follower's objective function is as follows:

$$\min_{T,c} \quad f\,(T, c)$$
$$\text{Subject to} \quad T \in \Xi, \quad c \in \Pi,$$

The optimum solution must simultaneously satisfy the leader's and follower's objective functions. The combination model could be applied for many situations. For example, road users always try to minimize their travel cost by choosing the minimum cost route. On the other hand, the decision makers apply tolls for maximizing system benefit. So it is necessary to get a model from which followers will receive maximum benefits as well as getting optimum revenue for leaders. Dual optimization techniques can often combine the two objective functions into one. Labbé et al. (1998) discuss such a technique when the leader wishes to maximize profit. However, our formulation involves a more complicated leader's objective, thus a simulated annealing approach is used.

2.9 Section Summary

As this research needs to do thousands of iterations to get the best solution, the performance of the model and data storage was a major concern in selecting algorithms and solution methods. This section described different approaches for specific algorithms along with solution methods in terms of performance of the model. On the basis of the discussion, best algorithms were selected in this model.

3. RURAL PRICING MODEL

3.1 Introduction

This section presents the formulation of the rural pricing model. The following sections describe the objective functions, the procedure of calculating all depending factors, and the procedure of estimating input data in this model. Note that this model is not looking at political factors, but purely economic ones. Section 3.2 formulates the rural pricing problem, the steps involved in calculating the objective function and the components of it. Section 3.3 describes the simulated annealing heuristic used to solve the problem. Section 3.4 presents the overview of procedure of estimating an input file and its component as well. Finally, Section 3.5 briefly summarizes the content of this section.

3.2 The Rural Pricing Problem

Pricing problems are often applied in urban areas for relieving congestion externalities, where minimizing total system travel time is the primary objective function. In that case, travel time is given by link performance functions relating demand for travel to delay. But in rural areas, due to the absence of traffic congestion, travel time is treated as constant, i.e., $t_{ij}(x_{ij}) = t_{ij}$ on each link. With constant travel times in rural areas, there are no questions about minimizing total system travel time, and simplifying the traffic assignment. But several factors need to be considered to optimize societal welfare such as present benefits of toll-funded maintenance actions, future benefits due to different loading profiles from diversion, the change of total system travel cost because of traffic diversion, and local economic impacts due to traffic diversions. Discontinuities in some of these components make the problem more complicated and restrict our choice of solution algorithm.

The objective function for our model is to maximize total benefits to society, given by:

$$F\ (T, x) = B\ (T, x) + M(x) - TSTC\ (T, x) + \Delta E$$

where *B(T, x)* expresses the benefits of present toll-funded maintenance actions as a function of net revenue (itself a function of the tolls *T* and link volumes *x*); *M(x)* expresses the infrastructure "value" (primarily future maintenance expenses) as a function of the flows, which determine the deterioration rate; *TSTC(T, x)* gives the total generalized cost of travel for in-region trips; and ΔE denotes the change of economic impact due to traffic diversion. All the components are considered in terms of monetary value. In the following sections, all the factors will be discussed in detail.

Furthermore, multiple vehicle classes were allowed to reflect the difference in pavement damage caused by different types of vehicles. Thus, rather than a single flow vector x, this model has a collection of vectors $x^1, x^2, x^3 \dots, x^k$ (and a corresponding collection of trip tables) where *k* is the number of vehicle classes. Differential pricing is allowed. A collection of toll vectors were considered for each vehicle class. Each class also has its own value of travel time (*VOTT*)*k.*

This section explains how the objective function is evaluated, given feasible toll vectors $T^1, T^2, T^3 \dots, T^k$. The following steps are performed in sequence. Steps requiring more explanation are discussed in more detail in the following subsections.

1. Calculate shortest paths for each vehicle class *k* with respect to generalized costs $(VOTT)^k t^k + T^k$ and load demand onto these paths, obtaining flow vectors $x^1, x^2, x^3 \dots, x^k$.

2. Determine the equivalent single-axle loading (ESAL) on each link by summing the loading caused by each vehicle class.
3. Calculate gross revenue by summing the inner products $< T_i, x_i >$ for each class.
4. Calculate net revenue by subtracting administrative costs.
5. Recalculate infrastructure value *M* based on new ESAL values and dynamic programming.
6. Identify all potential maintenance projects and their benefits based on new ESAL values.
7. Calculate immediate project benefits B by choosing the set of maintenance projects maximizing benefits within available revenue.
8. Calculate total generalized cost of in-state travel.
9. Calculate the change of economic impact due to traffic diversion in terms of monetary value.
10. Add the results of steps 5, 7 and 9, and subtract the result of step 8.

3.2.1 Equivalent Single Axle Loading on Each Link

The concept of ESALs is used by the American Association of State Highway Officials (AASHTO) to establish a relationship between traffic loading and pavement damage (FHWA 1990). Given a mixture of traffic on a roadway, ESAL tables are used to express the total loading in standard units, namely, repetitions of an 18,000-pound load. Typically, ESAL equivalents for passenger cars and semi trucks are 0.0007 and 0.39, respectively. In this research, simplified input values were selected for different parameters. In a real project, all classes of vehicles with different ESAL values could be considered. In this algorithm, simplifying the model, only two user classes were considered, passenger cars and semi trucks. The total load L_{ij} caused by different types of vehicle on each link *(i, j)* is expressed in equivalent single-axle loads converting all loads to a common unit. The difference in total load before and after setting a toll is used to calculate the pavement damage. Let L^k be the number of ESALs of damage caused by a single vehicle of class k.

$$L_{ij} = \sum_k L^k x_{ij}^k$$

3.2.2 Net and Gross Revenue

Gross revenue is calculated by summing the inner products of the tolls and flow vectors, i.e., $< T^i, x^i >$ for each class of vehicle. Due to having some administrative cost associated with collecting tolls, net revenue is calculated by subtracting administrative costs from gross revenue. Thus

Net Revenue = Gross Revenue – Administrative Cost

Let $\bar{R} = \sum_k \sum_{i,j} T_{ij}^k x_{ij}^k$ be the gross revenue from all travelers. The net revenue is written as $R = N\ (\bar{R}, T, x)$ as a function of (potentially) the gross revenue, the toll vector, and the flow vector. Examples of how each argument may influence the net revenue include accounting and regulatory overhead, which grows with the gross revenue, and the fixed cost associated with levying a positive toll at certain locations.

3.2.3 Deterioration and Maintenance Model

This section discusses pavement deterioration and the maintenance model. A simplistic relationship is intentionally chosen, because the objective function must be evaluated thousands of times to find an optimal toll policy for large networks, and a complicated pavement M & R model would be prohibitively expensive in terms of computational time. Finding an efficient way to incorporate more sophisticated deterioration and maintenance models is an important task for future research.

As discussed earlier, an integral pavement condition rating PCR_{ij} is associated with each link, representing its quality (100 = like new, 0 = unusable). This research is based on the deterioration model on the deterministic relationship (FHWA 1990) between the pavement's age τ and its condition, suggested by the Federal Highway Administration.

$$PCR = 100 - 0.76\,\tau^{1.75}$$

We also consider a set of maintenance actions that can be performed when needed depending on pavement deterioration. The set of maintenance actions *A* includes routine maintenance, complete replacement, and "do nothing." Each action $a \in A$ increases a link's PCR by a fixed improvement value $\min\{E_a, 100 - PCR\}$ with a cost of C_a. "Do nothing" maintenance action means no cost and no effect. However, to specify the change of pavement condition in terms of PCR to next year's PCR, a transition function $\phi(PCR, L, a)$ is needed to calculate the current PCR value to the next year's PCR value, given the loading *L* and the maintenance action *a* selected. We adopt this deterioration model to use the ratio between the actual loading *L* and the design load L_o used in lieu of the ageτ. Performing this substitution, and applying algebraic transformations to eliminate τ and express ϕ as a function of *PCR*, *L*, and *a* alone.

From the deterioration model the pavement age can be expressed in terms of PCR as

$$\tau = \left(\frac{100 - PCR}{0.76}\right)^{1/1.75}$$

The ratio between the actual loading, L and the design load L_o is used in lieu of age τ. So total pavements age: $\tau = \left(\frac{100-PCR}{0.76}\right)^{1/1.75} + \frac{L}{L_o}$. Now substituting the new pavement age into the deterioration model, the base future PCR is:

$$PCR = 100 - 0.76\left(\left(\frac{100 - PCR}{0.76}\right)^{1/1.75} + \frac{L}{L_o}\right)^{1.75}$$

Due to each action effect, $a \in A$ increases the link's PCR by a fixed amount E_a, which will add up with the base future PCR. Now the updated future PCR would be according to the following equation:

$$\phi(PCR, L, a) = PCR + E_a + \left[(100 - PCR) - 0.76\left(\left(\frac{100 - PCR}{0.76}\right)^{1/1.75} + \frac{L}{L_o}\right)^{1.75}\right]$$

PCR is bounded above by 100 and any action *a*, which would result in $\phi(PCR, L, a)$<0 is deemed infeasible.

With the transition function, the optimal maintenance actions for all links can be identified on the basis of maximizing total PCR of all links. On the other hand, traffic diversion due to setting tolls changes the optimal maintenance action as well. Dynamic programming is used to find these actions. Letting *Y* represent the time horizon and *y* any year between the present and *Y*, maintenance actions can be identified and more importantly for this research, a value function *V*(*PCR*,*L*,0) indicating the sum of expected future maintenance outlays and a terminal “salvage value” $V_0(PCR)$ for each facility based on its *PCR* at year *Y*. Introducing a discount factor ensures proper accounting of future costs and also minimizes the significance of the salvage values. These values can be calculated by solving the backward recursion for years *Y, Y-1… 0.*

$$V(PCR,L,Y)=V_0(PCR)$$
$$a^*(PCR,L,y)\in \arg\max_{a\in A}\{(1-\alpha)V(\phi(PCR,L,a),L,y+1)-C_a\}$$
$$V(PCR,L,y)=\max_{a\in A}\{(1-\alpha)V(\phi(PCR,L,a),L,y+1)-C_a\}$$

Although the state space for this problem can be quite large, the value function need only be calculated once and relevant values stored in a lookup table. During the toll-finding portion of the model, this table can be consulted for the necessary values, with interpolation applied as necessary.

3.2.4 Present Value of Infrastructure

The present value of infrastructure is determined by the *PCR* of each link. Traffic diversion due to setting tolls changes the traffic loading, which results in a new *PCR* on that particular link. The infrastructure present value M(x) is based directly on the value functions calculated in previous sections.

$$\mathrm{M}(x)=\sum_{(i,j)}V(PCR_{ij}^0,L_{ij}(x),0)$$

Where PCR^0 the vector of is initial pavement condition ratings and L_{ij} is given. In this way, the effect of diverting traffic on deterioration rates can be captured.

3.2.5 Immediate Project Benefit

Step 6 of the above procedure involves enumerating all potential maintenance projects, their costs, and their benefits. The number of potential projects is the product of the number of links, and the size of *A* (omitting the "do-nothing" action). The benefit of each project is given by

$$\mathrm{B}_{ij}^a(x)=V\left(\min\{PCR_{ij}^0+E_a,100\},L_{ij}(x),0\right)-V\left(PCR_{ij}^0,L_{ij}(x),0\right)$$

and the costs by

$$C_{ij}^a(x)=C_a$$

Given the net revenues *R* as the available budget, the benefit-maximizing set of projects can be identified by solving a knapsack problem with values a $B_{ij}^a(x)$ and weights $C_{ij}^a(x)$. A suitable cost discretization is applied to keep the state space small enough that the knapsack problem can be solved by dynamic programming (Silvano and Toth 1990). The value of the optimal solution to this knapsack problem is denoted by *B(T, x)*. This function is roughly concave, given diminishing marginal returns with increasing revenue as the most lucrative projects are enacted first.

3.2.6 Economic Impact Model

The economic impact model is developed to provide the estimates of the impact of traffic diversion on local cities and towns. Two approaches, zone-based and trip-based, were examined to evaluate the estimates of economic impact. The zone-based economic impact approach calculates the average dollar spending per truck at each zone. On the other hand, trip-based approach calculates average dollars spent per trip based on the distance traveled between following zones. In this model, zone-based approach was used because of easier implementation and greater accurate. The following subsections describe the source of economic impact and economic model formulation.

3.2.7 Economic Impact Model Formulation

In this particular model, the change in economic impacts is based on changing traffic movements as a result of tolling, and the resulting change in revenues in cities and towns from pass-through traffic (such as gas stations, hotels, and restaurants).

$$\Delta E\ (x,t) = \sum_{z\epsilon\ Z} \sum_{k\in K} \sum_{(r,s)\epsilon\ Z^2} a_{rs}^{zk}(t,T) d_{rs}^{k} bc$$

Where a_{rs}^{zk} is the dollar amount spent at zone *z* for each trip from origin *r* to destination *s* for class *k* (as a function of the travel times *t* and tolls *T*, which determine the shortest paths), d_{rs}^{k} is the demand for travel between origin *r* and destination *s* for class *k*, and *b* and *c* are multipliers, respectively, denoting the proportion of spending leading to economic development, and the impact factor due to change of employment, wage increase, increase of commodity price, loan and deposit in local bank and all other sources of economic impacts. *b* and *c* are taken as 0.60 and 1.25, respectively, based on an economic impact analysis performed by the Alabama Department of Transportation (2006) related to highway construction and traffic movements.

The a_{rs}^{zk} is calculated using the following procedure:

1. If *z* does not lie on the shortest path from *r* to *s* for arc costs $(VOTT)^k t^k + T^k$, a_{rs}^{zk} = 0.
2. Otherwise, let *u* and *v* be the zones (not nodes) preceding and following *z* on this shortest path. The "region of influence" for *z* is taken to be half the distance between *u* and *z*, and half the distance between *z* and *v* (Figure 3.1). Travelers are assumed to spend a fixed amount per hour traveled representing the costs of fuel, food, and lodging (these amounts may vary by vehicle class), and this money is spent in the zone whose region of influence they are in. (We do not assume that each vehicle spends its money in these proportions, but that this is the distribution characterizing total spending among all travelers between *r* and *s*.) a_{rs}^{zk} is thus the time spent in the region of influence for zone *z* multiplied by the class-specific rate of spending. These values are easily calculated using the shortest path information calculated when assigning vehicles to paths.

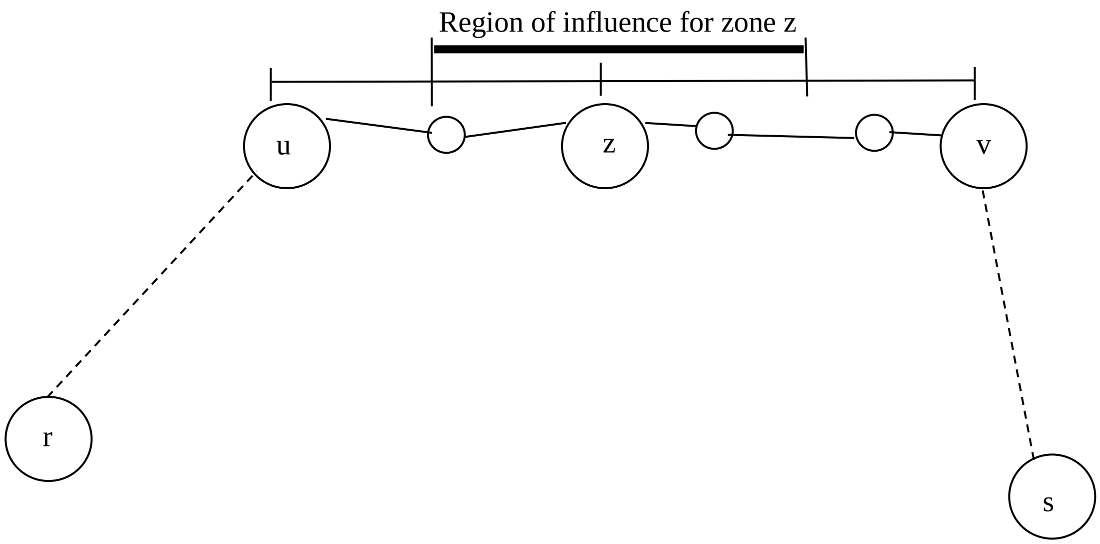

Figure 3.1 Demonstration of zone regions of influence. Large circles denote zones (cities), small circles transshipment nodes, and dashed lines longer paths.

3.3 Simulated Annealing Heuristic

In Section 2.6, SA was discussed in general for solving optimization problems. Now, in this section the implementation of SA on rural pricing model is discussed step by step. The goal is to select the link locations to be tolled, and the toll amounts, so as to maximize the objective function described in the previous section. Again, SA is used as the solution method because this objective function is not continuous or differentiable.

Applying simulated annealing to this pricing problem requires definition of a neighborhood of solutions "nearby" a given feasible solution as well as specifying a "cooling schedule" in which the algorithm parameters are adjusted as it progresses. Given an arbitrary feasible solution $\mathbf{T} = (\mathbf{T}^1, \mathbf{T}^2, \ldots, \mathbf{T}^K)$ (that is, a set of class-specific tolls on each link), neighbors include toll vectors that do not deviate more than a specified amount from $\mathbf{T}$ in each component. Furthermore, all links untolled in $\mathbf{T}$ must remain untolled in each neighbor. That is, the neighborhood $\mathcal{N}(\mathbf{T})$ can be written

$$\mathcal{N}(\mathbf{T}) = \mathop{\times}_{k=1}^{K} \left\{ \hat{\mathbf{T}}^{\mathbf{k}} \in \Re_{+}^{|A|} : \left| T_{ij}^{k} - \hat{T}_{ij}^{k} \right| \le \varepsilon, T_{ij}^{k} = 0 \Rightarrow \hat{T}_{ij}^{k} = 0 \;\; \forall (i,j) \in A \right\}$$

where ε is the maximum allowable deviation ($1 in our experiments which follow.) We use the procedure of Chiang and Russell (1996) to identify the cooling schedule based on the characteristics of a specific problem instance.

Generally, toll policies are easiest to implement when the number of toll locations is as small as possible (e.g., Hearn and Ramana 1998). Thus, our simulated annealing heuristic first examined all solutions tolling only one link, followed by those tolling two links, three links, and so forth. The algorithm is terminated after a given time limit, or when all combinations of links have been evaluated. In the demonstrations described in the next chapter, the solutions tolling two or three links were not significantly better than those tolling only one, giving confidence that program running time is good enough to get the solution. We also require the toll in both directions on the same freeway to be identical.

A second, more directed heuristic was also implemented, but did not yield any improvement in the solutions found: this second heuristic was a greedy algorithm, first finding the optimal toll on each link separately and choosing the best one; then fixing the toll on that link, finding the optimal toll on the remaining links separately and choosing the best one; then fixing the toll on those two, and so forth (Kirkpatrick 1983).

3.3.1 Parameters of Simulated Annealing

In this research, the procedure of identifying the cooling schedule was adapted from Chiang and Russel (1996). There are four problem-specific parameters that need to be specified, namely the initial temperature, the final temperature, the epoch length, and the rule specifying when and how the temperature is reduced.

The initial temperature is chosen in such a way that a move decreasing the objective function would be accepted with probability, p_0 which was set at 0.05. Then the initial temperature would be calculated according to the formula, $e^{-\frac{\Delta c}{T}} \approx p_0$. The initial temperature should be decreased in such a way that the associated Markov chains would not be very long. The most common decreasing rule follows the equation:$T_k = r * T_{k-1}$. The typical values of r lie between 0.85 and 0.95. A higher cooling ratio, r will require more steps before the algorithm stops, leading to better solutions but at a cost of higher computational requirements. In this report, r = 0.95 produced the best results.

The algorithm will stop running when the expected improvement of the objective function is rather small. In this pricing model, the execution of the algorithm was specified if it satisfies either of two conditions. The first condition specifies that if the objective function value found so far remains unchanged within a time limit; the second one is if all the combinations of links have been evaluated.

3.4 Estimating OD Matrix from Input Data

A major difficulty in calibrating regional models is developing a suitable OD matrix representing total flows from origins to destinations. In this research, a hybrid approach was used to estimate the OD matrix, using a gravity model to build a rough "target" matrix, which is then refined to match observed link counts as well as possible. Neither approach is sufficient on its own; the gravity model alone is an extremely rough approximation that is likely unrealistic in many ways, while the link counts are not accurate enough due to detector malfunctions, and do not provide enough information on their own to determine an OD matrix uniquely. A target matrix $\bar{d}_{rs}$ is obtained for inter-city movements using a standard gravity model with productions and attractions proportional to city populations, negative exponential deterrence, and iterative balancing to determine appropriate scaling factors.

A least-squares approach was then applied, with the goal of finding an OD matrix that is both similar to the target matrix $\bar{d}_{rs}$ and which would produce link flows similar to the observed counts $\bar{x}_{ij}$ if the demand in the OD matrix was assigned to shortest paths. Specifically the following equation was solved.

$$\min_{\mathbf{d},\mathbf{x}} \alpha \sum_{(i,j)} \left(x_{ij} - \bar{x}_{ij}\right)^2 + \beta \sum_{(r,s)} \left(d_{rs} - \bar{d}_{rs}\right)^2$$

under the constraint that the link volumes x are obtained by assigning demand d to shortest paths. α and β are the parameters representing the relative importance of matching the link counts or target OD matrix, respectively, and also serving as conversions between the two distance measures. Their values are set based on engineering judgment and relative confidence in the accuracy of the link counts and OD matrix. Table A.27 represents the calculated OD matrix.

3.5 Conclusion

In this section a general model has been developed that finds optimal maintenance action maximizing societal welfare, including current pavement conditions, future maintenance expenses, and economic impact as well. Here a bi-level program has been introduced where leader wants to optimize societal welfare and followers (users) want to minimize the cost of travel. The central contribution of this research is the incorporation of economic analysis with pavement deterioration and maintenance into toll selection. Simulated annealing was applied to get the best set of tolls.

4. NUMERICAL ANALYSIS

4.1 Introduction

This section analyzes and presents the numerical analysis of data given by the rural pricing model in a transportation network representing the state of Wyoming. The model generates some specific output such as objective function value, revenue, project benefit, infrastructure benefit, *TSTC*, local economic spending, amount of toll on tollable links, and flow as well. Each of the output results have been analyzed using the variation of PCR and VOTT. The results will give some specific conclusions to make effective decisions about transportation planning, pavement maintenance model, and pavement deterioration model.

4.2 Wyoming Statewide Network

This section presents a demonstration on a network representing the state of Wyoming. The main east-west freeway in the state of Wyoming is I-80, which is the main freight corridor linking San Francisco to New York and for which reasonable alternatives are lacking. The other north-south freeway, I-25, links Colorado to Montana. These two important freeways cross the state of Wyoming. More than 50% of the total traffic on I-80 in Wyoming is semi trucks. The Wyoming Department of Transportation (WYDOT) already completed a feasibility study on tolling of I-80 (Brinckerhoff 2008). The model considers only links of I-80 and I-25 in the state of Wyoming as tollable. The links of I-90 in Wyoming are not being considered as tollable because of less percentage of heavy vehicles. In terms of computational issues of this model, fewer tollable links give higher performance of the model. Figure 4.1 shows the Wyoming network containing 28 zones (all cities of at least 3,000 residents), 60 nodes and 176 links, 50 of which are tollable. In particular, some artificial links outside Wyoming represent external links so that out-of-state traffic could be examined. Basically, the external links represent route choice elasticity as a result of tolling I-25 or I-80. The pass-through traffic through Wyoming would have some other routes to avoid the toll links. In the following figure, the bold links represent tollable links and dashed links are artificial links in this model.

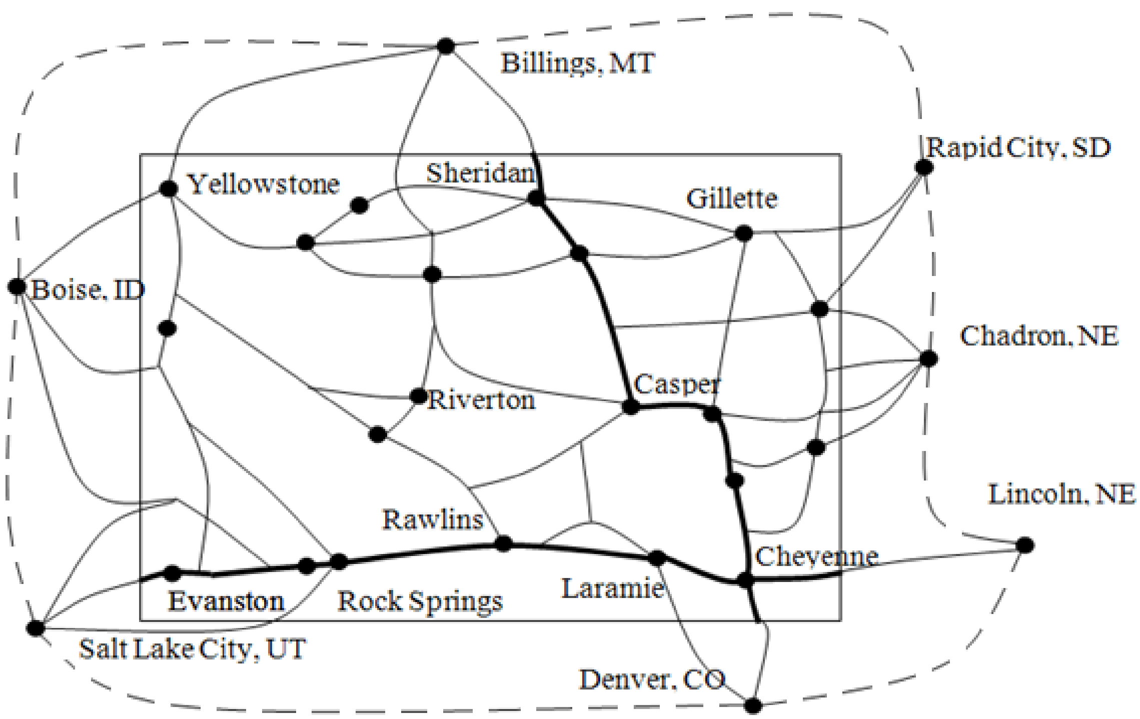

Figure 4.1 Simplified Diagram of Wyoming Network

4.3 Value of Input Parameters

Two user classes were considered, passenger cars and semi trucks. The ESAL equivalencies for these two user classes are taken as 0.0007 and 0.39, using typical values AASHTO 1993). Values of travel time for these two user classes are $10/hr. and $60/hr., respectively (Calfee 1997). Trip tables for each user class were estimated using a least-squares method based on volume counts published by the WYDOT (2008a) and a gravity trip distribution model. Link travel times are estimated as the quotient of link length and the speed limit. Two maintenance actions are considered: routine maintenance, which increases *PCR* by 10 at a cost of 10 units, and replacement, which restores *PCR* to 100 at a cost of 50 units. A $10/hr. value of time is assumed, and initial *PCR* values are randomly set between 50 and 90. Here, random selection of pavement condition means it has no control over selection of initial *PCR* values. Based on a technical report from the WYDOT (2008b), the function $N(\overline{R}, T, x)$ representing administrative overhead takes the form

$$N(\overline{R}, T, x) = \overline{R} - \sum_{(i,j)} I\left(\sum_k T_{ij}^k > 0\right)\left(\xi + \sum_k x_{ij}^k\left(\psi + \zeta T_{ij}^k\right)\right)$$

where ξ, ψ, and ζ respectively denote the fixed cost for tolling a link ($860,000, based on amortizing a $12 million total estimated expenditure over a 30-year lifespan at a 6% discount rate), the per-vehicle overhead cost ($0.27), and a coefficient representing income remaining after credit-card processing (0.97). $I(\cdot)$ is an indicator function equal to one if its argument is true, and zero otherwise.

Note that many significant and perhaps unrealistic assumptions were made in calculating these values, and thus this demonstration should not be interpreted as prescriptive advice for Wyoming. Rather, this chapter intends merely to show how this model may be used, and the type of analysis it provides. Field application requires much higher accuracy in estimating trip tables, the value of travel time, current pavement conditions, and the effects of maintenance actions.

4.4 Results

Figure 4.2 shows the optimal solution, with a recommended toll of $27.50 for passenger vehicles and $63.31 for heavy vehicles on I-80 between Rock Springs and Rawlins – the same location and order of magnitude as in the profit-maximizing solution recommended in WYDOT's initial feasibility study. This solution generated an estimated net annual revenue of $248 million, which was spent on roadway maintenance projects with a total benefit-cost ratio of 4.89. Here, benefit is just coming from maintenance actions taken and cost expresses the amount of money needed for maintenance, satisfying available budgets.

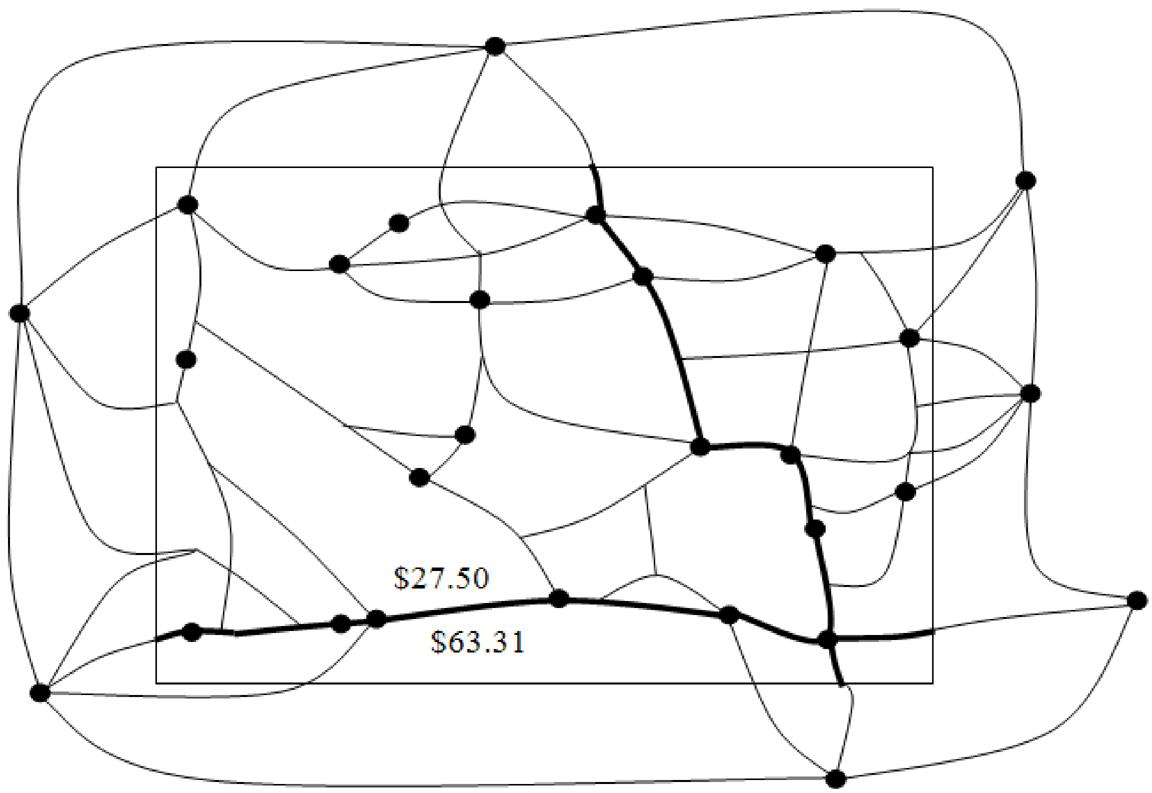

Figure 4.2 Optimal solution for original trip table

Another experiment compared these results as the trip table changed, adjusting all values by a demand multiplier ranging from 0.5 to 2.0, capturing the sensitivity of the model to the accuracy of these parameters, and providing guidance for future years when demand is likely higher. Figure 4.3 compares the toll and no-toll values for the objective function as the demand multiplier varies. Two observations are worth noting: first, the objective function decreases with demand even in the presence of tolls, indicating that the impact of higher roadway volume on pavement condition cannot be completely compensated for by tolling, given the constraints of our second-best pricing framework; second, the benefits of tolling increase with demand. Both of these results are intuitive.

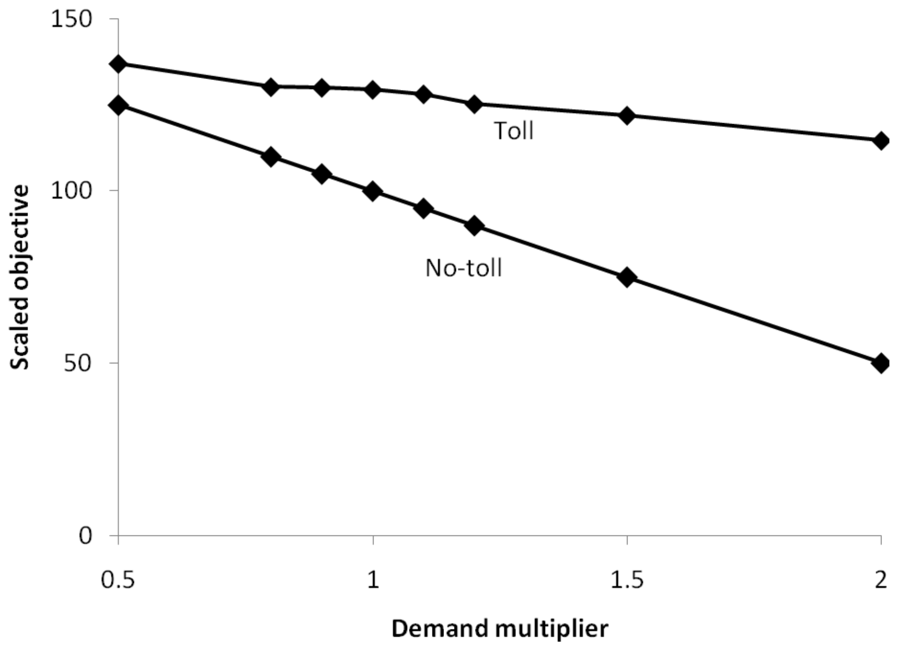

Figure 4.3 Comparison of toll and no-toll solutions for different demand multipliers

Figure 4.4 plots the annual revenue according to the demand multiplier; this relation is increasing and roughly concave. At the demand multiplier 1.25, annual revenue suddenly falls and then again follows the concave shape. This may be due to the fact that simulated annealing did not find the best solution within running time. Figure 4.5 shows the benefit/cost ratio of the projects funded by toll revenues; no clear trend is seen here with respect to demand. We speculate that this is due to two competing effects: as demand increases, revenue increases and more expensive (yet highly beneficial) projects can be funded; yet at the same time, the higher deterioration rate associated with higher demand decreases the project benefits. Figure 4.6 shows the locations selected for tolling, along with the number of demand scenarios in which that location was chosen. For every scenario except the lowest demand, I-80 was tolled between Rock Springs and Rawlings, likely because of a combination of high volume and limited diversion opportunities – in fact, for every demand scenario at least 20% above the current trip table, this was the only location chosen for tolling.

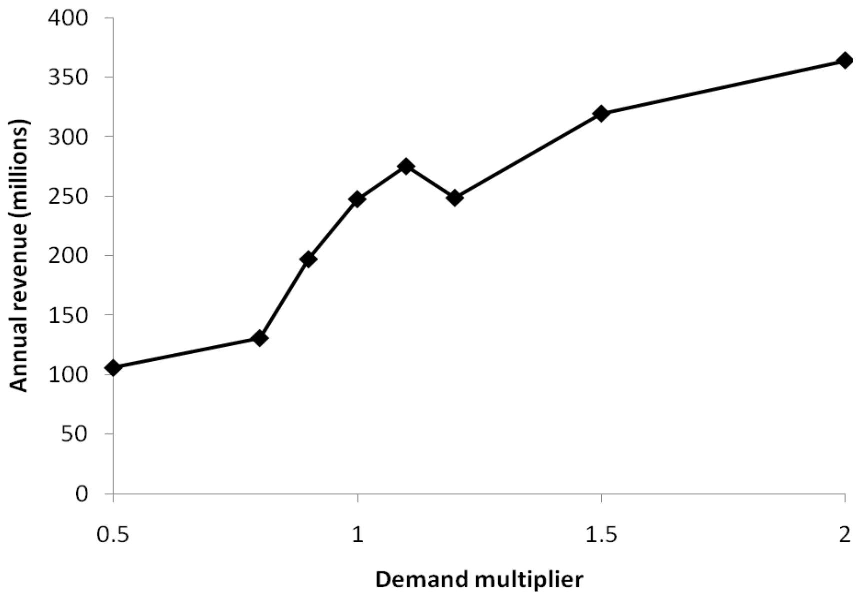

Figure 4.4 Revenue comparison for different demand multipliers

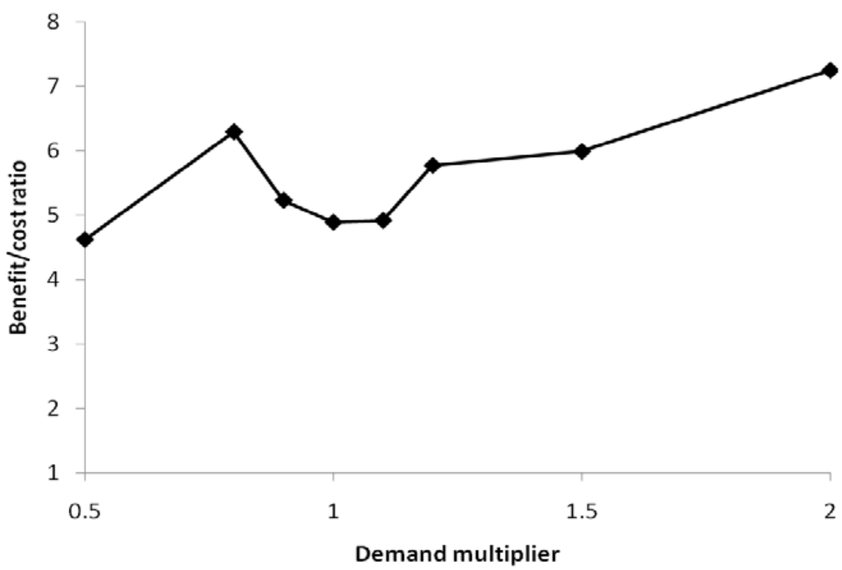

Figure 4.5 Benefit/cost ratio of toll-funded projects for different demand multipliers

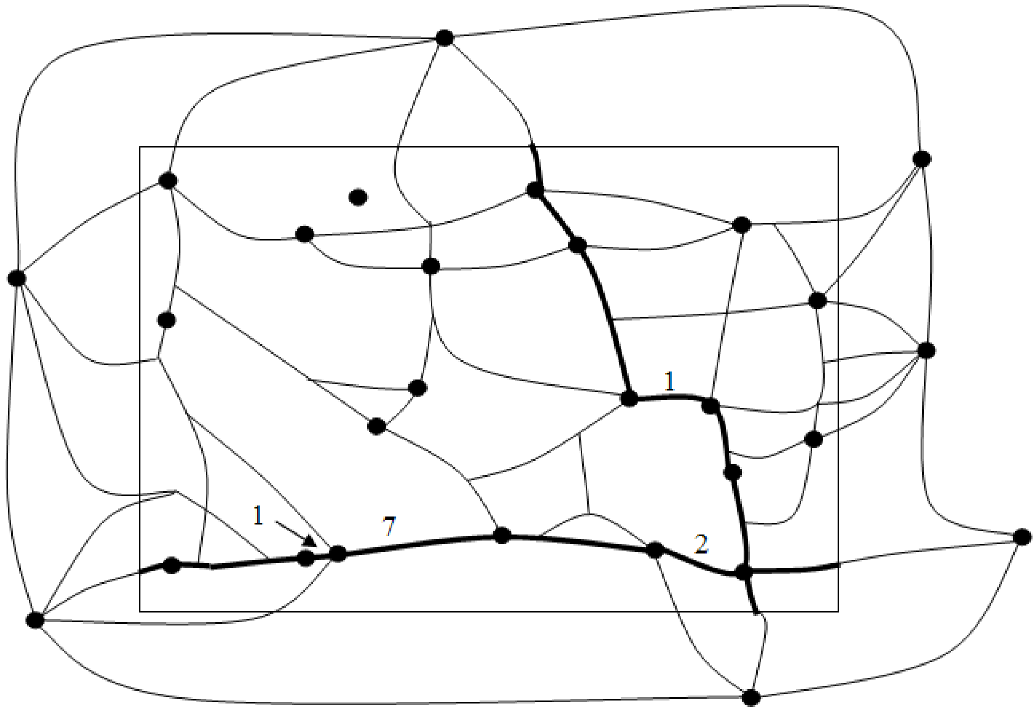

Figure 4.6 Number of demand scenarios (of 8) in which a location was selected for tolling

Additional sensitivity analyses was performed as the value of travel time and initial pavement condition varies in Figure A.1 to Figure A.10; however, fewer insights could be gleaned from these analyses, and their value instead lies in showing that the solutions are relatively stable even as these parameters vary. A set of figures and tables in the Appendix show these results, along with more details on the distribution of benefits among different components in the objective function.

4.5 Conclusion

In this section, the analysis of data and the outcomes of the rural pricing model were discussed in a sample transportation network in the state of Wyoming. Again, the purpose of these experiments is not to draw definitive conclusions about recommended toll values and revenue forecasts for Wyoming, but to illustrate the operation of the model developed here, and its utility in developing pricing policies in rural areas. Still, the values are consistent with those found in WYDOT's feasibility study, recommending slightly lower tolls; this is logical, as the goal of the model in this paper is maximizing total benefits to society, rather than revenue maximization.

5. CONCLUSION

5.1 Conclusions

Heavy vehicles in rural areas deteriorate the pavement faster than anticipated, while limited federal funding for pavement maintenance or complete replacement of those routes encourages DOTs to find another way to generate revenue. Roadway pricing is an established method of revenue generation and the main objective of this research was to identify the best tolls on the best set of links incorporating pavement deterioration and maintenance.

A bi-level program was used, where the leader wants to find the best tolls for maximizing social welfare, including current pavement conditions and future maintenance expenses. For finding the best tolls and links, simulated annealing was applied. This model was developed by simplifying obstacles, which urges some improvement of the precision of this model. The research was demonstrated for a transportation network representing the state of Wyoming. Results indicated tolls that are of the same order of magnitude as those suggested in WYDOT's initial feasibility study.

The rural roadway pricing model is composed of multiple smaller models, including a pavement deterioration model, an OD estimation model, and an economics model. A wide variety of parameters were incorporated, including network representation data and some other value of parameters, such as values of travel time, equivalent single-axle loads, fixed costs, variable costs, and vehicle classes. Some input parameters were calibrated, while the values of others were based on research papers. The output data from the model gives the best set of links with best tolls. It also gives the infrastructure benefit, present value of infrastructure, TSTC, and economic impact separately. From the analysis of the output data, the following observations can be drawn.

1. The benefits to society for toll condition are greater than no-toll condition and, furthermore, the difference between them increases with demand.
2. The relation in between revenue generation and demand multiplier is increasing and roughly concave.
3. The benefit/cost ratio is increasing with increasing traffic demand from present condition of traffic demand. At present condition of traffic demand, benefit/cost ratio is 4.89, and this ratio is going to increase with increasing traffic demand. So with additional revenue, more expensive (but more beneficial) projects can be funded.

5.2 Data for Application of Model

To implement a rural pricing model in a state, it is necessary to use valid input parameters shown in the following table. In this research, it was not possible to obtain all values of input parameters accurately. In this model, pavement condition data were randomly selected, and OD matrix was calibrated as well as possible. VOTT for different classes of vehicles, toll fixed, and variable costs were selected based on research papers. Those data could be improved based on where the model is being applied.

Network configuration data
Link data (cost, flow)
Origin destination matrix
Toll Fixed Cost
Toll Variable Cost
Class of vehicles i.e. passenger car, semi truck
VOTT for different class of vehicle
Set of maintenance actions and the improvement in terms of PCR value
Maintenance cost

5.3 Political Feasibility

Some other political issues arise regarding the toll amount and the maintenance. For example, the people who commute through Rawlins to Rocksprings have to pay $27 per car each way every single day, and this revenue will be spent to repair roadways throughout entire transportation network. Another example is, although the pavement damage caused by passenger cars is small compared with semi trucks, the amount of toll ratio for passenger car to semi truck is high enough considering the pavement damage ratio by those vehicles. In this model, the only externality considered was pavement deterioration. So these factors raise political support issues.

To be politically feasible, roadway pricing must be perceived by people as significantly beneficial to those using the facility. To analyze this issue, how many groups of people being affected by roadway pricing, who are the winners and who are losers, needs to be identified. Once the size of the specific group is known, political support for roadway pricing can be evaluated. If more groups of people are direct losers than winners, political support for roadway pricing would be difficult, although net value of objective function is higher in any tollable situation. The public acceptance of new fees that are imposed as toll needs to be evaluated also. For this, those drivers who are pushed off because of imposing tolls should be significantly low compared with the drivers who are the winners. But it is not sufficient that the number of losers is small. Public acceptance of roadway pricing also depends on the change of utility that satisfys the following three conditions studied by Charles Lave (1994):

1. Those who are pushed off because of new fees should have reasonable alternatives and be quite willing to take them.
2. Those who gain advantage by saving a substantial amount of travel time, pay the least amount of tolls as possible.
3. The proportion of losers to winners should be substantially low.

5.4 Future Work

Many improvements could be done in this research into modeling the rural roadway pricing. Relaxing some of the assumptions would improve its accuracy.

For example

1. Developing a continuous representation of ESAL loading would enhance the precision of this model. Dial's work (1999b, 1999c) on continuous representation of value of travel time might be helpful on this.
2. The value of travel time may vary from time to time and day to day. So, considering variability in the value of travel time would make the model more realistic.
3. In the conventional way of practicing transportation planning application, static OD matrices are used, where the trip rate between origins to destinations are assumed constant over a large period of time. Clearly this is an approximation of reality. In practice, one definitely observes temporal variation in OD matrices over the course of the analysis period.
4. An equity constraint or measurement could be added. Pricing may affect travelers differently based on their income, which is important to measure in order to see the full effects of pricing and to gather political support.
5. A more sophisticated model of pavement deterioration and repair can be used.

Thus, much work still remains in developing a full realistic model of rural pricing. A major challenge in incorporating the above features is finding a balance between model realism and computational requirements. Future research should consider these methods as well as different implementations and solution methods. While much research is required to make this model fully realistic, this research nevertheless provides an important step in this direction.

REFERENCES

A.S., Kercher. "Best-First" Policy is the Best Policy (http://www.kercherei.com/pw_institute/prev_maint/best.html).

AASHTO. "AASHTO Guide for Design of Pavement Structures." Washington DC, 1993.

Ahuja, R., T. Magnanti, and J. Orlin. Network flows. Englewood, NJ: Prentice-Hall, 1993.

ALDOT. "Initial Highway Impact Analysis." Alabama, 2006.

Bar-Gera, H. "Origin-based algorithm for the traffic assignment problem." *Transportation Science* 36 (2002).

Bellei, G., G. Gentile and N. Papola. "Network Pricing Optimization in Multi-user and Multimodal Context with Elastic Demand." *Transportation Research* Part B, 2002: Vol. 36, pp. 779-798.

Bellei, G., G. Gentile, and N. Papola. "Network Pricing Optimization in Multi-user and Multimodal Context with Elastic Demand." *Transportation Research* Part B 36 (2002): 779-798.

Bellman, R. Dynamic Programming. NJ: Princeton University Press, Princeton, 1957.

Bellman, R. "On a routing problem." *Quarterly of Applied Mathematics* 16 (1958): 87-90.

Bertsekas, Dimitri P. "Dynamic Programming and and Optimal Control." *Athena Scientific*, 2005: Vol. I.

Bertsekas, Dimitri P. "Dynamic Programming and and Optimal Control." *Athena Scientific* II (2007).

Bertsekas, Dimitri P. "Dynamic Programming and and Optimal Control." *Athena Scientific*, 2007: Vol. II.

Boyles, S.D. , L.M. Garner, and S.T. Waller. "Congestion Pricing Under Operational, Supply-Side Uncertainity." *Transportation Research* Part C 18 (2010): 519-535.

Boyles, S.D. "An Introduction to Engineering Optimization, CE 4920." pp. 1-5. 2009.

Boyles, S.D. "Transportation Network Analysis." pp. 1-5. 2010.

Brinckerhoff, P. "Interstate 80 Tolling Feasibility Study." 2008.

Calfee, J. and Winston, J. "The value of automobile travel time: implications for congestion policy." *Journal of Public Economics*, 1997.

Carnahan, J., W. Davis, M. Shahin, and M. Wu. "Optional Maintenance Decisions for Pavement Management." *Journal of Transportation Engineering* 113 (1987): 554-572.

Carrion-Madera, C., and D., Levinson. "Value of travel time reliability: A review of current evidence." 2010.

Chiang, W.C. and R.A. Russell. “Simulated annealing metaheuristics for the vehicle routing problem with time windows.” *Annals of Operations Research*, 1996.

Decorla-Souza, Patrick. Partners in time: USDOT is joining with Urban Partners in up to five metropolitan areas to alleviate. *Public Roads*, July-August 2007 Issue.

Dial, R.B. “Minimal-revenue Congestion Pricing Part I: A Fast Algorithm for the Single Origin Case.” *Transportation Research Part B* 33 (1999): 189-202.

Dial, R.B. “Minimal-revenue Congestion Pricing Part I: A Fast Algorithm for the Single Origin Case.” *Transportation Research* Part B, 1999: Vol 33, pp. 189-202.

Dial, R.B. “Network Optimized Road Pricing: Part I: A Parable and a Model.” *Operations Research* 47 (1999a): 54-64.

Dial, R.B. “Network Optimized Road Pricing: Part II: Algorithms and Examples.” *Operations Research* 47 (1999b): 327-336.

Dijkstra, E. “A note on two problems in connexion with graphs.” *Numerische Mathematik* 1 (1959): 269-271.

Economics, Bureau of Transport and Communication. “Pavement Management: Development of a life cycle costing technique.” Canberra, 1990.

Ferrari, P. “Road Network Toll Pricing and Social Welfare.” *Transportation Research* Part B 36 (1999): 471-483.

FHWA. “An Advanced Course in Pavement Management Systems.” Washington DC, 1990.

FHWA. “Economics: Pricing, Demand and Economic Efficiency-A Primer.” 2008.

Ford, Jr., L.R. and D.R. Fulkerson. Flows in Networks. Princeton University Press, 1962.

Hearn D.W. and M. Ramana. “Solving Congestion Toll Pricing Models.” In Solving Congestion Toll Pricing Models. In Marcotte O, & Nguyen S. (Eds.), 109-124. Kluwer Academic, 1998.

Henderson, J. “Road Congestion: A Reconsideration of Pricing Theory.” *Journal of Urban Economics* I (1974): 346-365.

Hine, John. “The economics of road investment (http://siteresources.worldbank.org/INTTRANSPORT/Resources/336291-1152796664200/2749337-1153139937005/04HineRoadAppraisal08.ppt).”

Jayakrishnan, R., W.T. Tsai, J.N. Prashker, and S. Rajadhyaksha. “A faster path-based algorithm for traffic assignment.” *Transportation Research Record*, 1994.

Kirkpatrick, S., C.D. Gelatt ad M.P.Vecchi. “Optimization by Simulated Annealing.” *Science*, 1983: Vol. 220, pp. 671-680.

Kirkpatrick, S., C.D. Gelatt, and M.P.Vecchi. “Optimization by Simulated Annealing.” *Science* 220 (1983): 671-680.

Klincewicz, John G. “A dual algorithm for the uncapacitated hub location problem.” (AT&T Labs) 1999.

Kong, J.S., and D.M. Frangopol. “Life-Cycle Reliability-Based Maintenance Cost Optimization of Deteriorating Structures with Emphasis on Bridges.” *Journal of Structural Engineering* 129 (2001): 818-828.

Labbe, M., P. Marcotte, and G. Savard. “A Bilevel Model of Taxationand Its Application to Optimal Highway Pricing.” *Management Science* 44 (1998): 1608-1622.

Lave, C. “The Demand Curve Under Road Pricing and the Problem of Political Feasibility.” *Transportation Research* A, 1994.

Madanat, S. and M. Ben-Akiva. “Optional Inspection and Repair Policies for Infrastructure Facilities.” *Transportation Science* 28 (1994): 55-62.

Martello, Silvano, and Paolo Toth. Knapsack problems: Algorithms and computer interpretations. 1990.

Martin, T.C., T. Toole, and J.W.H. Oliver. “The development of HDM-4 technology road deterioration models for Australia’s sealed granular pavements.” International Conference on Managing Pavements. 2004.

May, A.D. and D.S. Milne. “Effects of alternative road pricing systems on network performance.” *Transportation Research* Part A 34 (1999).

Niskanen, Esko. “Congestion tolls and consumer welfare.” *Pergamon Journals Ltd.*, 1986.

Parry, I. and A., Bento. “Revenue recycling and the welfare effects.” J*ournal of Economics* (Blackwell Publishers), 2001.

Patriksson, T. Larson and M. “An augmented lagragean dual algorithm for link capacity side constrained traffic assignment problems.” *Transportation Research* Part B 29 (1995): 433-455.

Pigou, A.C. “The Economics of Welfare.” Macmillan and Co. London, 1920.

Prozzi, J.A., and S.M., Madanat. “Development of pavement performance models by combining experimental and field data.” *Journal of Infrastructure System*, 2004.

RITA. “Traffic Data, http://www.bts.gov/publications/national_transportation_statistics/html/table_02_18.html.” March 16, 2010.

Robelin, C.A., and S. Madanat. “History Dependent Bridge Deck Maintenance and Replacement Optimization with Markov Decision Processes.” *Journal of Infrastructure System* 13 (2007): 195-201.

Saha, P. , S.D. Boyles, and R. Liu. “Pricing Model for Rural Roadway Networks Incorporating Pavement Deterioration.” *Under Review*, 2010.

Sigurbjornsdottir, K., J. Tervonen and A., Goebel. The socio-economic impacts of road pricing. Conference of European Directors of Roads, 2009.

Silvano, M. and P. Toth. “Knapsack Problems: Algorithms and Computer Implimentation.” (John Wiley and Sons, Inc.) 1990.

Silvano, M. and P. Toth. “Knapsack Problems: Algorithms and Computer Implimentation.” (John Wiley and Sons, Inc.) 1990.

Teodorović, D. and P. Edara. A real-time road pricing system: The case of a two-link parallel network. 2005.

Transportation, Oregon Department of. The value of travel-time: estimates of the hourly value of time for vehicles in Oregon 2005. Economics & Policy Analysis Unit, 2005.

Transportation, U.S. Department of. Revised departmental guidance: valuation of travel time in economic analysis. Office of the Secretary of Transportation, 2003.

Verhoef, E., M. Lijesen, and A. Hoen. “The economic effects of road pricing in the Ranstad area.”

WYDOT. “Traffic Data. Created 2008, http://www.dot.state.wy.us/wydot/planning-projects/Traffc-Data.” March 16, 2010.

Y., Sheffi. Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods. Prentice Hall, 1985.

Yaghini, Masoud. Network flows. 2010.

Yang, H. and M.G.H., Bell. “Traffic Restraint, road pricing and network equilibrium.” 1997.

Yang, H., and H., Huang. Principle of marginal-cost pricing: how does it work in a general road network? Hong Kong, 1997.

Zhan, F. Benjamin. Representing Networks (http://www.ncgia.ucsb.edu/giscc/units/u064/u064.html).

APPENDIX: NETWORK DATA AND ADDITIONAL RESULTS

Table A.1 Number of production and attraction of trips by cities for Wyoming network

Number of Production and Attraction				
Zone No	City	Population	No of Prod	No of Attraction
1	Denver	610345	30517	30517
2	Chadron	5634	282	282
3	Rapid City	59607	2980	2980
4	Billings	103994	5200	5200
5	Boise	205314	10266	10266
6	Salt Lake City	181698	9085	9085
7	Cheyenne	56915	2846	2846
8	Casper	54047	2702	2702
9	Laramie	27664	1383	1383
10	Gillette	26871	1344	1344
11	Rock Springs	20200	1010	1010
12	Sheridan	17197	860	860
13	Green River	12149	607	607
14	Evanston	11781	589	589
15	Riverton	10032	502	502
16	Jackson	9806	490	490
17	Cody	9309	465	465
18	Rawlins	8740	437	437
19	Lander	7264	363	363
20	Douglas	5971	299	299
21	Powell	5524	276	276
22	Torrington	5514	276	276
23	Worland	4958	248	248
24	Buffalo	4832	242	242
25	Newcastle	3390	170	170
26	Wheatland	3298	165	165
27	Yellowstone Park	0	0	0
28	Lincoln	251624	12581	12581

Table A.2 Some other necessary input data

Infrastructure Weight= 100000
Toll Fixed Cost= 860
Toll Variable Cost= 0.27
Out of State Zones= Denver, Chadron, Rapid City, Billings, Boise, Salt Lake City
ESAL equivalents = for passenger cars and semi trucks are taken as 0.0007 and 0.39 respectively.
VOTT= for passenger cars and semi trucks are taken as $0.167 and $1 per minute respectively.
Time horizon =60
Minimum pavement deterioration factor =0
Pavement deterioration increment=0.1
Number of pavement deterioration factors=21

Table A.3 Maintenance actions taken, their cost and effect

Maintenance Action	Cost	Effect (Increase of PCR)
Do Nothing	0	0
Routine Maintenance	1	10
Complete Replacement	20	Increase to 100

Table A.4 Summary of revenue from model outputs for different VOTT and PCR

VOTT ($/min)	**PCR-70**	**PCR-75**	**PCR-80**	**PCR-85**	**PCR-90**	**PCR-95**
0.11	1.E+09	1.E+09	1.E+09	1.E+09	1.E+09	1.E+09
0.13	1.E+09	1.E+09	1.E+09	9.E+08	7.E+08	1.E+09
0.167	1.E+09	1.E+09	1.E+09	9.E+08	7.E+08	1.E+09
0.185	1.E+09	1.E+09	1.E+09	9.E+08	7.E+08	1.E+09
0.20	1.E+09	1.E+09	1.E+09	9.E+08	7.E+08	1.E+09

Table A.5 Summary of long term infrastructure value from model outputs for different VOTT and PCR

VOTT ($/min)	**PCR-70**	**PCR-75**	**PCR-80**	**PCR-85**	**PCR-90**	**PCR-95**
0.11	-3.E+07	-3.E+07	-2.E+07	-2.E+07	-2.E+07	-2.E+07
0.13	-3.E+07	-3.E+07	-2.E+07	-2.E+07	-2.E+07	-2.E+07
0.167	-3.E+07	-3.E+07	-2.E+07	-2.E+07	-2.E+07	-2.E+07
0.185	-3.E+07	-3.E+07	-2.E+07	-2.E+07	-2.E+07	-2.E+07
0.20	-3.E+07	-3.E+07	-2.E+07	-2.E+07	-2.E+07	-2.E+07

Table A.6 Summary of short term project benefit from model outputs for different VOTT and PCR

VOTT ($/min)	**PCR-70**	**PCR-75**	**PCR-80**	**PCR-85**	**PCR-90**	**PCR-95**
0.11	2.E+07	3.E+07	2.E+07	2.E+07	2.E+07	2.E+07
0.13	2.E+07	3.E+07	2.E+07	1.E+07	1.E+07	2.E+07
0.167	2.E+07	3.E+07	2.E+07	1.E+07	1.E+07	2.E+07
0.185	2.E+07	3.E+07	2.E+07	1.E+07	1.E+07	2.E+07
0.20	3.E+07	3.E+07	2.E+07	1.E+07	1.E+07	2.E+07

Table A.7 Summary of in-state TSTC from model outputs for different VOTT and PCR

VOTT ($/min)	**PCR-70**	**PCR-75**	**PCR-80**	**PCR-85**	**PCR-90**	**PCR-95**
0.11	6.E+08	6.E+08	6.E+08	6.E+08	6.E+08	6.E+08
0.13	7.E+08	7.E+08	7.E+08	7.E+08	7.E+08	7.E+08
0.167	9.E+08	9.E+08	9.E+08	9.E+08	9.E+08	9.E+08
0.185	1.E+09	1.E+09	1.E+09	1.E+09	1.E+09	1.E+09
0.20	1.E+09	1.E+09	1.E+09	1.E+09	1.E+09	1.E+09

Table A.8 Summary of out-of-state spending in local economies from model outputs for different VOTT and PCR

VOTT ($/min)	**PCR-70**	**PCR-75**	**PCR-80**	**PCR-85**	**PCR-90**	**PCR-95**
0.11	1.E+07	1.E+07	1.E+07	1.E+07	1.E+07	1.E+07
0.13	2.E+07	2.E+07	2.E+07	2.E+07	2.E+07	2.E+07
0.167	2.E+07	2.E+07	2.E+07	2.E+07	2.E+07	2.E+07
0.185	3.E+07	3.E+07	3.E+07	3.E+07	3.E+07	3.E+07
0.20	3.E+07	3.E+07	3.E+07	3.E+07	3.E+07	3.E+07

Table A.9 Toll and flow on links for car from varying PCR ($VOTT_{nt}$ = \$6.6/hr., $VOTT_t$ =\$39.6/hr.)

		PCR-70		PCR-75		PCR-80		PCR-85		PCR-90		PCR-95	
Link	Class	Toll	Flow	Toll	Flow	Toll	Flow	Toll	Flow	Toll	Flow	Toll	Flow
(1,45)	2	0	536059	0	463403	0	463403	0	463403	0	463403	0	463403
(3,52)	2	0	151807	0	151807	0	151807	0	151807	0	151807	0	151807
(4,12)	2	0	42111	0	42111	0	42111	0	42111	0	42111	0	42111
(6,14)	2	0	1057455	0	1057455	0	1057455	0	1057455	0	1057455	0	1057455
(7,45)	2	0	665144	0	598648	0	778341	0	778341	0	778341	0	778341
(7,26)	2	0	208130	0	141606	0	188526	0	188526	0	188526	0	188526
(8,20)	2	0	325221	0	325221	0	306261	0	306261	0	306261	0	306261
(8,54)	2	0	198293	0	198293	0	178688	0	178688	0	178688	0	178688
(9,43)	2	0	972466	0	972466	0	1074581	0	1074581	0	1074581	0	1074581
(9,45)	2	0	1002106	0	996190	0	1042395	0	1042395	0	1042395	0	1042395
(10,52)	2	0	183841	0	183841	0	183841	0	183841	0	183841	0	183841
(10,24)	2	0	117939	0	117939	0	117939	0	117939	0	117939	0	117939
(11,32)	2	0	1275107	0	1275107	0	1275107	0	1275107	0	1275107	0	1275107
(11,18)	2	0	1211530	0	1211530	0	1211530	0	1211530	0	1211530	0	1211530
(12,24)	2	0	226530	0	226530	0	222353	0	222353	0	222353	0	222353
(13,32)	2	0	1276985	0	1276985	0	1276985	0	1276985	0	1276985	0	1276985
(13,31)	2	0	1294176	0	1294176	0	1294176	0	1294176	0	1294176	0	1294176
(14,31)	2	0	1168756	0	1168756	0	1168756	0	1168756	0	1168756	0	1168756
(18,43)	2	0	1055798	0	1055798	0	1074757	0	1074757	0	1074757	0	1074757
(20,49)	2	0	292530	0	292530	0	273571	0	273571	0	273571	0	273571
(24,54)	2	0	146518	0	146518	0	127559	0	127559	0	127559	0	127559
(26,48)	2	0	388598	0	388598	0	275253	0	275253	0	275253	0	275253
(28,46)	**2**	**80**	**860010**	**83**	**860010**	**80**	**860010**	**80**	**860010**	**80**	**860010**	**80**	**860010**
(45,46)	2	0	860093	0	860093	0	860093	0	860093	0	860093	0	860093
(48,49)	2	0	320916	0	320916	0	301312	0	301312	0	301312	0	301312

Table A.10 Toll and flow on links for truck from varying PCR ($VOTT_{nt}$ = \$6.6/hr, $VOTT_t$ =\$39.6/hr.)

		PCR-70		**PCR-75**		**PCR-80**		**PCR-85**		**PCR-90**		**PCR-95**	
Link	Class	Toll	Flow	Toll	Flow	Toll	Flow	Toll	Flow	Toll	Flow	Toll	Flow
(1,45)	1	0	1309125	0	1309125	0	1328426	0	1328426	0	1328426	0	1328426
(3,52)	1	0	629067	0	912192	0	912192	0	912192	0	912192	0	912192
(4,12)	1	0	544143	0	366767	0	366767	0	366767	0	366767	0	366767
(6,14)	1	0	2552964	0	2552964	0	2552964	0	2552964	0	2552964	0	2552964
(7,45)	1	0	1413989	0	434851	0	2209759	0	2209759	0	2209759	0	2209759
(7,26)	1	0	477601	0	1402943	0	807752	0	807752	0	807752	0	807752
(8,20)	1	0	2201138	0	2201138	0	2201097	0	2201097	0	2201097	0	2201097
(8,54)	1	0	1231776	0	1231776	0	1231734	0	1231734	0	1231734	0	1231734
(9,43)	1	0	1692999	0	767657	0	1986371	0	1986371	0	1986371	0	1986371
(9,45)	1	0	2624727	0	1253190	0	2272520	0	2272520	0	2272520	0	2272520
(10,52)	1	0	851772	0	1135084	0	1135084	0	1135084	0	1135084	0	1135084
(10,24)	1	0	295132	0	472508	0	472508	0	472508	0	472508	0	472508
(11,32)	1	0	2999994	0	2999994	0	2999994	0	2999994	0	2999994	0	2999994
(11,18)	1	0	2192417	0	2192417	0	2192417	0	2192417	0	2192417	0	2192417
(12,24)	1	0	1062706	0	1240246	0	1240246	0	1240246	0	1240246	0	1240246
(13,32)	1	0	3000010	0	3000010	0	3000010	0	3000010	0	3000010	0	3000010
(13,31)	1	0	2729136	0	2729136	0	2729136	0	2729136	0	2729136	0	2729136
(14,31)	1	0	2312825	0	2312825	0	2312825	0	2312825	0	2312825	0	2312825
(18,43)	1	0	1986336	0	1986336	0	1986377	0	1986377	0	1986377	0	1986377
(20,49)	1	0	1571782	0	1571782	0	1571741	0	1571741	0	1571741	0	1571741
(24,54)	1	0	540499	0	540499	0	540458	0	540458	0	540458	0	540458
(26,48)	1	0	1635013	0	1688783	0	1169414	0	1169414	0	1169414	0	1169414
(28,46)	**1**	**206**	**2142246**	**205**	**2142246**	**206**	**2142246**	**206**	**2142246**	**206**	**2142246**	**206**	**2142246**
(45,46)	1	0	2142249	0	2142249	0	2142249	0	2142249	0	2142249	0	2142249
(48,49)	1	0	1217157	0	1270921	0	1213733	0	1213733	0	1213733	0	1213733

Table A.12 Toll of cars on links as initial PCR varies for different VOTT

VOTT ($/min)	PCR-70	PCR-75	PCR-80	PCR-85	PCR-90	PCR-95
0.11	206	205	206	195	142	207
0.13	201	202	201	199	137	212
0.167	206	196	196	187	138	205
0.185	195	203	193	193	136	195
0.2	204	194	198	184	128	196

Table A.12 Objective function as initial PCR varies for toll-able situation

	PCR-70	**PCR-75**	**PCR-80**	**PCR-85**	**PCR-90**	**PCR-95**
Best objective	-8.E+10	-5.E+10	-2.E+11	-6.E+11	-6.E+11	-5.E+11
Revenue	1.E+09	1.E+09	1.E+09	9.E+08	7.E+08	1.E+09
Long-term infrastructure value	-3.E+07	-3.E+07	-2.E+07	-2.E+07	-2.E+07	-2.E+07
Short-term project benefit	2.E+07	3.E+07	2.E+07	1.E+07	1.E+07	2.E+07
In-state TSTC	9.E+08	9.E+08	9.E+08	9.E+08	9.E+08	9.E+08
Out-of-state spending in local economies	2.E+07	2.E+07	2.E+07	2.E+07	2.E+07	2.E+07

Table A.13 Objective function as initial PCR varies for no-toll situation

	PCR-70	**PCR-75**	**PCR-80**	**PCR-85**	**PCR-90**	**PCR-95**
Best objective	-2.569E+12	-2.56762E+12	-2.36602E+12	-2.00286E+12	-2.00861E+12	-2.10754E+12
Revenue	0	0	0	0	0	0
Long-term infrastructure value	-25680774	-256699	-23651023	-20019381	-20077382	-21066253
Short-term project benefit	0	0	0	0	0	0
In-state TSTC	917693179	917693179	917693179	917693179	874013648	917693179
Out-of-state spending in local economies	22814398	22814398	22814398	22814398	22363694	22814398

Table A.14 Variation of local economic spending at top five cities with different VOTT (PCR-70)

Zone	PCR-70-0.11	PCR-70-0.13	PCR-70-0.167	PCR-70-0.185	PCR-70-0.20
9	432901	553609	655264	728152	766161
7	361503	458571	538649	598672	627497
10	305081	416220	524501	535486	578904
18	287807	392279	491086	545021	589212
13	258775	352709	441548	490043	529776

Table A.15 Local economic spending at in-state zones from varying PCR ($VOTT_{nt}$ = \$6.6/hr., $VOTT_t$ = \$39.6/hr.)

ZONE \ PCR	70	75	80	85	90	95
7	361503	363021	361503	361503	361503	361503
8	31374	31374	31374	31374	31374	31374
9	432901	434521	432901	432901	432901	432901
10	305081	305081	305081	305081	305081	305081
11	195377	195377	195377	195377	195377	195377
12	158877	158877	158877	158877	158877	158877
13	258775	258775	258775	258775	258775	258775
14	150241	150241	150241	150241	150241	150241
15	113741	113741	113741	113741	113741	113741
16	118593	118593	118593	118593	118593	118593
17	50952	50952	50952	50952	50952	50952
18	287807	287807	287807	287807	287807	287807
19	123571	123571	123571	123571	123571	123571
20	136893	136893	136893	136893	136893	136893
21	53035	53035	53035	53035	53035	53035
22	55423	55423	55423	55423	55423	55423
23	113792	113792	113792	113792	113792	113792
24	99565	99565	99565	99565	99565	99565
25	98745	98745	98745	98745	98745	98745
26	215417	215417	215417	215417	215417	215417
27	29362	29362	29362	29362	29362	29362

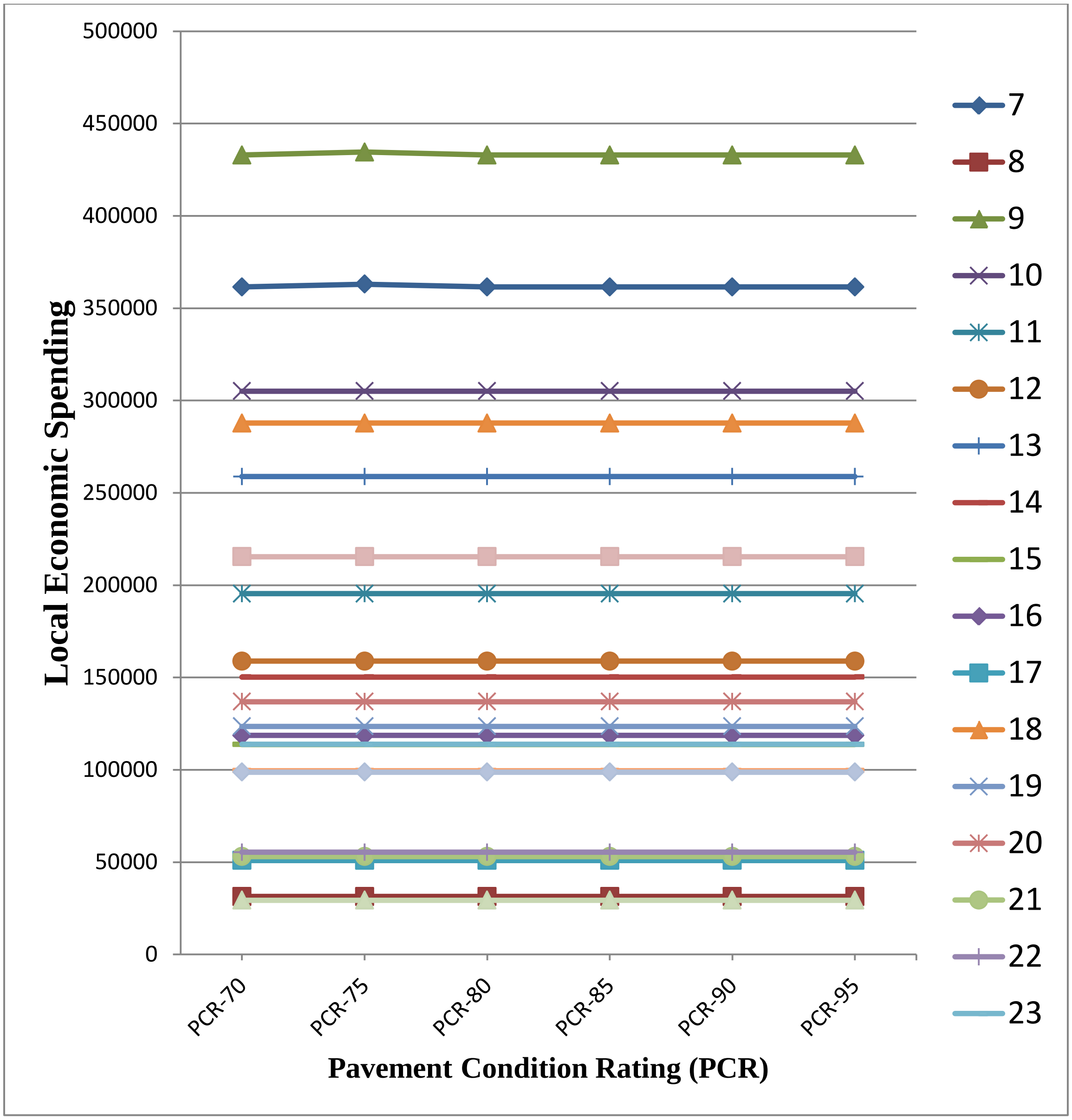

Figure A.1 Local economic spending at zones from varying PCR ($VOTT_{nt}$ = \$6.6/hr., $VOTT_t$ = \$39.6/hr.)

Table A.16 Local economic spending at zones from varying PCR ($VOTT_{nt}$ = $7.8/hr., $VOTT_t$ = $46.8/hr.)

ZONE \ PCR	70	75	80	85	90	95
7	458571	456871	458571	447131	434893	436363
8	42346	42346	42346	78410	79261	75678
9	553609	551796	553609	542152	529805	528394
10	416220	416220	416220	387041	391241	373558
11	266297	266297	266297	269374	272297	259990
12	216548	216548	216548	219050	221427	211419
13	352709	352709	352709	356784	360655	344354
14	204777	204777	204777	207143	209391	199927
15	155028	155028	155028	156820	158521	151356
16	161641	161641	161641	163508	165283	157812
17	69448	69448	69448	70250	71012	67803
18	392279	392279	392279	396812	401117	382988
19	168426	168426	168426	170372	172221	164437
20	186123	186123	186123	227700	230171	219768
21	72287	72287	72287	73122	73915	70574
22	75541	75541	75541	76414	77243	73752
23	155098	155098	155098	156890	158592	151424
24	135585	135585	135585	147574	149176	142433
25	135172	135172	135172	86885	87827	83858
26	293612	293612	293612	297005	300227	286658
27	40021	40021	40021	40483	40922	39073

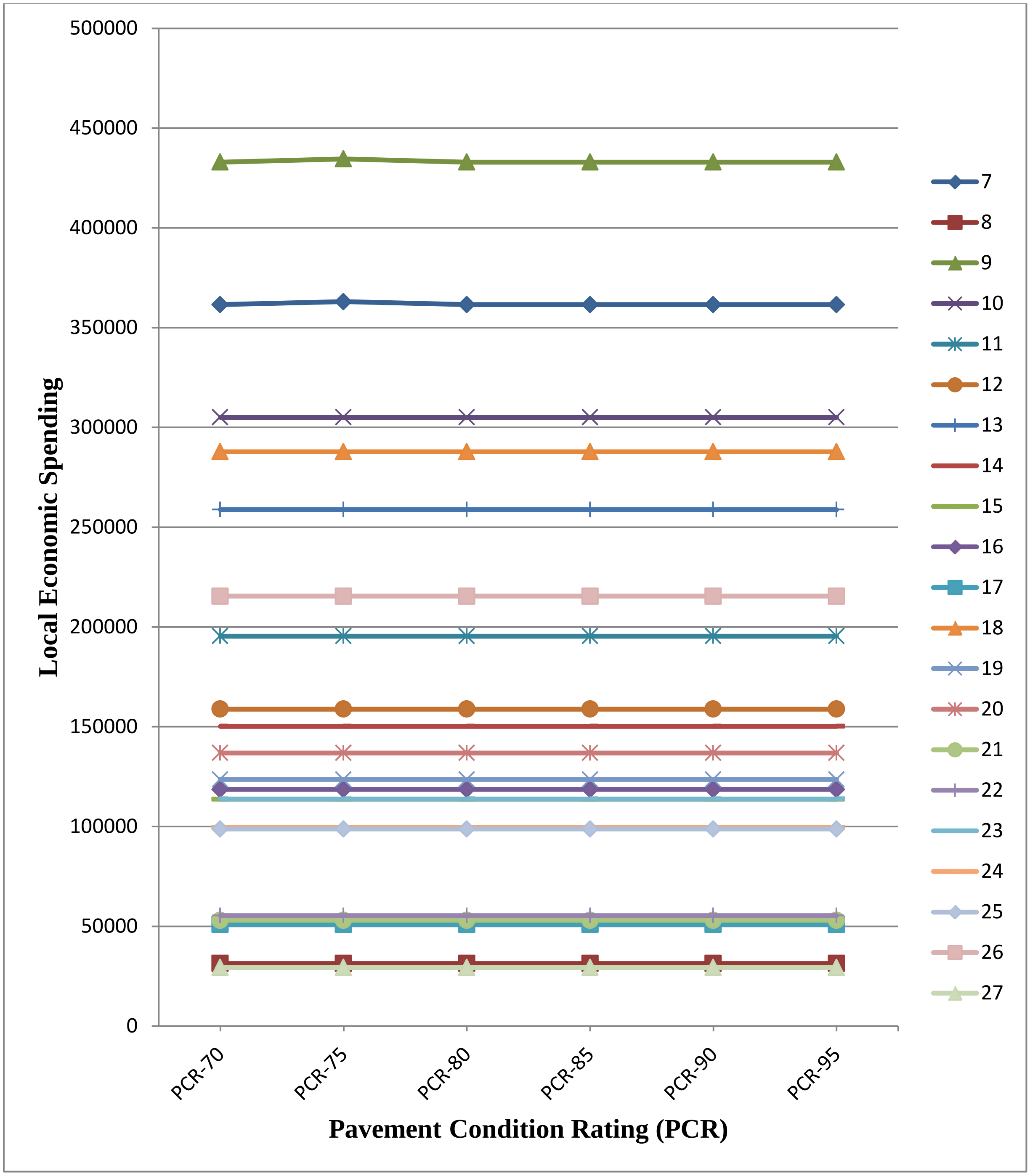

Figure A.2 Local economic spending at zones from varying PCR ($VOTT_{nt}$ = $7.8/hr., $VOTT_t$ = $46.8/hr.)

Table A.17 Local economic spending at zones from varying PCR ($VOTT_{nt}$ = \$10/hr., $VOTT_t$ =\$60/hr.)

ZONE \ PCR	70	75	80	85	90	95
7	538649	551618	551231	542470	509347	539706
8	49408	49408	49408	49408	52317	49408
9	655264	669098	668684	659339	623375	656392
10	524501	524501	524501	524501	517236	524501
11	333371	333371	333371	333371	330756	333371
12	271092	271092	271092	271092	268965	271092
13	441548	441548	441548	441548	438084	441548
14	256356	256356	256356	256356	254345	256356
15	194077	194077	194077	194077	192554	194077
16	202354	202354	202354	202354	200767	202354
17	86940	86940	86940	86940	86258	86940
18	491086	491086	491086	491086	487233	491086
19	210849	210849	210849	210849	209195	210849
20	229009	229009	229009	229009	230866	229009
21	90494	90494	90494	90494	89784	90494
22	94568	94568	94568	94568	93826	94568
23	194163	194163	194163	194163	192640	194163
24	168679	168679	168679	168679	168322	168679
25	174270	174270	174270	174270	168283	174270
26	367567	367567	367567	367567	364683	367567
27	50101	50101	50101	50101	49708	50101

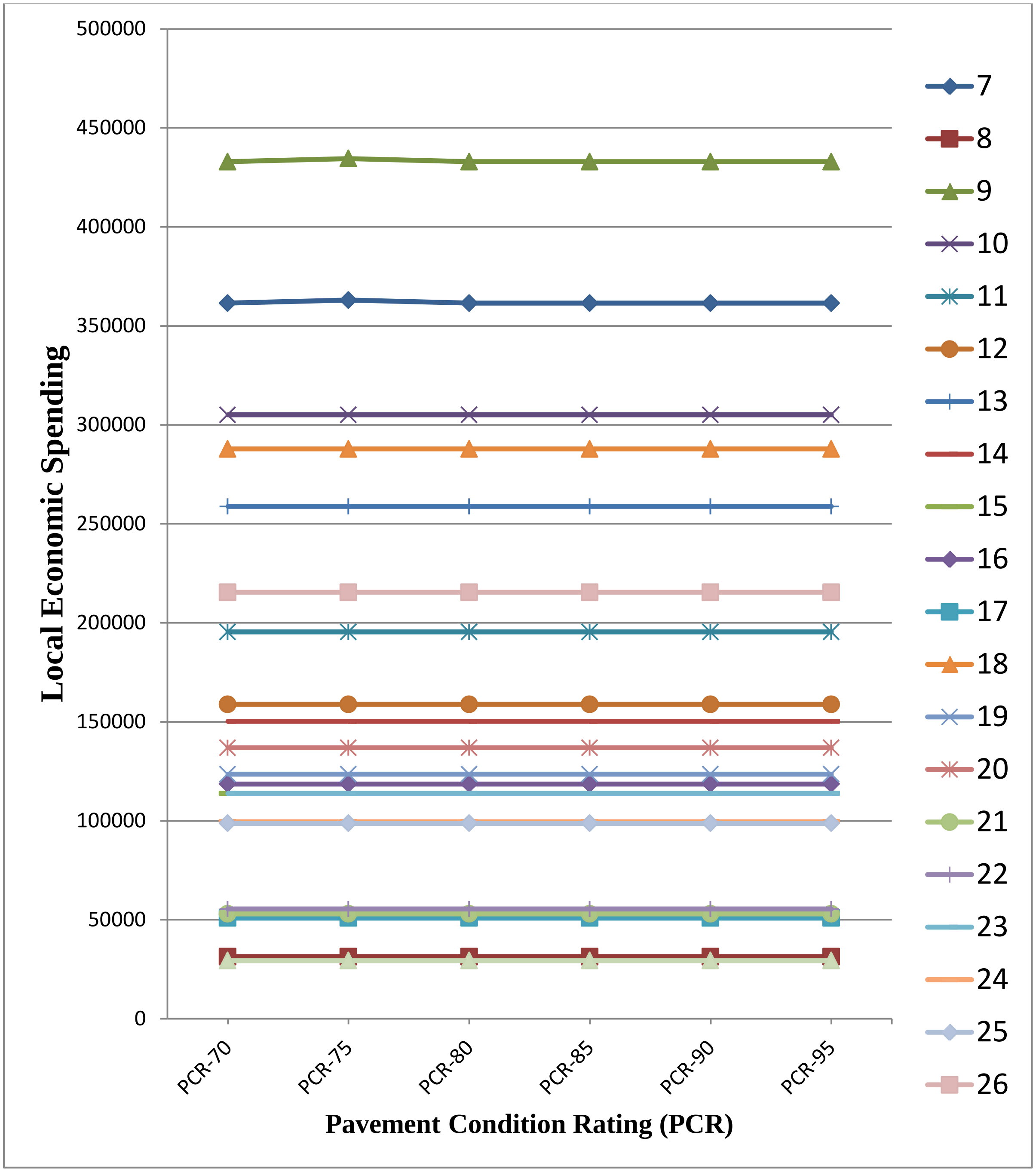

Figure A.3 Local economic spending at zones from varying PCR ($VOTT_{nt}$ = \$10/hr., $VOTT_t$ =\$60/hr.)

Table A.18 Local economic spending at zones from varying PCR ($VOTT_{nt}$ = \$11.6/hr., $VOTT_t$ = \$66.6/hr.)

PCR / ZONE	70	75	80	85	90	95
7	598672	585106	603050	578831	576708	598802
8	103630	102734	103630	102734	56544	103630
9	728152	712937	732822	706243	707517	728290
10	535486	531065	535486	531065	600259	535486
11	369985	366908	369985	366908	381523	369985
12	300866	298364	300866	298364	310248	300866
13	490043	485968	490043	485968	505325	490043
14	284512	282146	284512	282146	293384	284512
15	215392	213601	215392	213601	222109	215392
16	224579	222711	224579	222711	231582	224579
17	96489	95686	96489	95686	99498	96489
18	545021	540489	545021	540489	562018	545021
19	234007	232061	234007	232061	241304	234007
20	308240	305639	308240	305639	262086	308240
21	100433	99598	100433	99598	103565	100433
22	104954	104081	104954	104081	108227	104954
23	215488	213696	215488	213696	222208	215488
24	201502	199816	201502	199816	193043	201502
25	125034	124042	125034	124042	199442	125034
26	407936	404544	407936	404544	420658	407936
27	55604	55141	55604	55141	57338	55604

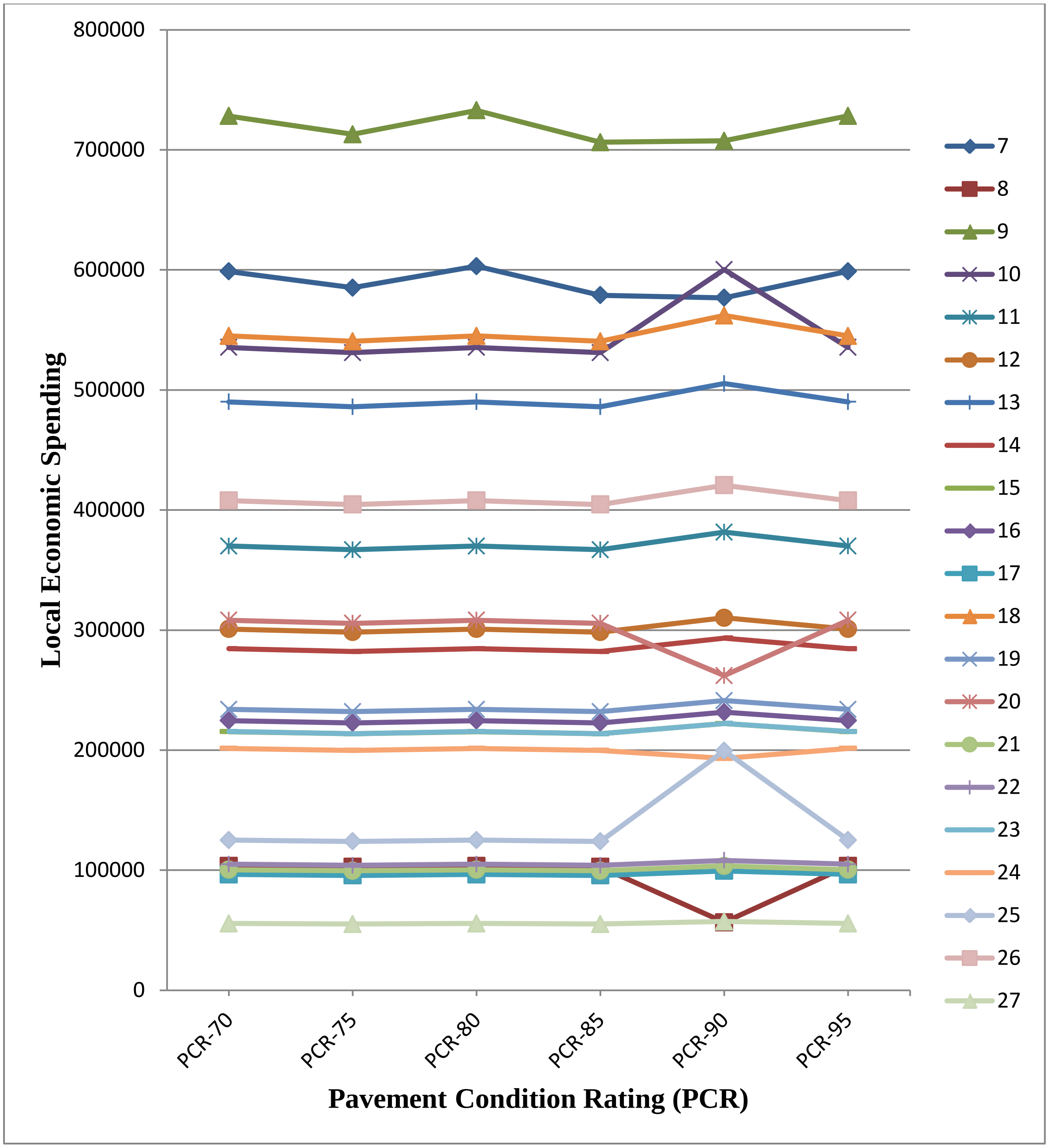

Figure A.4 Local economic spending at zones from varying PCR ($VOTT_{nt}$ = \$11.6/hr., $VOTT_t$ = \$66.6/hr.

Table A.19 Local economic spending at zones from varying PCR ($VOTT_{nt}$ = $12/hr., $VOTT_t$ =$72/hr.)

PCR / ZONE	70	75	80	85	90	95
7	627497	638570	634002	628978	609882	628395
8	112032	112032	112032	58824	112032	110241
9	766161	777972	773100	766996	747372	765629
10	578904	578904	578904	624463	578904	570062
11	399984	399984	399984	396907	399984	393830
12	325260	325260	325260	322758	325260	320256
13	529776	529776	529776	525701	529776	521626
14	307580	307580	307580	305214	307580	302848
15	232856	232856	232856	231065	232856	229274
16	242788	242788	242788	240920	242788	239053
17	104312	104312	104312	103510	104312	102707
18	589212	589212	589212	584680	589212	580147
19	252980	252980	252980	251034	252980	249088
20	333232	333232	333232	272654	333232	328030
21	108576	108576	108576	107741	108576	106906
22	113464	113464	113464	112591	113464	111718
23	232960	232960	232960	231168	232960	229376
24	217840	217840	217840	200827	217840	214469
25	135172	135172	135172	207484	135172	133187
26	441012	441012	441012	437620	441012	434227
27	60112	60112	60112	59650	60112	59187

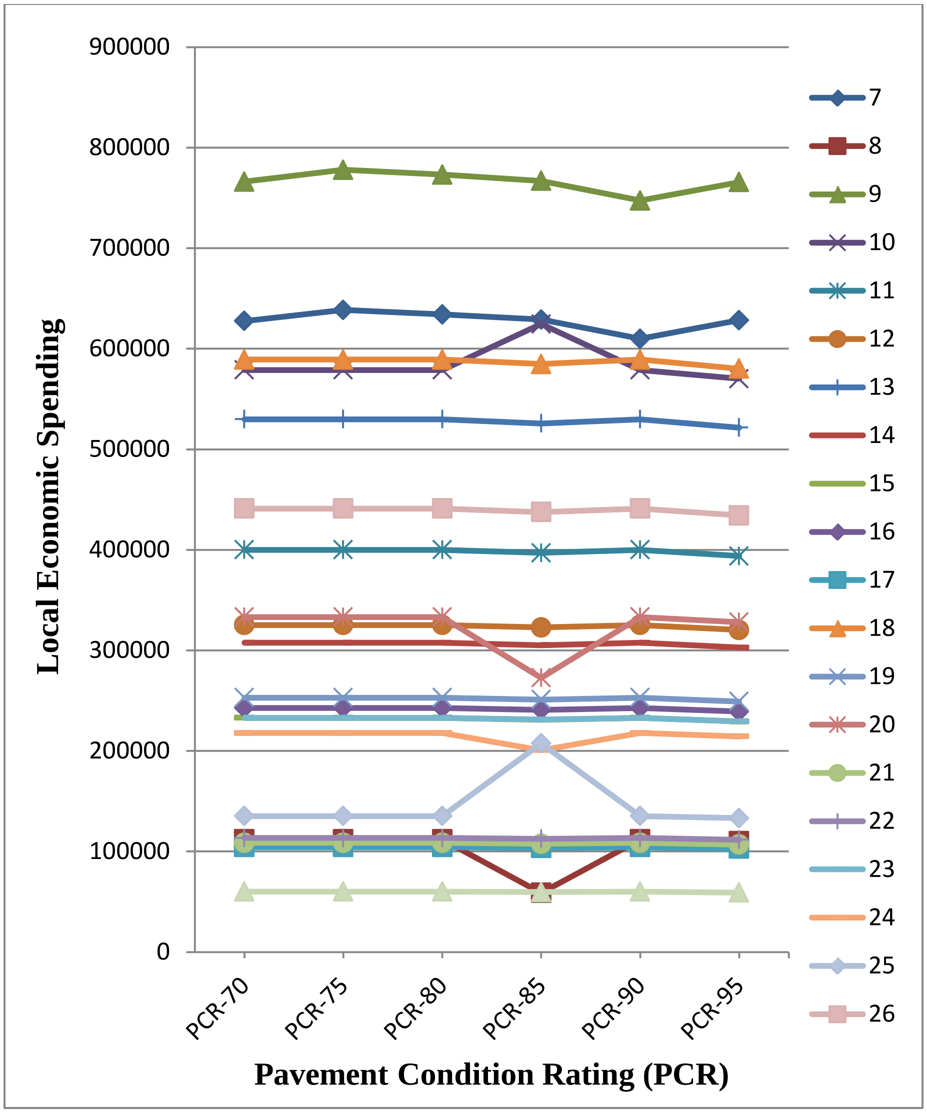

Figure A.5 Local economic spending at zones from varying PCR ($VOTT_{nt}$ = \$12/hr., $VOTT_t$ = \$72/hr.)

Table A.30 Variation of local economic spending at top five cities with different VOTT (PCR-70)

	PCR-70-0.11	PCR-70-0.13	PCR-70-0.167	PCR-70-0.185	PCR-70-0.20
9	**432901**	553609	655264	728152	766161
7	**361503**	458571	538649	598672	627497
10	**305081**	416220	524501	535486	578904
18	**287807**	392279	491086	545021	589212
13	**258775**	352709	441548	490043	529776

Table A.21 Toll and flow on links for car from varying PCR (VOTT$_{nt}$ = $6.6/hr., VOTT$_{t}$ =$39.6/hr.)

		PCR-70		PCR-75		PCR-80		PCR-85		PCR-90		PCR-95	
Link	Class	Toll	Flow	Toll	Flow	Toll	Flow	Toll	Flow	Toll	Flow	Toll	Flow
(1,45)	2	0	536059	0	463403	0	463403	0	463403	0	463403	0	463403
(3,52)	2	0	151807	0	151807	0	151807	0	151807	0	151807	0	151807
(4,12)	2	0	42111	0	42111	0	42111	0	42111	0	42111	0	42111
(6,14)	2	0	1057455	0	1057455	0	1057455	0	1057455	0	1057455	0	1057455
(7,45)	2	0	665144	0	598648	0	778341	0	778341	0	778341	0	778341
(7,26)	2	0	208130	0	141606	0	188526	0	188526	0	188526	0	188526
(8,20)	2	0	325221	0	325221	0	306261	0	306261	0	306261	0	306261
(8,54)	2	0	198293	0	198293	0	178688	0	178688	0	178688	0	178688
(9,43)	2	0	972466	0	972466	0	1074581	0	1074581	0	1074581	0	1074581
(9,45)	2	0	1002106	0	996190	0	1042395	0	1042395	0	1042395	0	1042395
(10,52)	2	0	183841	0	183841	0	183841	0	183841	0	183841	0	183841
(10,24)	2	0	117939	0	117939	0	117939	0	117939	0	117939	0	117939
(11,32)	2	0	1275107	0	1275107	0	1275107	0	1275107	0	1275107	0	1275107
(11,18)	2	0	1211530	0	1211530	0	1211530	0	1211530	0	1211530	0	1211530
(12,24)	2	0	226530	0	226530	0	222353	0	222353	0	222353	0	222353
(13,32)	2	0	1276985	0	1276985	0	1276985	0	1276985	0	1276985	0	1276985
(13,31)	2	0	1294176	0	1294176	0	1294176	0	1294176	0	1294176	0	1294176
(14,31)	2	0	1168756	0	1168756	0	1168756	0	1168756	0	1168756	0	1168756
(18,43)	2	0	1055798	0	1055798	0	1074757	0	1074757	0	1074757	0	1074757
(20,49)	2	0	292530	0	292530	0	273571	0	273571	0	273571	0	273571
(24,54)	2	0	146518	0	146518	0	127559	0	127559	0	127559	0	127559
(26,48)	2	0	388598	0	388598	0	275253	0	275253	0	275253	0	275253
(28,46)	**2**	**80**	**860010**	**83**	**860010**	**80**	**860010**	**80**	**860010**	**80**	**860010**	**80**	**860010**
(45,46)	2	0	860093	0	860093	0	860093	0	860093	0	860093	0	860093
(48,49)	2	0	320916	0	320916	0	301312	0	301312	0	301312	0	301312

Table A.22 Toll and flow on links for semi truck from varying PCR ($VOTT_{nt}$ = $6.6/hr., $VOTT_t$ =$39.6/hr.)

		PCR-70		PCR-75		PCR-80		PCR-85		PCR-90		PCR-95	
Link	Class	Toll	Flow	Toll	Flow	Toll	Flow	Toll	Flow	Toll	Flow	Toll	Flow
(1,45)	1	0	1309125	0	1309125	0	1328426	0	1328426	0	1328426	0	1328426
(3,52)	1	0	629067	0	912192	0	912192	0	912192	0	912192	0	912192
(4,12)	1	0	544143	0	366767	0	366767	0	366767	0	366767	0	366767
(6,14)	1	0	2552964	0	2552964	0	2552964	0	2552964	0	2552964	0	2552964
(7,45)	1	0	1413989	0	434851	0	2209759	0	2209759	0	2209759	0	2209759
(7,26)	1	0	477601	0	1402943	0	807752	0	807752	0	807752	0	807752
(8,20)	1	0	2201138	0	2201138	0	2201097	0	2201097	0	2201097	0	2201097
(8,54)	1	0	1231776	0	1231776	0	1231734	0	1231734	0	1231734	0	1231734
(9,43)	1	0	1692999	0	767657	0	1986371	0	1986371	0	1986371	0	1986371
(9,45)	1	0	2624727	0	1253190	0	2272520	0	2272520	0	2272520	0	2272520
(10,52)	1	0	851772	0	1135084	0	1135084	0	1135084	0	1135084	0	1135084
(10,24)	1	0	295132	0	472508	0	472508	0	472508	0	472508	0	472508
(11,32)	1	0	2999994	0	2999994	0	2999994	0	2999994	0	2999994	0	2999994
(11,18)	1	0	2192417	0	2192417	0	2192417	0	2192417	0	2192417	0	2192417
(12,24)	1	0	1062706	0	1240246	0	1240246	0	1240246	0	1240246	0	1240246
(13,32)	1	0	3000010	0	3000010	0	3000010	0	3000010	0	3000010	0	3000010
(13,31)	1	0	2729136	0	2729136	0	2729136	0	2729136	0	2729136	0	2729136
(14,31)	1	0	2312825	0	2312825	0	2312825	0	2312825	0	2312825	0	2312825
(18,43)	1	0	1986336	0	1986336	0	1986377	0	1986377	0	1986377	0	1986377
(20,49)	1	0	1571782	0	1571782	0	1571741	0	1571741	0	1571741	0	1571741
(24,54)	1	0	540499	0	540499	0	540458	0	540458	0	540458	0	540458
(26,48)	1	0	1635013	0	1688783	0	1169414	0	1169414	0	1169414	0	1169414
(28,46)	**1**	**206**	**2142246**	**205**	**2142246**	**206**	**2142246**	**206**	**2142246**	**206**	**2142246**	**206**	**2142246**
(45,46)	1	0	2142249	0	2142249	0	2142249	0	2142249	0	2142249	0	2142249
(48,49)	1	0	1217157	0	1270921	0	1213733	0	1213733	0	1213733	0	1213733

Table A.23 Summary of Results from varying PCR ($VOTT_{nt}$[1]= $6.6/hour, $VOTT_t$[2] = $39.6/hour)

	PCR-70	PCR-75	PCR-80	PCR-85	PCR-90	PCR-95
Best objective	-8.E+10	-5.E+10	-2.E+11	-2.E+11	-2.E+11	-2.E+11
Revenue	1.E+09	1.E+09	1.E+09	1.E+09	1.E+09	1.E+09
Long-term infrastructure value	-3.E+07	-3.E+07	-2.E+07	-2.E+07	-2.E+07	-2.E+07
Short-term project benefit	2.E+07	3.E+07	2.E+07	2.E+07	2.E+07	2.E+07
In-state TSTC	6.E+08	6.E+08	6.E+08	6.E+08	6.E+08	6.E+08
Out-of-state spending in local economies	1.E+07	1.E+07	1.E+07	1.E+07	1.E+07	1.E+07

Table A.24 Summary of Results from varying PCR ($VOTT_{nt}$ = $7.8/hour, $VOTT_t$ =$46.8/hour)

	PCR-70	PCR-75	PCR-80	PCR-85	PCR-90	PCR-95
Best objective	-8.E+10	-5.E+10	-2.E+11	-6.E+11	-6.E+11	-5.E+11
Revenue	1.E+09	1.E+09	1.E+09	9.E+08	7.E+08	1.E+09
Long-term infrastructure value	-3.E+07	-3.E+07	-2.E+07	-2.E+07	-2.E+07	-2.E+07
Short-term project benefit	2.E+07	3.E+07	2.E+07	1.E+07	1.E+07	2.E+07
In-state TSTC	7.E+08	7.E+08	7.E+08	7.E+08	7.E+08	7.E+08
Out-of-state spending in local economies	2.E+07	2.E+07	2.E+07	2.E+07	2.E+07	2.E+07

Table A.25 Summary of Results from varying PCR ($VOTT_{nt}$ = $10/hour, $VOTT_t$ =$60/hour)

	PCR-70	PCR-75	PCR-80	PCR-85	PCR-90	PCR-95
Best objective	-8.E+10	-5.E+10	-2.E+11	-6.E+11	-6.E+11	-5.E+11
Revenue	1.E+09	1.E+09	1.E+09	9.E+08	7.E+08	1.E+09
Long-term infrastructure value	-3.E+07	-3.E+07	-2.E+07	-2.E+07	-2.E+07	-2.E+07
Short-term project benefit	2.E+07	3.E+07	2.E+07	1.E+07	1.E+07	2.E+07
In-state TSTC	9.E+08	9.E+08	9.E+08	9.E+08	9.E+08	9.E+08
Out-of-state spending in local economies	2.E+07	2.E+07	2.E+07	2.E+07	2.E+07	2.E+07

[1] $VOTT_{nt}$ = Value of travel time for non-trucks
[2] $VOTT_t$ = Value of travel time for trucks only

Table A.26 Summary of Results from varying PCR ($VOTT_{nt}$ = \$11.1/hour, $VOTT_t$ =\$66.6/hour)

	PCR-70	PCR-75	PCR-80	PCR-85	PCR-90	PCR-95
Best objective	-8.E+10	-5.E+10	-2.E+11	-6.E+11	-6.E+11	-5.E+11
Revenue	1.E+09	1.E+09	1.E+09	9.E+08	7.E+08	1.E+09
Long-term infrastructure value	-3.E+07	-3.E+07	-2.E+07	-2.E+07	-2.E+07	-2.E+07
Short-term project benefit	2.E+07	3.E+07	2.E+07	1.E+07	1.E+07	2.E+07
In-state TSTC	1.E+09	1.E+09	1.E+09	1.E+09	1.E+09	1.E+09
Out-of-state spending in local economies	3.E+07	3.E+07	3.E+07	3.E+07	3.E+07	3.E+07

Table A.27 Summary of Results from varying PCR ($VOTT_{nt}$ = \$12/hour, $VOTT_t$ =\$72/hour)

	PCR-70	PCR-75	PCR-80	PCR-85	PCR-90	PCR-95
Best objective	-8.E+10	-5.E+10	-2.E+11	-6.E+11	-6.E+11	-5.E+11
Revenue	1.E+09	1.E+09	1.E+09	9.E+08	7.E+08	1.E+09
Long-term infrastructure value	-3.E+07	-3.E+07	-2.E+07	-2.E+07	-2.E+07	-2.E+07
Short-term project benefit	3.E+07	3.E+07	2.E+07	1.E+07	1.E+07	2.E+07
In-state TSTC	1.E+09	1.E+09	1.E+09	1.E+09	1.E+09	1.E+09
Out-of-state spending in local economies	3.E+07	3.E+07	3.E+07	3.E+07	3.E+07	3.E+07

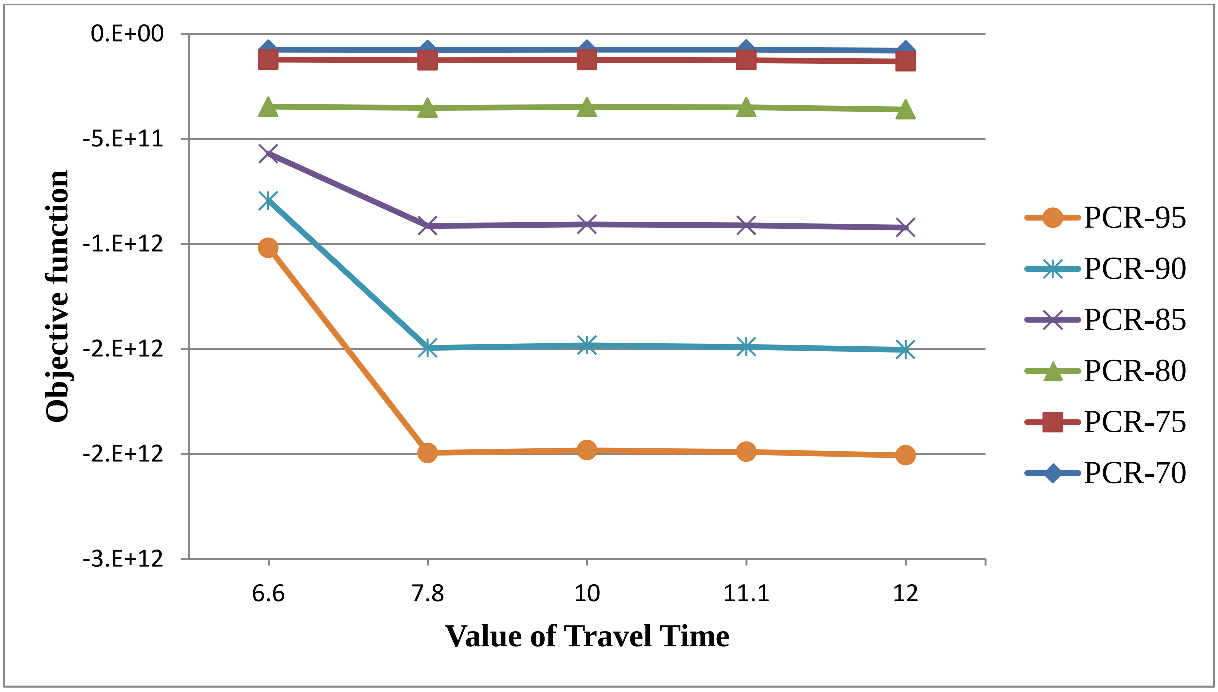

Figure A.6 Objective function as value of travel time and initial PCR vary

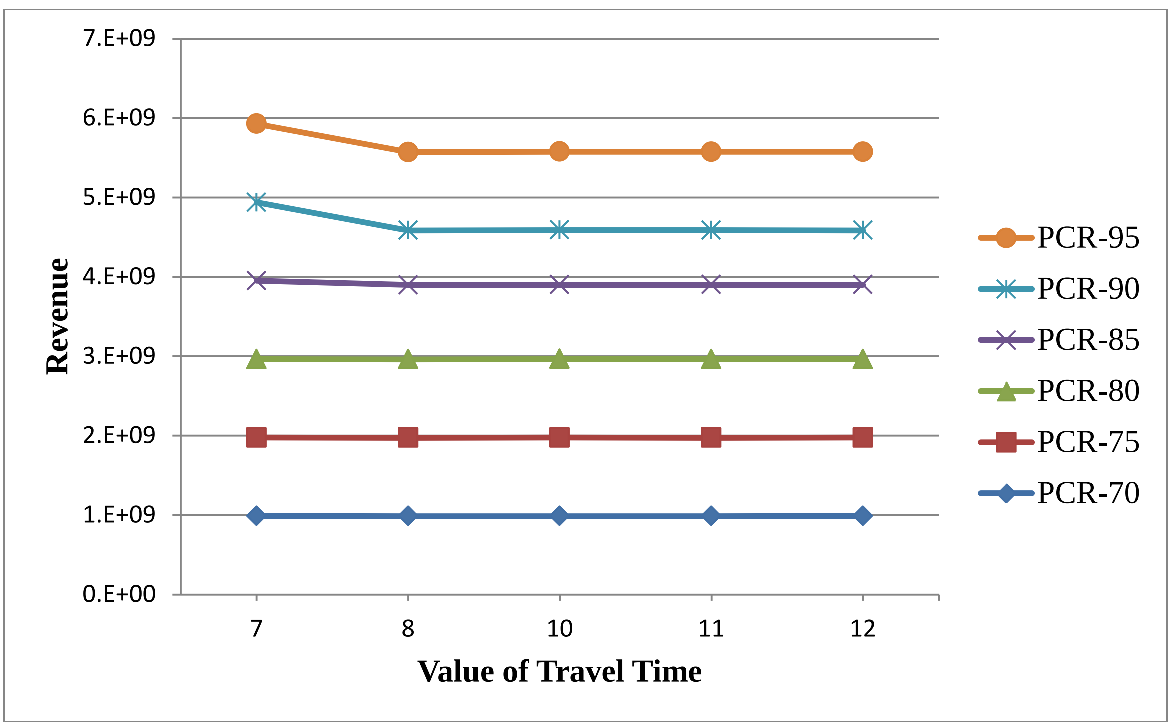

Figure A.7 Revenue as value of travel time and initial PCR vary

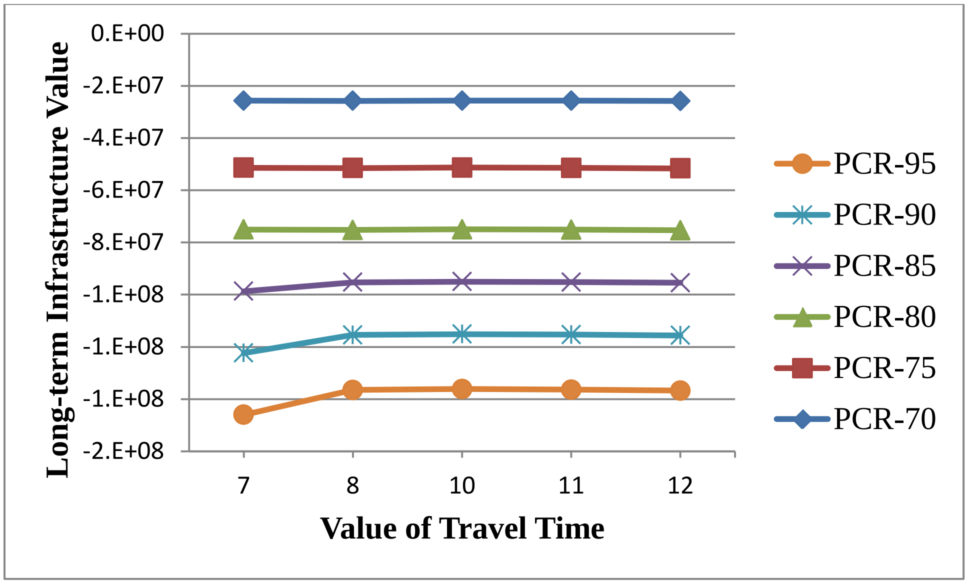

Figure A.8 Long-term infrastructure value as value of travel time and initial PCR vary

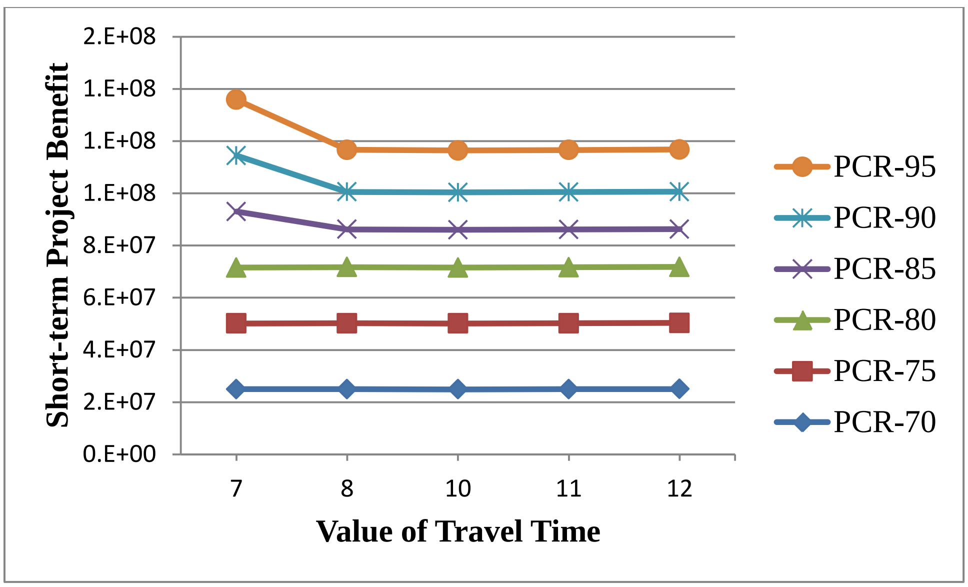

Figure A.9 Short-term project benefit as value of travel time and initial PCR vary

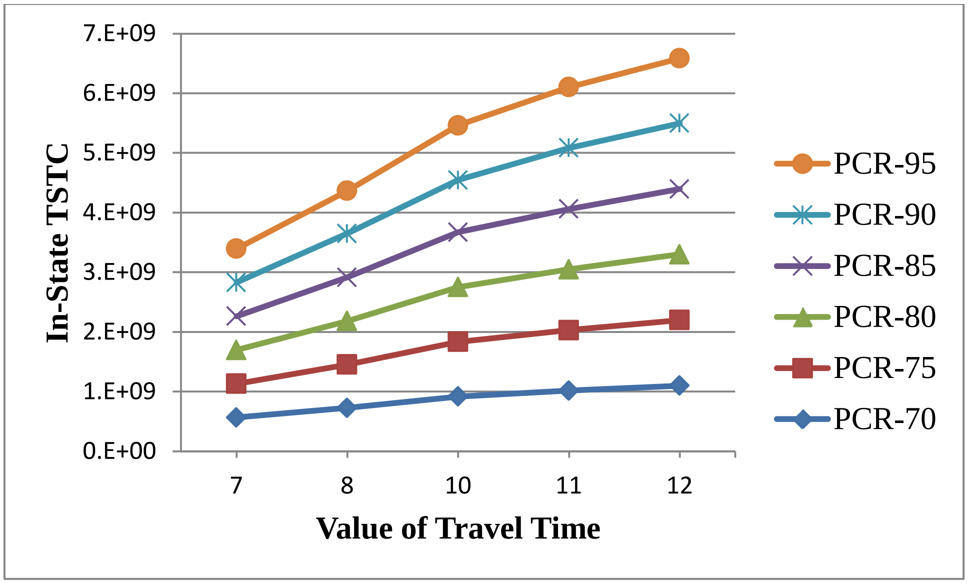

Figure A.10 In state TSTC as value of travel time and initial *PCR* vary

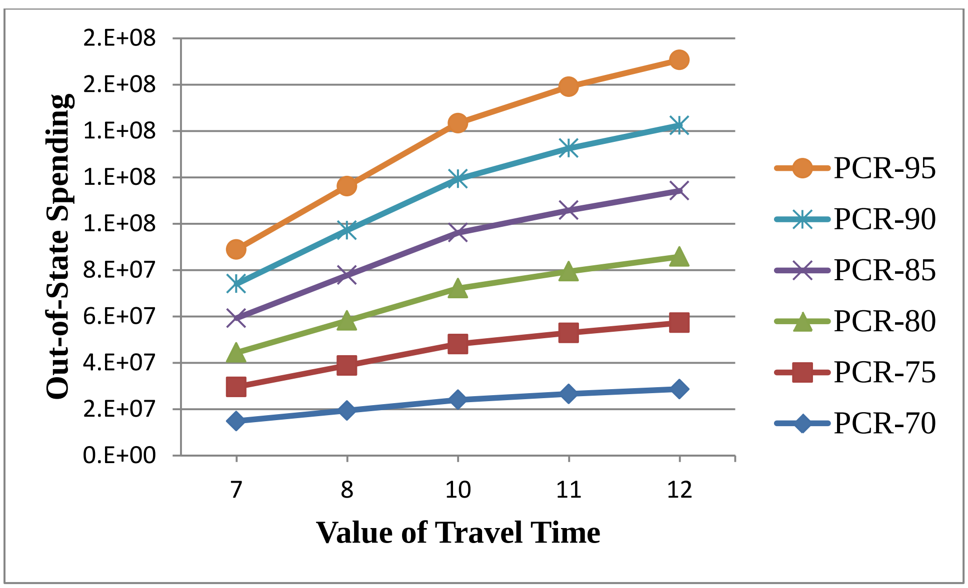

Figure A.11 Out-of-state spending as value of travel time and initial *PCR* vary

Table 5.28 Calculated OD matrix

5665577.935,19295.84071,0,0,22.790235,140909,170047.1534,163298.8823,0,0,0,0,8.64539,21.503975,0,0,0,0,0,0,5.493615,0,0,5.176065,176604.6551,0,1139077.71

19318.0568,867.89919,0,59785.43269,0,0,141087.2599,193423.993,0,44113.10503,0,173069.1822,0,0,0,0,68727.30599,0,0,0,0,205596.5675,0,53786.30583,107894.4796,0,0,34472.27608

0,0,127754.0343,105749.61,0,35,0,209010.2358,70977.61348,32527.24218,0,145711.1591,11.278865,24.13745,0,0,31664.74718,0,12638.33488,288534.74,0,0,0,15308.37339,0,0,0,0

0,59723.68089,105771.7455,383014.4608,0,0,0,242992.4848,88275.55551,59678.71363,0,117600.0873,0,0,0,0,44318.09925,0,0,303908.8046,0,0,0,204848.7186,0,0,0,0

21.856565,0,0,0,1622058.791,0,104004.863,0,28613.72934,0,77153.20068,0,48454.30809,0,325791.9595,0,0,69761.05497,0,0,354224.6083,22775.30103,36412.90662,0,0,0,222102.2642,65525.5227

140855.6564,0,35.463035,0,0,924305,335177.8728,0,81801.64358,35.4342,293227.2983,0,217563.6951,226652.5834,229204.4718,11723.24739,0,244189.5994,28.8642,0,10938.61127,190588.0573,9183.242685,33.896455,0,0,219088.1614,342636.6803

170088.3137,141102.9151,0,0,104564.4357,335274,49916.6116,136564.6109,257241.2493,0,45684.46361,0,95138.8644,83908.58236,114873.541,95238.71161,0,50652.93742,6.5116,0,0,4.80413,41.947625,0,115337.1198,340994.5694,0,7509.598695

163330.5997,193422.8962,209018.6994,242980.1441,0,0,136543.273,79467.30798,336945.4459,185503.2598,0,0,0,0,0,0,0,0,0,554457.0982,0,199193.798,0,0,0,322.42859,0,76423.85184

0,0,70984.42182,88267.34082,25438.58412,81225,257540.1569,336944.9871,12222.29802,64242.76889,5901.524035,0,16782.11381,727.270895,10224.86436,16758.93011,0,16099.77077,2.16883,0,3.16601,169136.8697,222.543785,0,77474.43061,553337.9527,0,174716.5345

0,44042.46585,32532.57301,59666.79273,0,35,0,185498.7217,64240.1471,17261.95778,0,138891.7261,11.25514,24.11409,0,0,30042.00646,0,18451.49606,287487.3408,0,0,0,14443.55224,0,0,0,0

0,0,0,0,77520.79729,293092,45488.22647,0,6361.553245,0,7943.82715,0,59976.07767,56496.97651,15096.85844,72400.19915,0,7.189405,0,0,0,37.53368,44.00951,0,0,0,92389.21866,43.52114

0,173079.7957,145798.7029,117551.8974,0,0,0,0,0,138973.6011,0,7434.93685,0,0,0,0,0,0,0,174150.1056,0,0,0,120164.7594,65223.96445,0,0,0

7.9424,0,11.72088,0,48874.88408,217469,95004.11005,0,16644.11899,11.692045,60014.53297,0,2991.26041,12.858585,33318.06177,126525.636,0,46486.87487,5.122045,0,6.119225,17089.33504,168.420125,10.1543,0,0,133813.1625,7789.105475

20.687105,0,24.46522,0,0,226794,84025.58931,0,676.98083,24.43675,56771.24371,0,12.744705,3100.81297,25856.43028,0,0,43610.95628,17.866385,0,18.863565,6110.814305,53.30241,22.899005,0,0,0,76.87046

0,0,0,0,325478.561,230018,115490.161,0,7886.496235,0,14964.34081,0,32643.0242,26528.49456,2147.001175,374012.9227,0,66191.48017,548457.725,0,0,37575.386,5.891465,0,0,0,0,28275.15643

0,0,0,0,0,11807,95235.50143,0,16229.78705,0,72592.34939,0,126679.2634,0,374389.0374,2391.09091,0,60176.79336,0,0,171699.5263,17320.72643,90789.24408,0,0,0,16175.41848,8020.49686

0,68727.37388,31741.05043,44308.79613,0,0,0,0,0,30113.12196,0,0,0,0,0,0,2121.710325,0,0,69672.86586,486416.24,0,463252.9312,17751.71332,0,0,0,0

0,0,0,0,70390.42849,244330,50719.6492,0,15949.6835,0,7.388695,0,46723.22405,43611.57715,65641.27041,60259.60821,0,1347.381075,0,0,0,1532.977735,13.84883,0,0,0,0,464.789175

0,0,12235.20442,0,0,29,5.3217,0,1.13004,18039.89359,0,0,4.896475,17.755425,548711.869,0,0,0,1079.62766,0,347620.0852,8.09716,277785.571,15106.27617,1.28699,0,0,14.08462

0,0,288540.2818,303900.6889,0,0,0,554454.941,0,287488.1854,0,174180.5736,0,0,0,0,69713.8831,0,0,804.37824,0,0,0,54754.67894,258.20319,0,0,0

0,0,0,0,354222.6976,11516,0,0,2.13014,0,0,0,5.89694,18.75589,0,171652.4435,486273.6207,0,347141.8414,0,767.688805,0,108958.9999,0,0,0,197006.4527,0

5.47646,205608.3197,0,0,23356.17517,190694,5.2195,199194.6467,168834.2883,0,38.312955,0,17220.15725,5989.875205,36954.8338,17320.00446,0,1746.87905,9.337065,0,0,584.59276,0,0,181531.378,154875.3174,0,11.588385

0,0,0,0,36787.57036,7950,41.115425,0,176.931925,0,44.20515,0,186.65954,53.54915,5.746195,91098.82503,463184.1652,13.54661,278220.7905,0,108962.0838,0,561.763105,0,0,0,169818.8572,49.878345

0,53900.1194,15498.07739,204903.9362,0,34,0,0,0,14628.26925,0,120268.0482,9.67688,22.53583,0,0,17866.98579,0,14378.38733,54827.40373,0,0,0,569.56206,0,0,0,0

5.156355,107895.3826,0,0,0,0,115337.3392,0,77474.37842,0,0,65214.32297,0,0,0,0,0,0,1.082955,257.672845,0,181535.4937,0,0,271.45415,0,0,3378.479785

176616.4194,0,0,0,0,0,340977.7112,321.997525,553339.427,0,0,0,0,0,0,0,0,0,0,0,154875.8484,0,0,0,198.538465,0,253762.7066

0,0,0,0,222041.6417,219026,0,0,0,0,92525.57244,0,133909.8298,0,0,16117.2258,0,0,0,0,196995.3315,0,169734.336,0,0,0,496530.3492,0

1138971.569,34468.01215,0,0,66136.74915,342685,7496.110485,76433.4528,174413.9484,0,44.436195,0,7903.965865,78.22972,27638.64279,8003.813075,0,752.319385,15.460305,0,0,11.724165,50.89633,0,3382.382365,253759.6709,0,2284554.059

1416394.484,0,0,0,0,72656,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,463403.4525

0,216.97498,0.01606,17371.42602,0,0,73.129575,21510.83591,28935.12644,0.047815,0,20112.75998,0,0,57.940465,0,0,0,0,0,0,53500.78276,14.42115,11.324125,17267.01157,0,0,0
0,380.03216,31938.5085,47716.39416,11585.2387,4572,0,2106.31353,15058.13158,7840.368265,99.916195,32127.17773,172.913275,231.52242,132.95271,109.880695,0,0,1411.003495,6939.66543,0,8508.03393,19.757085,12796.02364,0,0,0,0
0,17396.0763,47356.43152,95753.61528,8532.64588,545,0,31963.84242,29981.48143,38194.89429,88.425995,14718.2381,116.401785,131.283565,51.786565,0,0,0,91.723405,21863.01492,0,9219.95986,8.26725,26359.78061,0,0,0,0
0,0,11349.4936,8580.89669,405514.6978,0,38653.59928,0,24203.28432,4203.74296,21180.53171,0,13014.88202,0,16529.57506,18338.56397,0,29325.9396,0,0,17331.48298,0,17514.65932,0,0,0,19596.16161,0
72411.912,0,7661.00106,1577.23143,0,231076,172228.1455,0,75718.70871,478.736555,108966.4255,0,104855.0085,80025.48971,8732.480095,22072.34205,0,115013.9809,4131.1284,0,12886.95353,76775.23771,9717.56436,0,0,0,19169.37186,165033.3134
0,46.598455,0,0,38557.59954,172758,12479.1529,10135.59631,92580.83636,0,59287.73731,0,56960.68966,83072.04543,13740.86556,29871.54708,3801.00196,42301.81078,9516.670915,0,0,0,14961.17371,0,0,111865.8997,842.097705,0
0,21485.24576,1849.132705,32071.89556,0,0,10162.95963,19866.827,68019.4144,0,0,0,0,0,29.32045,29.66428,0,0,47.697835,54154.71712,0,24879.78846,0,0,17144.10329,0,0,0
0,28925.58351,14715.41191,29997.2184,24121.24291,76272,92602.98018,68037.04463,3055.574505,7533.147035,5692.721405,49283.00153,12244.01443,955.11667,0,7011.111625,0,233.685775,0,11929.87827,0,11196.70387,0,26241.29942,20390.36657,248298.6365,0,62837.54006
0,0,7182.26487,37898.096,3782.57603,1423,0,0,7217.76331,4315.489535,94.53208,32124.72566,137.830205,196.43935,97.86964,74.797625,0,0,691.013255,1081.118685,0,0,14.373335,8193.480945,0,0,0,0
0,0,0,0,21214.09894,109647,59436.47809,0,5821.972285,0,1985.95697,0,8033.190465,26224.92187,0,2525.866795,0,16351.82079,0,0,0,0,0,0,0,0,25823.96937
0,19893.63333,31521.6993,14398.77441,0,311,0,0,49352.98408,32177.1444,81.296085,1858.734395,109.271875,124.153655,44.656655,0,0,68.5032,63.03404,37386.60581,0,0,1.13734,22987.43392,2673.39067,0,0,0
0,0,0,0,13180.90847,105686,57259.01073,0,12509.93627,0,8165.649695,0,747.81492,26971.53886,0,10691.51649,0,16311.05795,0,0,0,0,0,0,0,0,21870.56385
0,0,0,0,0,80972,83485.76745,0,431.867635,0,26490.06809,0,27086.94492,775.203425,0,0,0,41506.9762,0,0,0,5760.447155,0,0,0,0,0,47805.6425
0,0,0,0,16701.22543,7921,13938.32216,0,39.58863,0,36.63943,0,64.61522,98.56971,536.750385,1135.565005,0,23.84618,4760.38402,0,4154.473435,9.10018,1238.68298,0,0,0,0,8.34974
0,0,0,0,18368.46002,22122,30005.10058,0,7128.30838,0,2511.38177,0,10544.57224,0,989.60917,597.77291,0,10656.79003,0,0,0,0,1974.6938,0,0,0,0,0
0,0,0,0,0,408,3494.946905,0,54.02292,0,61.59229,0,89.56808,104.44986,24.95286,0,530.42749,48.79904,69.705145,0,14570.51457,0,21119.62964,0,0,0,0,33.3026
0,0,0,0,29253.81524,115583,42337.9644,0,241.198935,0,16239.47087,0,16072.90677,41129.52641,0,10565.5831,0,336.84536,0,0,3490.21541,0,320.82624,0,0,0,0,6699.584855
0,0,3529.873025,0,0,3161,9552.89169,0,10.69304,103.78921,18.262045,0,46.237835,61.119615,4601.35206,0,0,5.468795,269.906915,0,8755.825495,0,5586.436325,0,0,0,0,0
0,0,6623.280875,21905.08737,0,0,0,54162.0653,11919.46993,1344.737745,0,37306.29887,0,0,49.442535,0,0,0,0,201.09456,0,0,5.922855,14630.62387,63.485545,0,0,0
0,0,0,0,17541.83248,11866,0,0,170.175775,0,72.43206,0,170.54771,229.15649,3944.556825,0,14866.31933,3434.770085,8704.94121,0,191.92211,0,36850.68908,0,0,0,12236.64435,0
0,53503.31257,8275.854875,9249.553695,21.80145,77216,0,24873.63785,11082.61472,0,0,0,18.122615,5254.9196,0,0,0,0,0,0,0,146.14819,0,0,25813.11682,8060.266165,0,0
0,0,0,0,17305.88516,8526,14782.04266,0,206.307855,0,80.158745,0,206.67979,265.288935,1223.112445,1740.224735,21293.69412,134.03895,5365.04375,0,37050.42365,0,140.440685,0,0,0,11055.67553,51.869055
0,0,12089.71944,25938.19904,0,990,0,0,26209.96307,8144.56766,87.62409,22886.21321,115.59988,136.56548,50.98466,51.328125,0,74.83084,258.273635,14609.68601,0,0,7.465345,142.390515,0,0,0,0
0,17230.13087,0,0,0,0,0,17037.40868,20344.14151,0,0,2855.65342,0,0,47.568625,47.91209,0,0,65.94601,63.39466,0,25621.63709,4.04931,0,67.863355,0,0,0
0,0,0,0,0,0,111891.0303,0,248308.7503,0,0,0,0,0,0,0,0,0,0,0,0,0,8064.184075,0,0,0,49.634525,0,66495.74745
0,0,0,0,19473.03397,19083,682.24413,0,50.824425,0,0,0,26.253355,0,21.754365,0,0,45.600545,40.131385,0,12087.2389,0,11031.45048,0,0,0,124132.5872,30.104105
463391.2257,0,0,0,21.206135,165618,0,0,62882.00984,0,25742.41632,0,21640.08934,47459.82179,0,0,0,6731.544255,0,0,0,0,0,0,0,66524.07109,0,571138.5147