A system dynamics approach to study the state of U.S. roads: validation of dynamic hypothesis

By

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Abstract

The United States of America which has the world's biggest road network, is falling behind when it comes to the condition of roads. The 2021 Report Card for America's Infrastructure found the nation's road infrastructure earns a cumulative grade of a 'D'. Between 2000 and 2020, the percentage of roads nationwide in poor condition increased from 9% to over 22%. As the maintenance and rehabilitation needs grow, the challenge is that there is a gap between available funding for maintenance and the required cost of maintenance. Hence there has been an increasingly increasing backlog of deferred road maintenance.

To study the problem, the system dynamics model of National highway system, following ageing-chain has been constructed. By making explicit the key feedback structure behind the ageing-chain-maintenance needs-maintenance budgeting system, the model reveals the reinforcing mechanisms caused by the rapid growth of new roads in early 50's led to increase in the need of maintenance activities. During the 1950s and 1960s, U.S. investment in its infrastructure rose sharply, in part to meet the increased demands of the baby boom generation. Initiatives such as the interstate highway system also accounted for consistent increases in roads infrastructure spending. Since the 1970s there has been a decline in funding that supports the infrastructure of the United States. The decline in federal infrastructure funding continued during the 1980s as most of the wealth of the United States was devoted to consumption rather than to the enhancement of the nation's infrastructure. This declining funding caused to build lesser new roads and thus increasing the average age of US roads. The increasing average age caused an increase in maintenance demand and thus locking the road system into vicious poor maintenance cycle in USA.

The model provides a simulation environment to examine the deteriorating condition of road, the increasing gap in maintenance funding and analyze how deferred maintenance affects road network performance in the long-term (National Research Council, 1979; Hunt P. et. al, 2001) The simulation shows that in base case scenario, given that the GDP grows as it has over past few years, the system will continue to increase the fraction of poor roads and will peak to 26% in 2030 and then slowly fall to 22% in 2050.

Chapter 1. Introduction

The United States of America which has the world's biggest road network, is falling behind when it comes to the condition of roads. The 2021 Report Card for America's Infrastructure found the nation's road infrastructure earns a cumulative grade of a 'D'. Between 2000 and 2020, the percentage of roads nationwide in poor condition increased from 9% to over 22%. As the maintenance and rehabilitation needs grow, the challenge is that there is a gap between available funding for maintenance and the required cost of maintenance. Hence there has been an increasingly increasing backlog of deferred road maintenance.

Road infrastructure is one of the basic facilities that serve social and economic purposes in a country. It is associated with the development capacity and competitiveness of any region, as it facilitates the transport of goods and passengers, and ensures access to basic services, which are necessary conditions in the modern economy (Schwab, K., 2018). The deterioration of this type of infrastructure significantly affects economic activities, the environment, and quality of life of all the inhabitants of a country. For these reasons, an efficient infrastructure network must be a priority for governments.

The road system in the United States has evolved over time to a complex network of physical structures that include roads, bridges, and overpasses, all designed to carry an enormous amount of traffic. The system has been created and continues to be changed and maintained by an equally complex set of human systems, centered on a hierarchy of governmental agencies with their associated financial support. The road system provides unlimited access for millions of Americans. The current network of highways connects their communities and support their economy. Running from coast to coast, through beautiful rural landscapes and great cities, the National Highway System (NHS) is comprised of over 4 million miles of road carrying people and goods to their destinations every day.

1.1 Brief history of U.S. road system

A large and extensive road system co-evolved in the United States when cars became a major mode of transportation in the early twentieth century. The pattern of the system mirrored land uses and transportation corridors of the nineteenth century. Roads were narrow, primarily composed of dirt and gravel, and for the most part, followed existing topography. Before 1900, only 4% of the roads were paved, leading to poor and unreliable traveling conditions. Yet this system formed the template for the current system.

There was no national system of freeways, however, until 1956, when the U.S. Congress enacted a plan to build and finance the National System of Interstate and Defense Highways, now known as the interstate highway system, to serve auto, truck, and strategic military needs. The interstate system was to be 42,500 miles of four-lane (and higher) divided highways with limited access throughout. Standard vertical and horizontal clearances were designed to support military vehicles, such as trucks carrying tanks. The federal government would pay 90% of the cost (Forman, R. et. al., 2003). The interstate highway system was considered complete in 1990 and could be enlarged only if a state used its own funds to build a road to interstate standards and then petitioned the federal government to have the route added.

The National Highway System Designation Act of 1995 was signed into law by President Bill Clinton on November 28, 1995 and designated about 160,955 miles (259,032 km) of roads, including the Interstate Highway System, as the National Highway System (NHS).

The NHS became network of strategic highways within the United States, including the Interstate Highway System and other roads serving major airports, ports, military bases, rail or truck terminals, railway stations, pipeline terminals and other strategic transport facilities. Altogether, it constitutes the largest highway system in the world.

The historical context for roads is an important consideration because history affects the current maintenance effects of roads. For example, the designers of a modern interstate highway would be more likely to be sensitive to the hydrological and ecological effects of the project than the designers of a two-lane rural road built with county funds or 50 years ago without federal review. In addition, ecological impacts, environmental mitigation, and simple scale of the road surface area vary widely by road type. For example, depending on the scale of concern, an eight-lane interstate highway connecting major cities would have much greater fragmenting effects than a two-lane rural road.

We provide this brief historical overview for three reasons:

(1) to show that the layout of the current road system is unlikely to change dramatically and that most development will be done along the current spatial template;
(2) to show that the road system has been developing and also aging over the
(3) to show that increased maintenance is required because of the aging road system.

As we point out later, maintenance provides opportunities for mitigating or reducing the adverse ecological effects of roads, and such opportunities should be taken advantage of.

1.2 Problem Description and Problem Definition

The U.S. population has more than doubled since the 1960s, when most of the country's major infrastructure systems were built. Many are reaching the end of their lifespan, and are dangerously overstretched, references say.

The American Society of Civil Engineers. (2021) has compiled regular "report cards" on the state of U.S. infrastructure since the 1980s. In its 2021 report, the ASCE found that the nation's road infrastructure averaged a 'D,' meaning that conditions were mostly below standard, exhibiting significant deterioration with a strong risk of failure.

These roadways are expected to withstand an ever-increasing volume of traffic each year, with vehicle miles traveled reaching more than 3.2 trillion in 2019, an 18% increase from 2000. Unfortunately, the growing wear and tear to the USA's roads has left more than 23% of the public roadways in poor condition, a number that has increased gradually over the past several years.

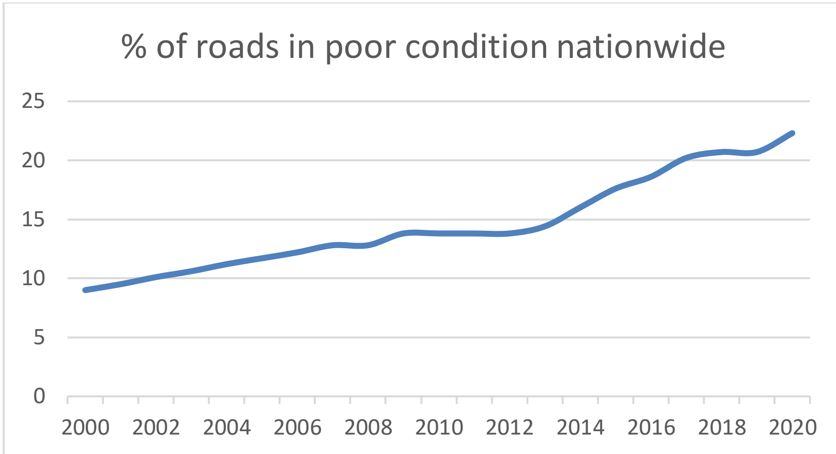

Figure 1: Percentage of roads in poor condition nationwide

Source: Report Priorities (2019)

Overall, our deteriorating roads are forcing the nation's motorists to spend nearly $130 billion each year on extra vehicle repairs and operating costs. Even more troubling is that the share of roads in "poor" condition has risen from 13% to more than 22% over the last decade

The report also highlighted the fact that U.S. has been underfunding its roadway system for years, resulting in a $786 billion backlog of road and bridge capital needs. The bulk of the backlog ($435 billion) is in repairing existing roads, while $125 billion is needed for bridge repair, $120 billion for system expansion, and $105 billion for system enhancement (which includes safety enhancements, operational improvements, and environmental projects). However, in 2017, federal, state, and local governments spent $177 billion on roads and bridges, with an increasing focus on operations and maintenance needs. Note that bridge maintenance is outside scope of this thesis as it pertains to roads only.

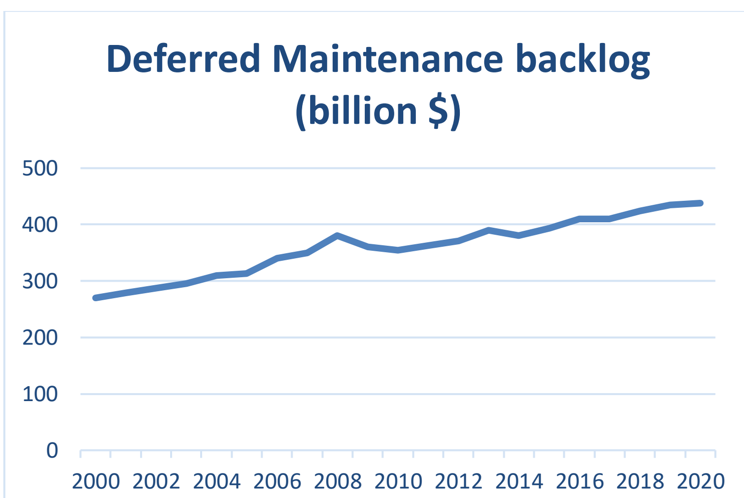

Figure 2: Deferred maintenance backlog (billion $)

Source: Report Priorities (2019)

Roads in poor condition directly impact the lives of citizens by increasing wear and tear on vehicles, driving up repair costs, inflating travel times, and sometimes introducing new safety concerns. For freight users, poor conditions can increase the cost of doing business and delay the delivery of millions of tons of goods and agricultural products across the country. Trucks transport the majority of U.S. freight, so keeping the roads in good condition is critical to America's competitiveness. Below graph shows the roads lifecycle curve, according to Kahn, M. E., & Levinson, D. M. (2011), the cost of maintenance rises to 2-folds (4 times) when the age of infrastructure rises by 1-fold (2 times).

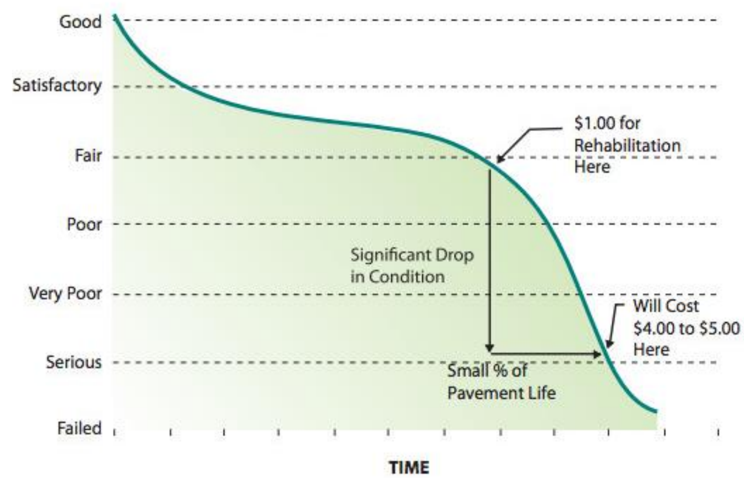

Figure 3: Typical pavement lifecycle curve

Source: Kahn, M. E., & Levinson, D. M. (2011)

1.3 Research Objectives and Research Questions

In accordance with the problem definition in the previous section, the research objectives and corresponding research questions have been formulated. To address the defined problem, the research project was designed to follow below objectives.

The first objective is to investigate the construction and degradation of public roads in the U.S. and the factors underlying the dynamics of ageing of road infrastructure and factors influencing the budgeting for the new construction and maintenance of road infrastructure. A model and simulation-based analysis allows this research a comprehensive causal representation of the fundamental characteristics of the road infrastructure, for which there is a construction of new roads and maintenance of existing roads based on budget allocation. The model explains how maintenance backlog has soared in recent years.

Based on the model, it becomes realistic to achieve the second research objective: to validate the underlying theories (hypothesis) around the causes of increasing maintenance backlog and decreasing quality of roads in the U.S. and develop robust strategies to facilitate the interaction of road infrastructure variable so that the conditions of US roads starts improving.

To fulfill the stated research objectives, the following research questions were formulated for the project to answer:

1. What are the fundamental characteristics and elements of the roads infrastructure including the ageing and deterioration of roads and funding as the factor determining maintenance and construction of new roads ?
2. What are the causal relationships between the factors affecting funding strategies and reporting of issue of under funding on maintenance?
3. What are the reasons explaining the currently observed inability of the government to satisfy the demand of maintenance need generated by the expanding roads infrastructure?
4. What are the core uncertainties, associated with economic aspects of road maintenance that potentially may cause a significant impact on our assessment of the related economics?
5. What could be the robust policies with regard to closing the gap between funding of maintenance and the desired maintenance needs?

   Questions 1-3 are steered to fulfilling our first research objective, while questions 4-5 are addressing our second research objective.

1.4 Research Strategy

The method employed in this study is quantitative system dynamics modeling and simulation-based analysis. This allows us to represent, explicitly, coherently and consistently, relevant hypotheses and, eventually, theories by way of simulation models. In that way, it is possible to facilitate a variety of formal analyses that enhance our understanding of the condition of roads in USA and allow us to formulate and assess the impact of strategies and policies intended to improve the condition of roads in US and reduce or at the least stabilize the ever-growing deferred maintenance backlog.

1.5 Literature Review and Research

As it was mentioned in paragraph 1.3, the backbone of the quantitative and qualitative data for the constructed system dynamics model was obtained from the extensive analysis of the documents and literature related to the defined problem. This section provides an overview of the literature employed throughout the research project. We would like to note here that publicly available sometimes served as both sources of literature (to form an understanding of perspectives on the issue) and sources of data (provided estimations, structural knowledge, etc.). This study draws reference from Sustainable Decision-Making in Road Development: Analysis of Road Preservation Policies (Ruiz, A., et. al., 2020) to understand fundamental characteristics and elements of the road's infrastructure. The literature talks about the deterioration phenomena of road networks, different types of activities related to road preservation (construction, maintenance, and rehabilitation), as well as costs associated with them. In addition, the available budget constraint was added to the formulation of the road deterioration model, which means that the variables associated with construction and maintenance rates change from exogenous parameters to variables directly depending on the budget namely GDP and share of GDP spent on road system.

Conceptually, there are three parts to the literature review process; first one relates to the road ageing chain. This is to understand about the construction and deterioration of roads over period of time. Population models using aging chains are a common part of many system dynamics models. When modelling city dynamics, Forrester, J. W. (1969) uses three simple aging chains for human population (with respect to employment, not age), commercial sphere and housing development. Each chain is composed of three stages following one another. In the project "Limits to Growth", Meadows, D. H. et. al, (2005) enhance an older Forrester's model of the world population and use a population model with four age groups. In this model, however, the condition of road is tracked in a ageing chain composed of five stages with respect to average age of roads in different condition based on Sterman,, J. D., (2000) and Ruiz, A. et. al., (2020).

Typically, the outflow of items from the stocks in these chains depends on the age of road. For instance, the rate at which good roads become fair, fair roads become mediocre depends on the service age of the good roads and service age of mediocre roads. In such chains, items flow from one stock to the next: there is a disaggregation of a (first order) material delay into an nth-order one, where each outflow from submaterial-delay flows into the next sub-material-delay (Figueiredo, P., et. al, 2014). Literature review and data collection with regards to ageing chain helps to understand the dynamics of development of public road infrastructure. The history of road infrastructure also plays a major role in understanding the underlying cause behind the increasing maintenance needs and poor condition of current road network.

Second part deals with the budget allocation by government for maintenance of roads and building new roads and the factors influencing budget decisions. Based on A Decision Support System for Road Maintenance Budget Allocation (Bjornsson, H. C., et. al., 2000) and several news reports (Plumer, B., 2015; O'Toole, R. 2015; Olson, P., et. al.,2017) few of the factors influencing the budget decisions making is listed below. All these factors are considered while formulating the hypothesis to explain the causes of the highlighted dynamic problem.

And finally, the third part deals with the revenue and expenses of highway trust fund of the U.S. based on a Congressional Research Service report by Kirk, R. S., et. al. (2020) to find out how the revenues are generated and why is government finding it so hard to increase the funding for the maintenance even when there is an outcry on the issue.

The comprehensive report card on America's infrastructure (American Society of Civil Engineers. (2013); American Society of Civil Engineers. (2016); American Society of Civil Engineers. (2021)) provided most valuable snapshots of the condition of roads in U.S. for the system dynamics model in this project.

1.6 Key Concepts

According to the *WisDOT Facilities Development Manual*, roads offer an expected good service life of roughly 20 to 25 years. The primary goals of pavement management systems (PMS) are to maintain or improve the quality of the roadway network, while utilizing available funding in beneficial way. Pavement management systems prioritize the maintenance of already deteriorated roadway segments utilizing historic data and deterioration modelling to plan for future conditions. The use of pavement management systems allows the optimum use of available resources (e.g., money and materials) while meeting set constraints of budget and time requirements (Molenaar, P. C. M., et. al, 2014) Pavement management systems can be used at the local, county, state, or federal level. Benchmarking and tracking the condition changes within the roadway network are important in predicting future deterioration and managing assets. PMS uses pavement roughness to determine the quality of roads.

Pavement Roughness

Pavement roughness values are measured in the form of an international roughness index (IRI), which is a primary indication of road quality. The IRI was developed in 1982 as part of an international experiment conducted in Brazil. It constitutes the smoothness, safety, and the ease of the driving path (Prasad, J. R.,et. al., 2013). The IRI depends on the pavement distresses present, it is a measure of the surface texture, and it is a key indicator in driving safety. The IRI is usually correlated to condition of available roads. The Federal Highway Administration (FHWA) provided guidelines on the various IRI measures as shown in the Table 1 below (*FHWA 1999*). IRI is also calculated in accordance with ASTM Standard E 1926 (*ASTM 1999e*).

Condition Term Categories	PSR Rating		IRI Rating (inches/mile)		Interstate & NHS Ride Quality
	Interstate	Other	Interstate	Other	
Very Good	≥ 4.0	≥ 4.0	< 60	< 60	Acceptable 0 - 170
Good	3.5 - 3.9	3.5 - 3.9	60 - 94	60 - 94	
Fair	3.1 - 3.4	2.6 - 3.4	95 - 119	95 - 170	
Mediocre	2.6 - 3.0	2.1 - 2.5	120 - 170	171 - 220	Less than Acceptable > 170
Poor	≤ 2.5	≤ 2.0	> 170	> 220	

Table 1: IRI and Condition (FHWA, 1999)

Pavements with high IRI values can be indicative of surface degradation, and low road quality. The major reference for this part of the literature review is 'Failure to Act' report prepared by the American Society of Civil Engineers (*ASCE*). Also referred as 'Report Card for America's Infrastructure', grades the current state of national infrastructure categories on a scale of A through F.

An indication of the importance of the roughness progression model in life cycle costing analysis was highlighted in a 1997 parametric study. This study showed that the rates of pavement deterioration (including roughness progression) had the most impact on the annual maintenance and rehabilitation costs in a pavement life cycle cost analysis. In other words, the single most important factor in a pavement life cycle cost analysis from a road agency perspective is pavement performance.

1.7 Hypothesis

The underlying hypothesis for the problem of increasing share of poor roads and shooting maintenance backlog is based on several literature reviews as discussed in this section. The main cause of the problem always comes to the point that US spends too much on new roads and too little on repairs (Plumer, B., 2015).

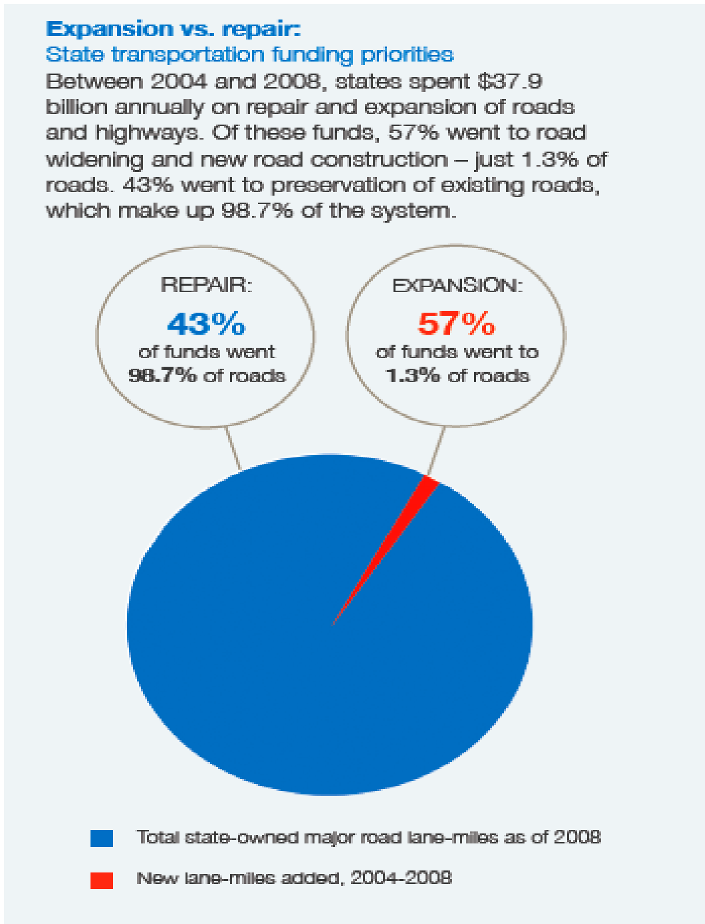

Figure 4: funding priorities Expansion vs Repair

There is strong influence of bureaucracy in approving the budget, the decision to use the fund allocation is based on political negotiation. Road maintenance is politically unattractive-new road construction and road rehabilitation is more visible and produces greater political prestige (Rusbintardjo, G., 2015). Below listed are some of the causes leading to the problematic behavior and find answers to research questions 1-3.

Ribbon-cutting and Publicity

Fifty years ago, America's transportation infrastructure was funded almost entirely out of user fees (or state taxes paid by users) and USA had the world's best transportation system. Since then, funding decisions have increasingly been made by politicians more interested in ribbons than brooms. Higher federal spending would likely fund unnecessary new projects, not needed repairs. This is because politicians prefer ribbons, not brooms. Ribbon-cutting projects provide more photo opportunities than do ongoing maintenance projects. And politicians make matters worse by favoring big, glitzy new projects over low-key ones that can do more at a far lower cost. (O'Toole, R., 2015; Rusbintardjo, G., 2015).

Political lobbying

With the billions spent on federal elections growing by the cycle, campaign finance is a more prominent — and controversial — topic of discussion than ever before. Each election cycle, journalists and voters have to evaluate all kinds of competing claims about the role of money in elections. How and from whom do politicians get their contributions? How effectively does all that money translate into votes? And to what extent do big campaign contributors get special access or favors in return for their donations? Studies offering a formal description of interest group behaviour aimed at influencing government policy typically use an 'influence function' to represent the transformation of resources into political influence (Potters, J., et. al., 1990).

A PAC is a Political Action Committee that raises and spends money to elect or defeat candidates. Most PACs represent businesses, such as the Microsoft PAC; labor unions, such as the Teamsters PAC; or ideological interests, such as the EMILY's List PAC or the National Rifle Association PAC. An organization's PAC will solicit money from the group's employees or members and make contributions in the name of the PAC to candidates and political parties. Individuals contributing to a PAC may also contribute directly to candidates and political parties, even those also supported by the PAC.

Some economists worry about expanding the federal role, given what they see as a history of politically driven and wasteful federal infrastructure spending. Some argue that a steady flow of federal money gives states an incentive to build things they don't need

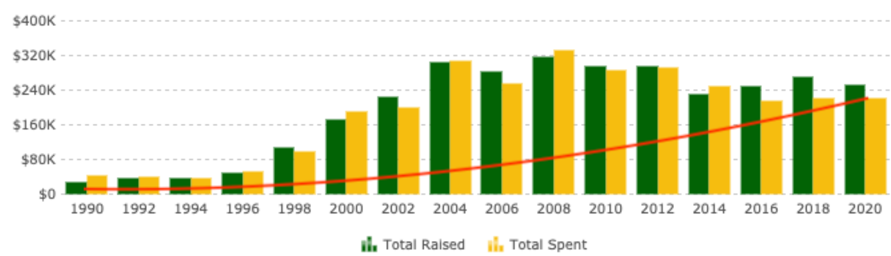

Figure 5: Contributions made by road and transport assn builder PAC

Source: Juliano, R. (2017). PAC Contribution Data, 2017-2018.

Many people are skeptical of increasing government spending on infrastructure because they worry the money will be used inefficiently—either because politicians favor projects regardless of the merits or politicians can't distinguish high-return from low-return projects (Olson, P., et. al., 2017). Increasing Contribution made by new road and transportation association builder PAC hints that politicians have favored new roads over maintaining old and putting money into maintenance tends to avoid getting support from new road builders.

Issue reporting and public awareness

Economic Development Institute (*EDI*) seminar series highlighted that lack of awareness and understanding of the problem with the deteriorating roads condition and maintenance of the road system was one of the causes of inadequate national commitment to tackle the situation. The need for increased reporting and awareness based on transparent actions and information was suggested. Increased reporting would increase the awareness among public about the accountability and efficiency of the government in fulfilling road maintenance gaps.

The participants of the seminar identified as one of the more critical tasks of road authorities the creation of a raised level of awareness and commitment to the priority of road maintenance for ministers, not only for their own ministry but also for those of finance. They should also promote public awareness campaigns using media, NGO's, road user association and other means.

In order to infuse the effect of reporting and public awareness on decision related to budget allocation, one should look beyond the confines of publicity, political lobbying and analyse from the dynamics of issue reporting and increased level of public participation.

Cash-strapped highway trust fund (HTF)

For decades, gasoline taxes and other fees on motor vehicle users paid the lion's share of the cost of constructing the nation's massive emerging network of highways. Through the mid-1970s, roughly 70 percent of the cost of highway construction, maintenance and operation nationwide was paid for through taxes on road users, with another 10 percent coming from bonds, many of which were intended to be paid off with future user revenue such as gas taxes or tolls. By the 1980s, however, the relationship between the amount of money paid by drivers and the amount spent on highways had begun to weaken. And since 2005, the bottom has fallen out of the "users pay" model of transportation finance in the United States (Dutzik, T., et. al., 2015).

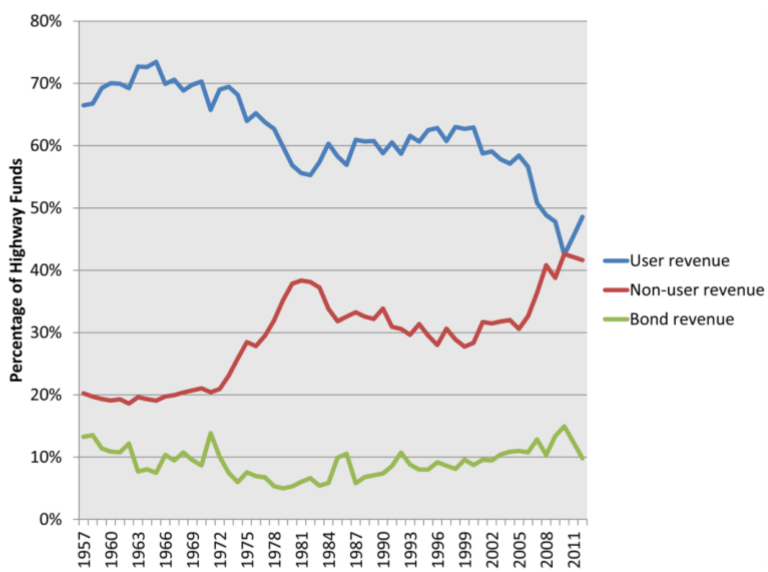

Figure 6: Percentage of Highway Spending from Various Sources, All Levels of Government

The Highway Trust Fund (HTF), created in 1956 partially funds the creation and maintenance of the interstate highway system. The HTF raises money through the gas tax (which has not increased in over two decades) and other transportation-related taxes, and spends it on roads and highways (about 80 percent) as well as mass transit projects (about 20 percent). But analysts say that the HTF is facing insolvency, and a deficit of over $6 billion as soon as 2022. (*McBride, J., et. al., 2021*).

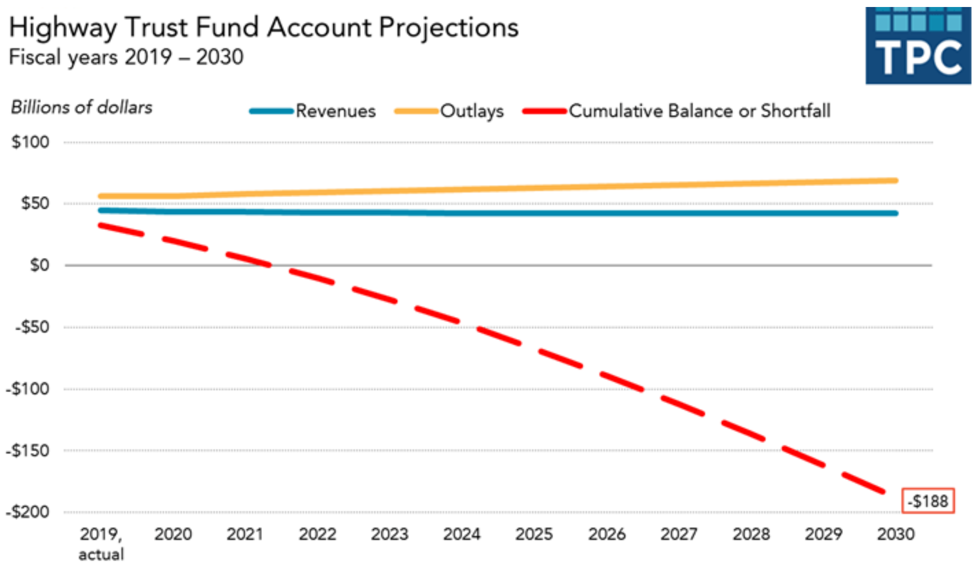

Figure 7: Highway trust fund account projection

Source: Congressional budget office, Highway trust fund accounts (CBO's January 2020 baseline, January 2020)

Chapter 2. Model Description

2.1 Model Overview

The previous chapter described the problem definition and a number of issues related to the research design aimed at addressing the stated problem. This section describes the scope of the model and key concepts leading to the model structure. Based on simulation runs, the dynamics of relevant variables is generated. Based on this description, the purpose of the model is explained.

Together all these elements provide an overview of the model so that the reader can understand what generally the model is about without referring to exact specifications used in the model. The next section discusses how the chosen scope, spacing and timing of the model translate into the model's assumptions. Then the discussion shifts to a much more detailed level of describing the structure of the model's sectors in terms of stocks and flows and major formulations.

After that a step back to a less detailed perspective structure will be taken, whereby the major feedback loops and their interactions will be presented.

The model focuses on the dynamics of building of new roads and their aging at the level of the US. As such the model generates the dynamics of the following key variables:

- Annual maintenance needs of the roads.
- approved budget to carry out maintenance.
- average age of the roads.
- effect of aging of roads on maintenance needs.
- Annual approval of new roads

The model is then used for testing hypothesis surrounding the budget allocation on building new roads and budget allocated for the maintenance needs.

In accordance with the research objectives and research questions, the scope, spacing and timing of the model were specified. Initially the time range was selected for the period starting year 2000 however the simulation runs didn't cast the clear picture of the problem. Although simulations showed the growing roads in poor roads and increasing maintenance backlog, it failed to give any insight on the dynamics of the problem. It was obvious from the simulations that the problem might have started prior to the date range we selected for simulation runs. We then decided to simulate the run starting year 1950. As discussed in section…. 1950 saw major road projects and forming of interstate highway system. Having longer duration of simulation run allowed to trace the point of inflection. While having year 2000 as starting period, the graph showed degrading road condition and increasing maintenance backlog from start but to inflection point signified a specific point on a graph where the trend fundamentally changed.

The time frame of the model simulation is 70 years from the starting point, which is the current year of 2020. The choice of 70 years is dictated by the following reasons:

- This is based on the lifetime of roads (normally around 70-100 years)

- The formation of Interstate highway system (also NHS) happened in early 1950s and during those periods there was a heavy investment from the government in the area of roads constructions and it becomes important to include those activities in model boundary, particularly when we are analyzing maintenance of infrastructure

As such, the model can be described as a highly aggregate overview of the system comprised of complex interactions between the physical process of road degradation, maintenance needs, maintenance carried out and rehabilitation of roads. As the scoping model, it is characterized by the following crucial features characterize:

• aging chain of road with maintenance and their interaction being at the core of the model.

• The model incorporates an important feedback mechanism between need of maintenance and approval of budget for maintenance.

While the statement that more roads influences need for more maintenance sounds pretty trivial (open loop thinking), the reverse statement that more maintenance decreases the building of new roads and drives the maintenance needs as well is usually omitted (closed loop thinking) by the analysts. Yet, this feedback mechanism was found to be central to the system being modeled for this project.

• A crucial variable that makes the link between maintenance carried out and actual need for the maintenance is the average age of road infrastructure.

• building of roads, maintenance of roads, reporting of issues and public participation in decision making are all very simplified representations, which, however, together generate a complex dynamic resulting from the interaction of those elements.

2.2 Model Assumptions

Assumption 1: System Boundaries

Two important variables are chosen to be exogenous in the model, namely:

- **GDP is treated as exogenous.**

We recognize the important role of GDP in determining the total available budget for road system. GDP is a monetary measure of the market value of all the final goods and services produced in a specific time of a country, which is beyond the scope of this modeling effort.

- **Share of GDP spent on roads.**

We do not develop an endogenous structure to include the effect of road infrastructure on GDP and share of GDP spent on roads. Existing data available is being fed in as exogenous input using graphical function.

Few of the references discussed about the effect of changing climatic condition on life of road in some states of US which has faced drastic climatic change like draught, flash floods and so on. However, we have not included climatic factors. We assume that although there is climatic impact however when we consider the total road network of US, the road length impacted is minimum. This however has a scope of future research.

Assumption 2: Categorizing roads into different conditions

FHWA categorizes condition of roads in 5 different groups based on IRI values however as we have grouped very good and good road into one. This will make the aging chain simpler and as key group being analyzed here is of roads in *poor* condition, the behavior of stock of poor roads is not being altered.

Assumption 3: Research reporting and press coverage

The reporting or press coverage could be either in favor of increasing budget for maintenance or in favor of increasing budget for new roads. The reporting could impact the public participation and pressure on government to make decisions. The type of reporting and its effect of public participation will be discussed more in section 2.4 (Feedback Perspective). For the initialization and simulation purposes the assumption is that the reporting is done highlighting the need to increase maintenance budget over building new roads.

2.3 Model Structure

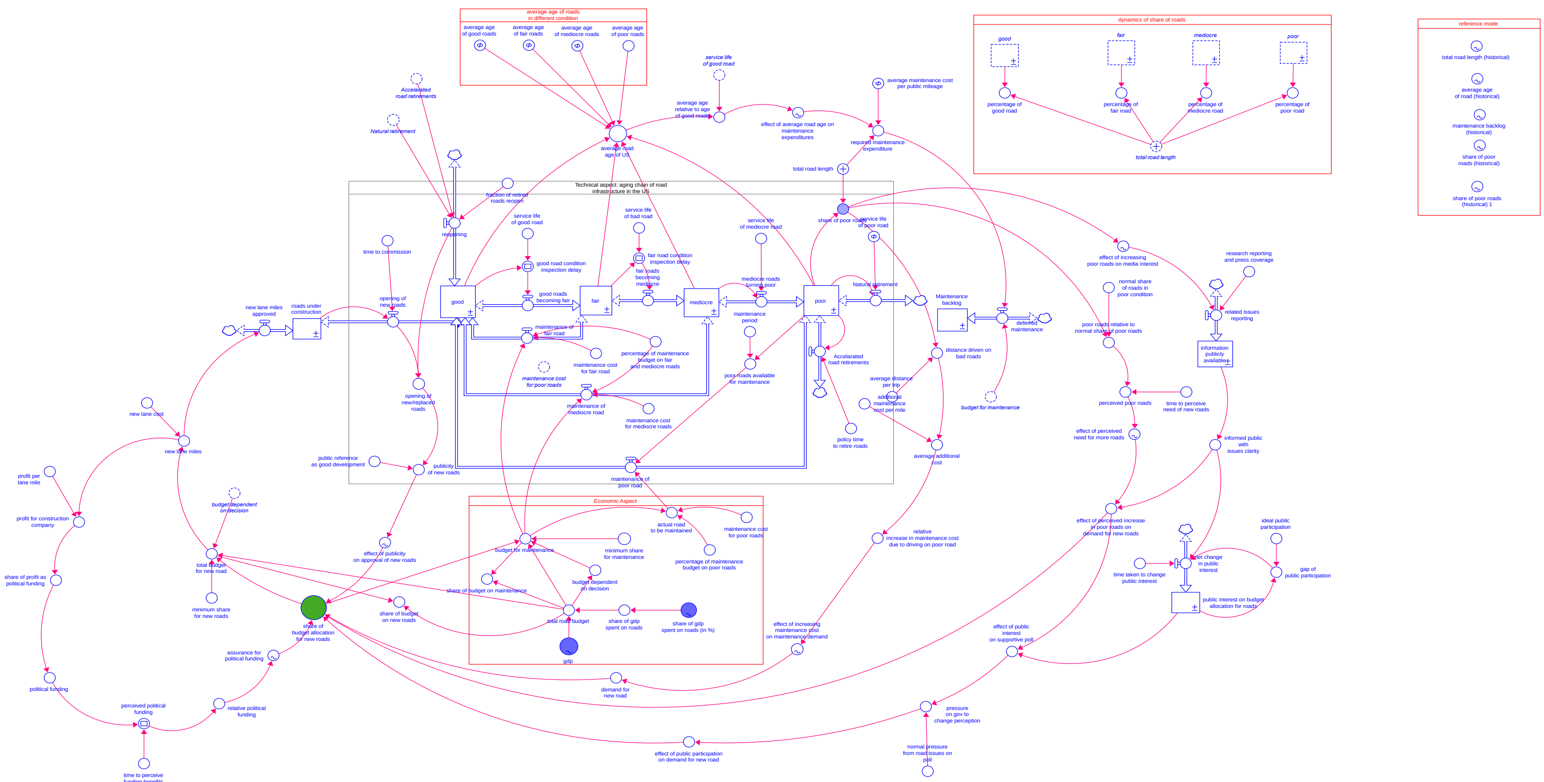

Figure 8: Model Overview

The model has three main components: technical, economic, and social components. The first one is composed of a aging chains, which recreate the road network condition over time. The economic aspects are represented by the variables, *budget for road maintenance* and *required maintenance expenditures*, and political aspects are represented by *publicity of new roads, political funding, public participation, research reporting and press coverage*, as shown in figure above.

The model structures are based on research done on similar topics before. The technical component has ageing chain structure following the literatures from Sterman, J. D. (2000), Rahmandad, H., et. al., (2010), Fallah-Fini, et. al., (2015) and Ruiz, A., et. al., (2020).

The economic aspect has the model structure following literature from Queiroz, C., et. al., McBride, J., et. al., (2021) and Ruiz, A., et. al. (2020).

Finally, the social or political aspect of the model structure followed research work done on income and political inequality in the United States by Khaled, G., & Kopainsky, B. (2019). A study on income and political inequality in the United States.

Following the relationships identified in the Causal Loop Diagram (CLD), there is a feedback loop between the technical and economic components. On the one hand, the budget for road maintenance determines the ability of governments to intervene in the road network; at the same time, the execution of these interventions decreases the available budget, resulting in a balance loop between the maintenance of roads and construction of new roads. On the other hand, the budgeting component is directly related to the socio-political components, since decision making is associated with all the factors included in the model.

The model simulates the processes of deterioration, maintenance, and rehabilitation of the national road network, which are represented through the aging chain. Four stocks compose the chain—good, fair, mediocre, and poor—and are measured through mile-roadways. There is a stock of roads under construction which feeds in the stock of good roads. The dynamics for the processes of deterioration and maintenance of roadways follows the aging chain and maintenance activities performed. These dynamics are presented in figure…which shows the variables involved in the aging chain and their relationships

As shown in Figure 4, the stocks are connected through rates, which are represented by double-line arrows with a valve attached to them. The new roads rate denotes the roadways that are built each year and are expected to be in good condition. On the other hand, degradation of roads over given time, correspond to the processes that lead roadways to a fair, mediocre and poor condition, respectively. Both rates are directly related to the miles of roadways in each stock and the average age of roadways. The average age for degradations of roads were calculated using partial calibration methods (Oliva, R., 2003). However, the roadway condition does not depend exclusively on the deterioration process, but also on the interventions performed. In addition to the construction of new roads, two types of interventions are considered: the first is called maintenance activities, which take roadways from fair condition to good condition. Likewise, the roadways in poor condition are intervened to take them to good condition through rehabilitation and reconstruction activities. There are two highly influential factors in the number of interventions carried out: the budget available for the preservation of roads and the government's goals regarding the desired condition of the network.

The model assumes that the government gives priority to building new roads over maintenance, that is, following several factors leading to the budgeting decision, the government executes the required rehabilitation and construction activities. After these interventions are performed, the costs associated with these types of activities are quantified and compared to the available budget for road preservation. If there are available resources, a percentage of this is allocated to execute maintenance activities. The maintenance rate is directly related to the availables available after executing both types of interventions, maintenance and rehabilitation activities.

Additionally, the decision on budget is calculated. This is done using decision factors (measured as dimensionless) associated with related hypothesis that were obtained from the literatures and references discussed in section 1.6 (Hypothesis**)**. Publicity of ribbon-cutting ceremony of new roads, political lobbying, poor roads inducing need for more roads, reporting of issues are the variables that represents the factors influencing the budget decision making aspect in the model. In order to mitigate growing maintenance backlog and increasing share of poor roads in the country, policies are suggested in the model. Therefore, the variables of percentage of accelerated road retirement, sustainable maintenance, and sustainable rehabilitation are added, which represent the proportion of interventions that will be carried out. In other words, other flows of poor roads retiring would be accelerated, and behave exactly as the ones explained above, but at a increases magnitude, and these new flow would bring the stock of poor roads down, eventually bringing the average age of roads in the US and thus lowering the required maintenance expenditures.

2.4 Feedback Perspective

To formulate the equations between budget variables and maintenance activities, it is necessary to identify what type of relationships and feedbacks exist between them. Feedbacks can be reinforcing or balancing loops, labeled with the letter R and B, respectively. Reinforcing loops represent interactions that promote their own growth, and balancing loops refer to mechanisms that help the system reach an equilibrium condition (Sterman, J. D., 2000).

Figure below portrays the causal loop diagram of the model. Such representation allows us to employ explicitly the feedback perspective to the current analysis. In its turn, the feedback perspective both assumes and leads to the endogenous view on the issue. Under endogenous view we mean here the explanation of behavior patterns under concern by the presence and interaction of feedback loops constituting the system we are modeling

As roughly paraphrased from *Feedback Thought in Social Science and Systems Theory* by *George Richardson*, a good social scientist is a feedback thinker (Richardson, G. P., et. al., 2002). Taking this idea as an inspiration for our analysis, we will focus on the description of feedback loops and how they produce the behavior that the model exhibits.

Figure 2 exposes the developed CLD, which shows that the road system's ageing behavior which is highly influenced by the age of roads in different conditions, which is a result of the deterioration processes of the pavement. With the purpose of reducing this deterioration, maintenance and rehabilitation activities are implemented thus improving the condition of road network which forms first order balancing loops **B1, B2** and **B3**.

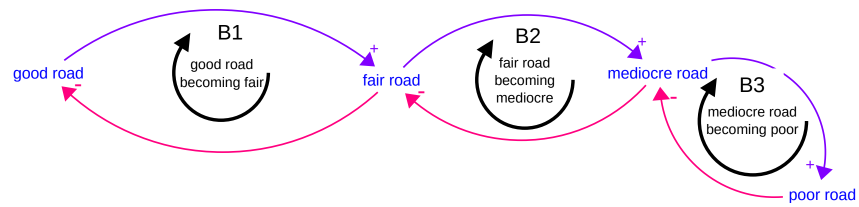

Figure 9: Minor feedback loop of ageing chain

As highlighted earlier, there was mega expansion of roads in early 50's and the amount of good and fair roads were much higher initially. The construction of new roads lead to more good roads and process of degradation over time increased the stock of fair, mediocre, and poor roads. The construction of new roads eventually increased the total road length of the country.

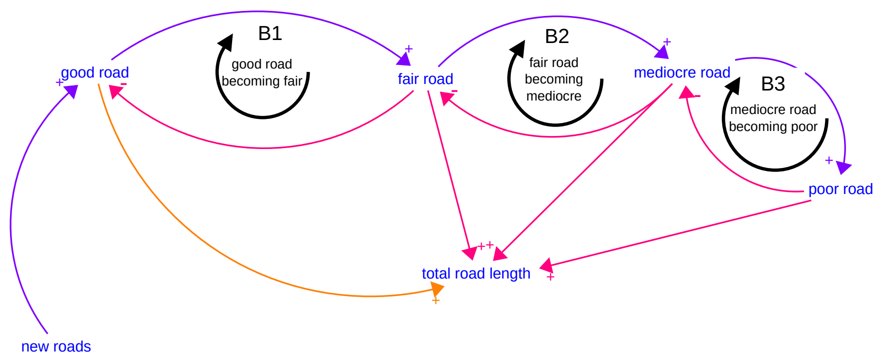

Figure 10: Causal Loop Diagram 1

The rate of construction of new roads, which was very high initially started to fall in the following years which constrained the growth of good roads, and the ageing of road infrastructure increased the stock of poor roads. Increasing amount of poor roads over time increased the share of poor roads in the US. That is how the first version of the problem definition presented in Introduction Chapter can be formulated.

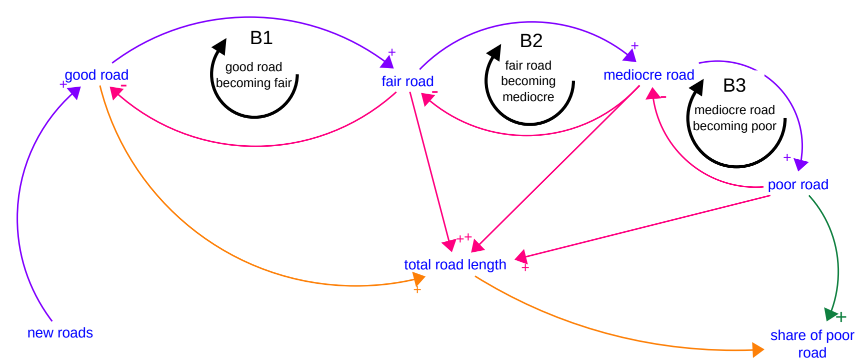

Figure 11: Causal Loop Diagram 2

The fact that construction of new roads consumes part of the resources allocated to the preservation of the road network, reducing the resources available for support and maintenance activities. The insufficient maintenance budget supply constraints adequate maintenance of roads. Currently roads infrastructure is characterized by unsatisfied demand for maintenance needs of a relatively high level. The inability to satisfy this demand in the present context not only halted the maintenance of poor roads to the state of good roads but over time through continuous accumulation, the maintenance backlog has been shooting to an unprecedented levels (**RL1**), which describes second version of the problem highlighted in the introduction..

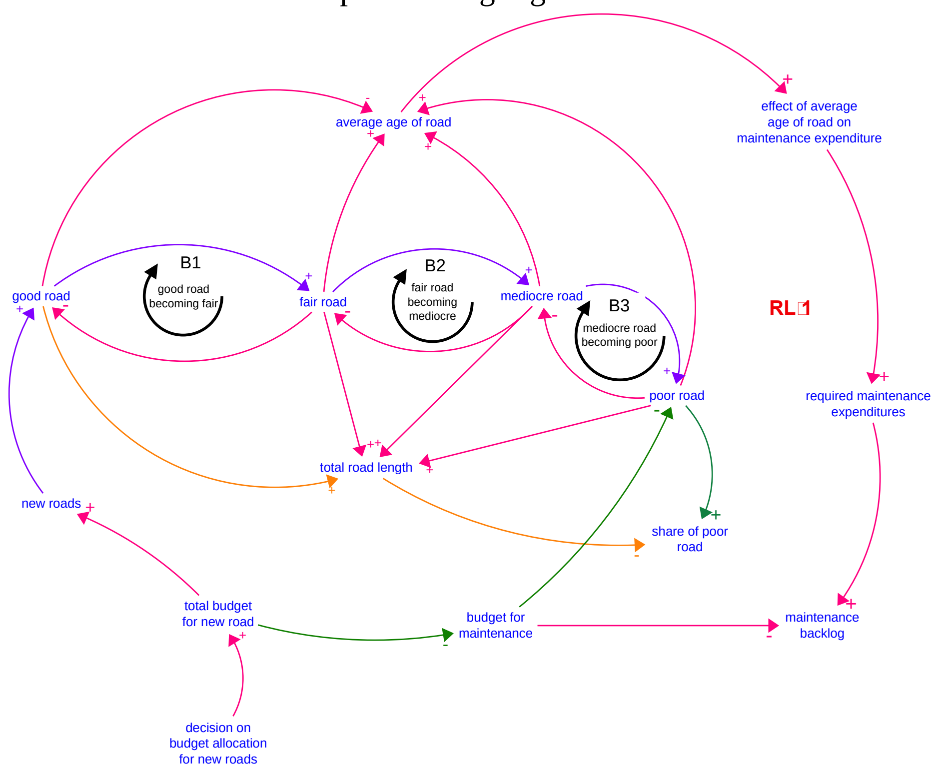

Figure 12: Causal Loop Diagram 3

The maintenance demand is modeled based on condition-based replacement theory (Rausand, M., 2004) which treats the deterioration of the item (road) as a function of time t. Following that theory, the demand for maintenance need in the model is anchored to the average road age of US, which is based on stock of roads in various conditions and the average age corresponding to those roads.

The concept of demand for maintenance needs is crucial to understanding the work of reinforcing link (**RL1**) formed between

average road age of US → required maintenance expenditures → deferred maintenance → maintenance backlog.

If the above mentioned reinforcing link (**RL1**) is dormant, the logical question (research question 3) arises why it is so. Apparently unsatisfied demand pressure does not lead to supply of sufficient funds for maintenance because of the factors affecting the decision making process for budget allocation. Now we shall see the interaction of feedback loops formed by the dynamics of factors affecting budget allocation as discussed in section 1.6 (Hypothesis).

Increasing share of poor roads give rise to additional maintenance cost for vehicles running on roads (Antich, M., 2010). The increasing maintenance cost leads to increase in the maintenance demand thus balancing the budget allocation for new roads **(B4).**

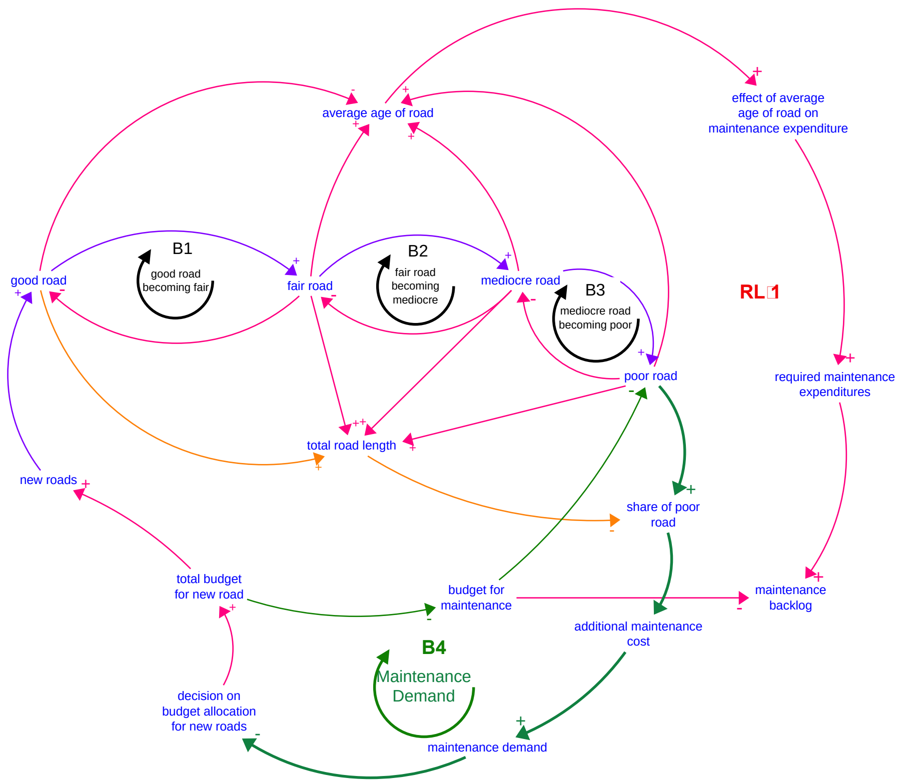

Figure 13: Causal Loop Diagram 4

Here we see the first important interaction between feedback loops: B1,B2 and B3 responsible for increasing share of poor roads, RL1 responsible for increasing maintenance backlog and the controlling mechanism for budget allocation represented by loop B4.

The next question is logically why the loop B4 is not strong enough to increase budget for maintenance and thus reducing poor roads. That is because of the presence of counter acting loops working simultaneously to weaken loop B4. The CLD below shows explicitly that fulfilling maintenance need does not depend just on the presence of that need.

One point to note here is that we referred reinforcing loops as counteracting because the basic assumption related to key variable 'decision on budget allocation for new roads' is biased towards building new roads and hence these loops leading to the variable counteracts to weaken the budget allocation for maintenance.

Further below I explain the formation and working of all these counteracting loops which make the case for funding for maintenance of roads weaker.

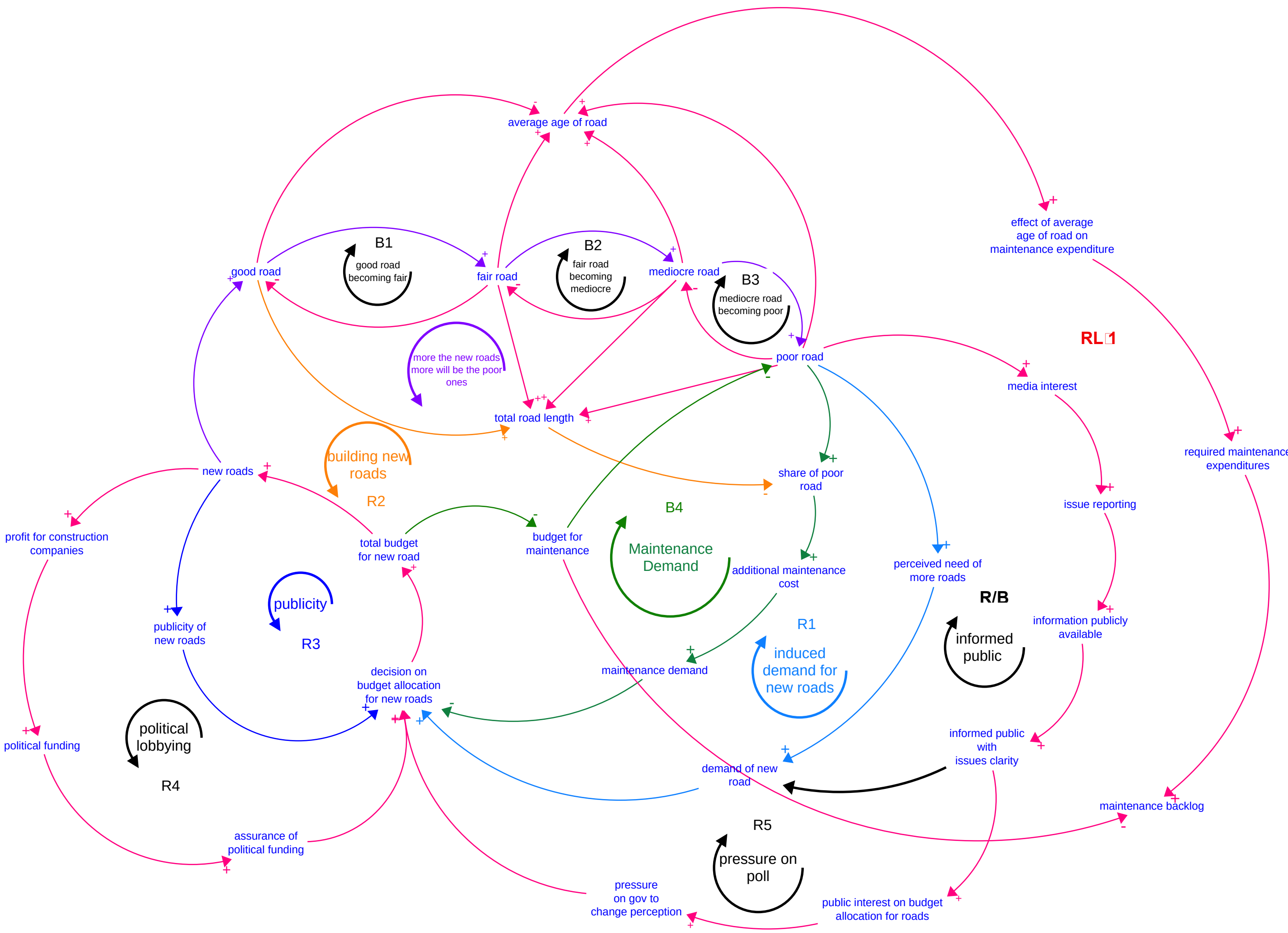

Figure 14: Overall System's Feedback loop mechanism

Loop R1 (induced demand for new roads) is characterized by the fact that when there is increase in poor roads there's perception to build more roads. Demand for new roads will reinforce the decision on budget allocation for new roads eventually leading to a vicious circle of more roads giving rise to more poor roads in turn supporting new roads. Although this loop has been modeled at a very aggregate levels there are many literatures supporting this loop structure (Marte Dæhlen et. al., 2020).

Loop R2 (new roads reduces share of poor roads) comes into effect when there is a higher budget on building new roads invites more new roads leading to more good roads, eventually reducing the average life of roads meanwhile increasing the total length of roads in US and as the total length of roads increases the share of poor roads would decrease thus decreasing the demand for maintenance and then increasing the funds for new roads next time around

Loop R3 (publicity) depicts the strengthening of budget allocation for new roads due to publicity gained during opening ceremonies of new roads. More the new roads, more opportunities for politicians to showcase themselves as progressive leader thus increasing the tilt towards supporting fund for new roads rather than approving budget for maintenance.
politicians are willing to build new roads while the costs are below the benefits, While the model contains a simple formalized structure representing this idea, the CLD employs the variable effect of publicity on approval of new roads to reinforce decision on
budget allocation for new roads.

Loop R4 (political lobbying) comes from a thought that there are political action committees that spends money to elect or defeat candidates. In this model the lobby represent road builders assn. The approval of bigger budget for new roads increases business opportunities for road builders brining in increased profit and hence increased affordability for political funding to support parties pitching for increased budget for new roads. The same scenario applies for maintenance as well however the profit from building new roads is much more than maintenance and moreover the interaction of loop R2 and R3 makes it easier for politicians to support higher budget for new roads.

At the moment there's a significant gap between approval of funding for new roads and funding for maintenance needs. The only loop providing some resistance is balancing loop B4 which kicks in only when there is increase in additional maintenance needs for general public. As the share of poor roads increase the travel time on poor roads increase as well. Driving on poor roads can lead to increased maintenance of the vehicle and also additional cost on fuel and time value lost while driving on poor roads. This increased additional maintenance cost when reaches level of discomfort there's an increase in demand for maintenance of poor roads and it is then when the budget approval considers the demand for maintenance needs.

Increasing cost for additional maintenance does not make approval for budget for maintenance strong enough to match overall maintenance needs. Thus, loop B4 is not operating to the desired extent so that the interaction of loops leading to decision on budget allocation for new roads weaker to increase the growth in maintenance funding.

Consequently, the focus of the problem shifts to how to increase the maintenance funding to decrease the ever growing deferred maintenance backlog. Reinforcing loop R2 represents the potential realistic mechanism, which can lead to lowering share of poor roads in US. We should be very careful about this loop as on the one hand it drives the whole system: when R2 is operational then B1,B2,B3 strengthens towards increasing stock of poor roads increasing the unsatisfied demand of maintenance and awakens reinforcing loop B4 bringing the demand for maintenance high.

Yet, on the other hand there is a great deal of uncertainty surrounding the mechanism behind loop R/B (informed public). The loop name itself suggests its ambiguous and this requires some clarification: the fact that the increasing percentage of poor roads invites media attention and there's an increase in media reports related to poor state of roads, the clarity of issues gained by public depends on reporting done by media or in other words information publicly available highlighting the root cause of the issues. For example, if there are reports showing the cause of poor state is due to underfunding on maintenance then there will be an increase in public support towards increase in maintenance fund which will create pressure on government to change perception (Loop R5: pressure on poll). However, if the reporting is done highlighting the skyrocketing increase in maintenance demand is following the average age of road, then the public support will be towards accelerated replacement of poor roads with new roads and hence support for new roads would increase. Thus, with the increase in issue reporting we can safely expect the informed public effect kicking in and increasing the pressure on government to address the issue.

Thus, the interaction of all the loops leading to the decision on budget allocation for new roads is at the focus of the model and are responsible for the model's behavior.

Another important interaction between the feedback loops in the system: loop R5 and loop B4 enables increased funding for maintenance close to required demand

Another side of this important interaction is that for the public to remain informed about the issue to create pressure on government there should be a constant increase in issue reporting, which can only be achieved if balancing loop B1,B2 and B3 keeps increasing the share of poor roads.

Consequently, the model grasps an interesting interaction among different loops. The strength of loops depends on the decision to allocate budget.

However, in the present context this feedback mechanism doesn't cast a clear picture if the biases towards increase in funding has caused the increase in share of poor roads as well as the skyrocketing deferred maintenance backlog. One thing which is evident is that the effect of increasing average age of road has direct and strong impact on maintenance needs and even if there's an increase in maintenance budget the issue of growing maintenance backlog, although would fall, it would still remain. The only way to decrease the accumulating stock of poor roads is by increasing the outflow (retiring poor roads) from poor roads more than the inflow of mediocre roads becoming poor net flow. This is a much broader problem description presented by the CLD than the one we started with in the beginning of this section.

Moreover, as portrayed by the CLD, the story from the feedback perspective already suggests hints for potential policy options. The described analysis identifies clearly the need for accelerating retirement of poor roads through the mechanisms other than described in the model so that the level of good roads increases and thus lowering down the share of poor roads. The other potential policy would be to seek funding for a mega maintenance drive to rehabilitate poor roads to the state of good roads. The issue with second policy is that the life of rehabilitated road would not be same as new road and that segregation of good roads as new or rehabilitated road is one of the clear limitation of this model.

The policy structure is described in the Policy Chapter.

The CLD exhibits other feedback loops, which are not at the core of problem definition.

The feedback perspective is crucial for explaining behavior through structure. However, the interaction of loops is characterized by non-linearities resulting in some of the loops being dormant or having different strength throughout the time. The resulting behavior of multiple loops interacting together cannot be predicted and can be counterintuitive. That is why in system dynamics methodology we conduct simulation: to test what we cannot grasp by deduction or induction only. This chapter described the major feedback loops and their interactions. The description of model behavior will be linked back to the feedback perspective to build the basis for understanding the simulation runs and serves as a reference point for explanations in the next chapter.

Chapter 3. Validation

3.1 General considerations and model validation

System dynamics modelers have developed several tests for validation purposes which seek to find flaws in the model formula and ensure its efficiency to fulfill the objective for which it was built (Schwaninger, M., et. al., 2016). Once the objective and scope of the model are established, the next step is to formulate it. Dimensional consistency and structural testing tests were carried out during and at the end of this formulation process. To ensure dimensional consistency, all units of measure for each variable were specified as the model was built. The objective of evaluating the structure of the model is to verify that it is consistent with the real system and functional for the purpose of this project. The development of the model structure was done through stock and flow formulations that were used in other studies that analyzed road networks (Ruiz, A., et. al., 2020) where first-order aging chains were employed to endogenously capture the pavement deterioration process. In the structure evaluation, it is also important to verify that physical laws are not violated, therefore in this case, the formula used guarantees that stocks and flows remain at positive values under any circumstance.

To carry out the integration error test, a time step and integration method were chosen in such a way that if the method was changed or the time step was reduced by half, the simulation results would not change significantly. Additionally, behavior anomaly tests were performed; for this, the relationships between construction and maintenance rates and the budget were modified or deleted. Anomalous behaviors arise when the feedback loop governed by the budget is deleted; this indicates the importance of including these relationships. Behavior reproduction tests were also performed; the purpose of this test is to evaluate the model's capacity to represent historical data. The results of these indicators suggest that the model successfully recreates historical data trends. Additionally, parameter assessment, sensitivity, and extreme condition tests (Sterman, J. D., 2000) were carried out in Stella Architect (i.e., software for SD modeling).

The parameter values were estimated using partial model calibration from numerical data. This helped to confirm that model results were consistent with previous studies on pavement deterioration and system dynamics (Fallah-Fini, et. al., 2015; Rahmandad, H., et. al., 2010). The sensitivity analysis was performed through Monte Carlo simulation procedures; for each exogenous parameter, a set of possible values was established. All sets follow a triangular distribution, where the most likely value is the value previously estimated through partial model calibration. The results showed that the model exhibited a logical behavior for any value of a set of values, and that the mean of the simulations exhibits trends similar to historical data.

For validation of the developed model four key parameters namely *total road length*, *share of roads in poor condition*, *average age of road* and *maintenance backlog*
were chosen to contrast simulated behavior against the historical one.

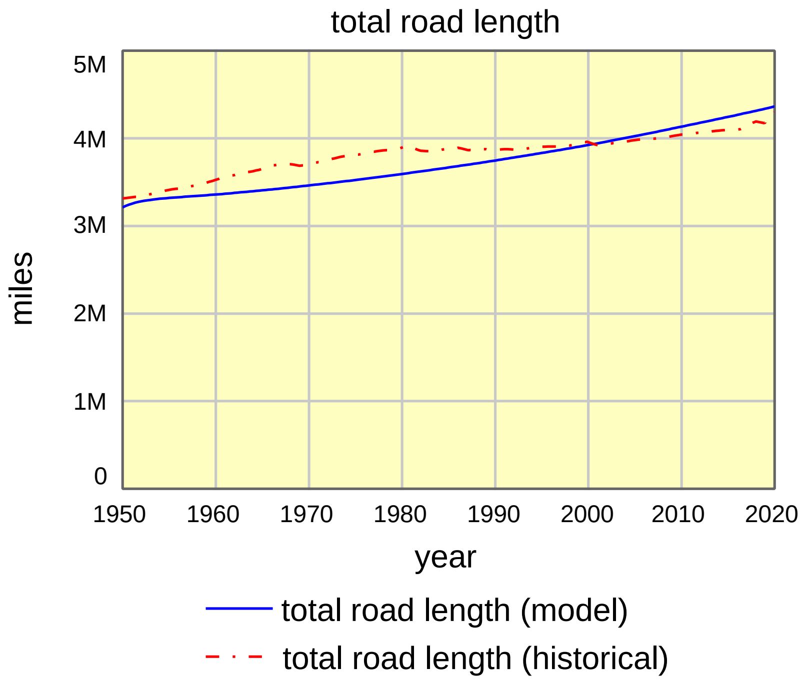

Figure 15: Validation: road length

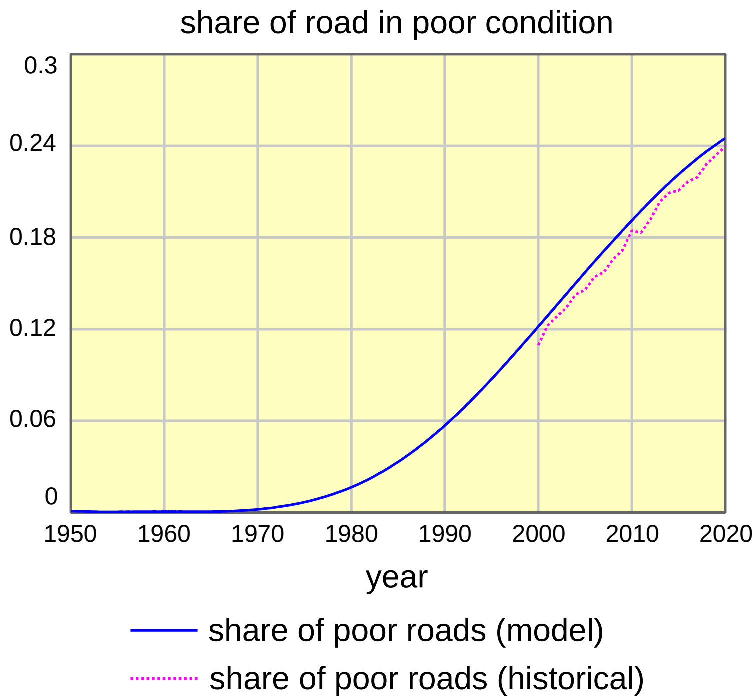

Figure 16: Validation: Share of roads in poor condition

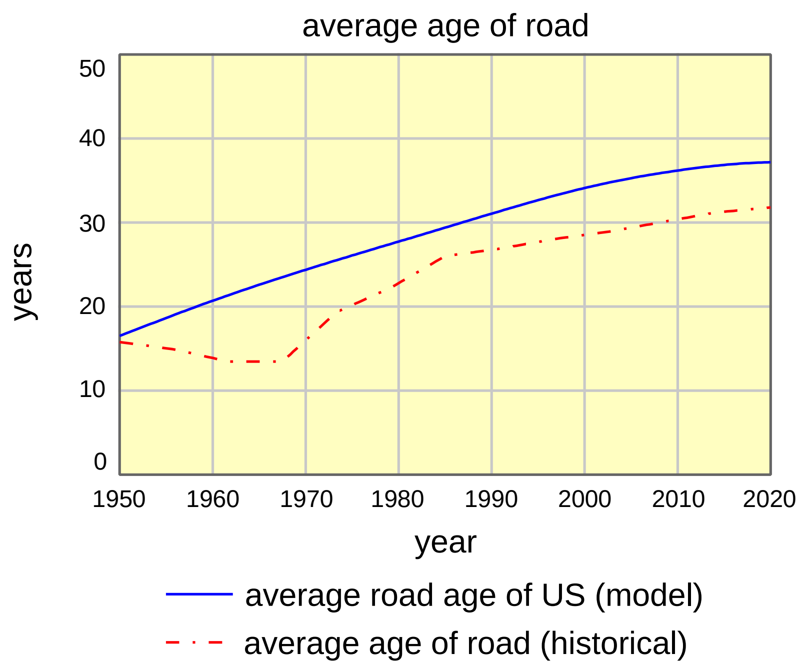

Figure 17: Validation: average age of road in the US

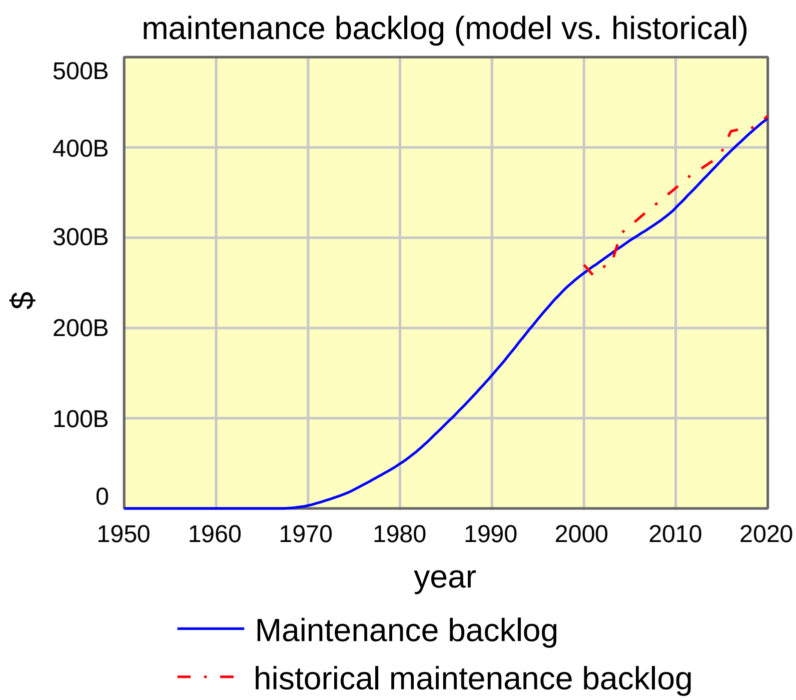

Figure 18: Validation: maintenance backlog

3.2 Sensitivity Analysis

Sensitivity analysis is used to determine how "sensitive" a model is to changes in the value of the parameters of the model and to changes in the structure of the model. In this section, we focus on parameter sensitivity.

Parameter sensitivity is usually performed as a series of tests in which the modeler sets different parameter values to see how a change in the parameter causes a change in the dynamic behavior of the stocks. By showing how the model behavior responds to changes in parameter values, sensitivity analysis is a useful tool in model building as well as in model evaluation. Sensitivity analysis helps to build confidence in the model by studying the uncertainties that are often associated with parameters in models Forrester, *J. W., Breierova, L.*, & Choudhari, M. (1996). *An Introduction to Sensitivity Analysis*.

In this exploration, we conduct sensitivity analysis on all the constant parameters in the model. However, in a this model, such an extensive treatment of sensitivity analysis is extremely time consuming and not as useful hence I picked few parameters to gain confidence on the model structure.

Parameter1: Average age of good roads

While running a sensitivity run on 'average age of good roads' following an incremental distribution with a starting value of 10 years and ending value of 20 years we get below range of behavior. Although the initial value changes the overall behavior exhibited remains same. While calibrating the model to match the reference mode value of 15 years was chosen.

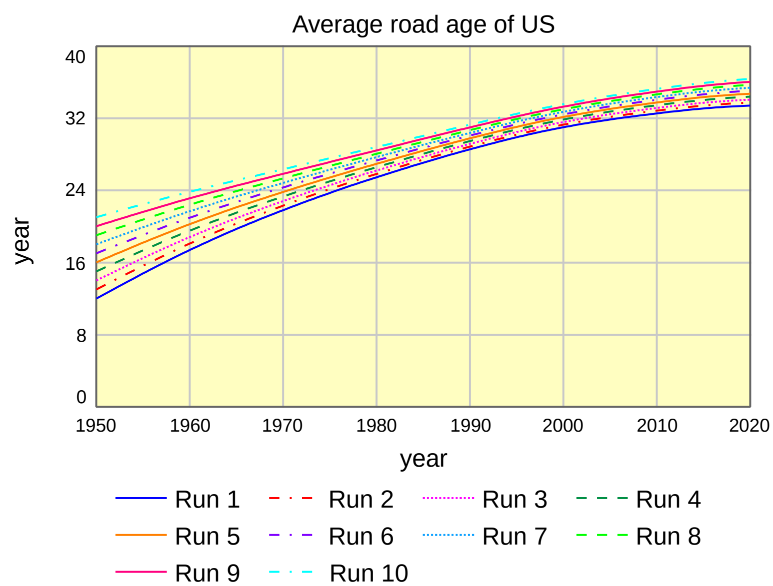

Figure 19: Sensitivity runs - average road age

One thing to notice was that the range of value chosen for 'average age of good roads' didn't alter the behavior of parameter depicting 'share of poor roads.'

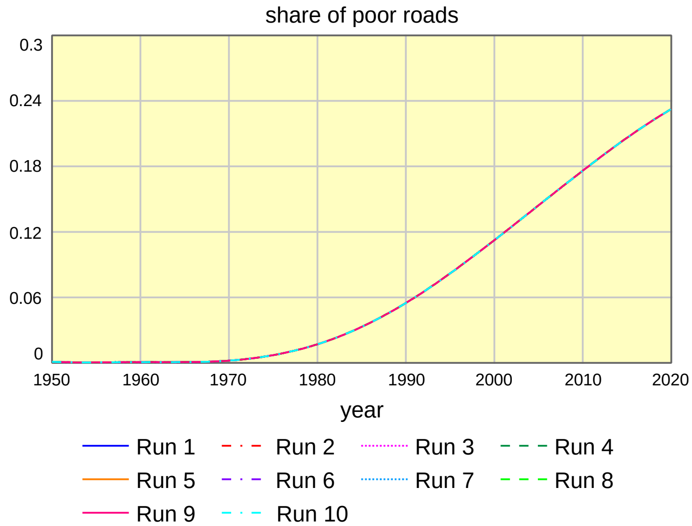

Figure 20: Sensitivity runs – share of poor roads

Similar was the case with all other parameters having average age respective to condition of the roads.

Parameter2: New Lane cost

While running a sensitivity run on 'new lane cost' following an incremental distribution with a starting value of 4 million dollars and ending value of 8 million dollars, the result is as expected. Higher the new lane cost lower is the new lane miles and vice versa. The cost of building new lane mile exhibited only a slight deviation in the behavior of 'average age of the roads' and 'share of poor roads' parameters.

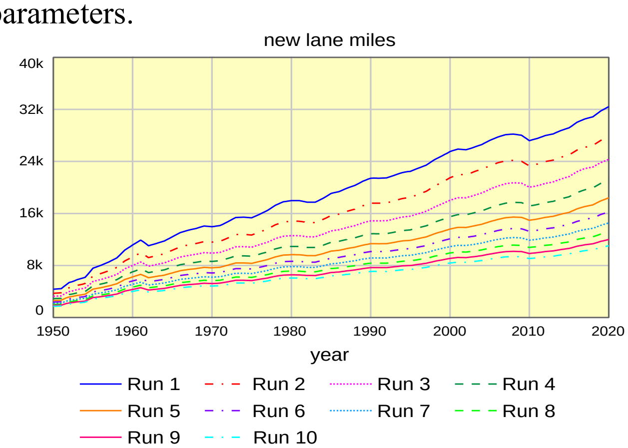

Figure 21: Sensitivity runs – new lane miles

As expected, the behavior of the important parameter depicting 'share of poor roads' and 'share of poor roads' didn't alter by big margin showing confidence in the model being built. Below figures shows the behaviors corresponding to sensitivity test done on parameter named 'new lane cost'

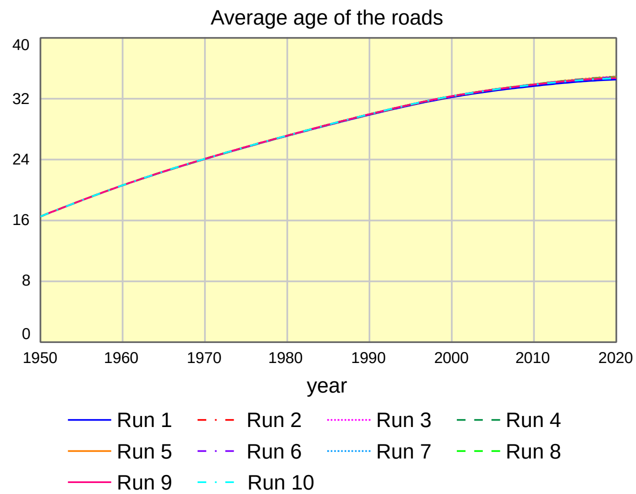

Figure 22: Sensitivity runs - average road age

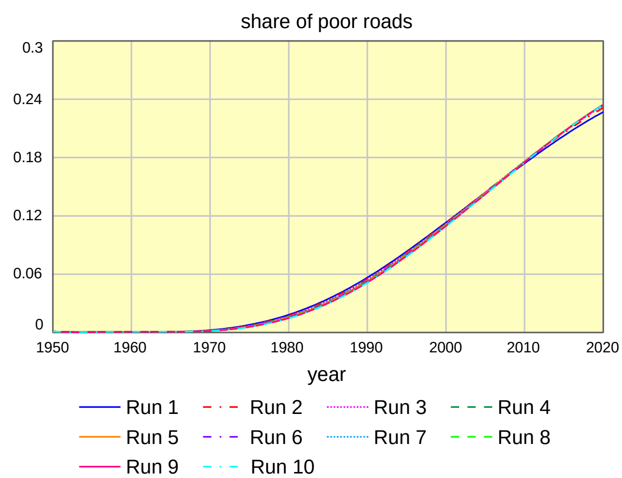

Figure 23: Sensitivity runs - average road age

4.1 Base Run

The baseline run is the model simulation in "as-it-is" scenario. This means that we start the model simulation with the initial values. The ageing chain mechanism is the core of the model and the initial value of roads in different conditions in the model corresponds to the numbers in year 1950. The initial conditions describe the road condition way better than the current one. Higher initial amount of good and poor roads and correspondingly low length of poor roads give low share of poor roads. The key variables we look at for the baseline simulation runs are decremental stock of good road, incremental and then decremental fair and mediocre roads, incremental poor roads, incremental *average road age of US, share of roads in poor condition, required maintenance expenditure* and *budget for maintenance*. Deferred maintenance is the resulting variable derived from the last two and is important for assessing the maintenance demand pressure within the system.

Both Incremental percentage of poor roads and decremental percentage of good roads are portrayed in figure below. They exhibit a corelated dynamics as there is a direct link between good roads and poor roads via fair and mediocre roads.

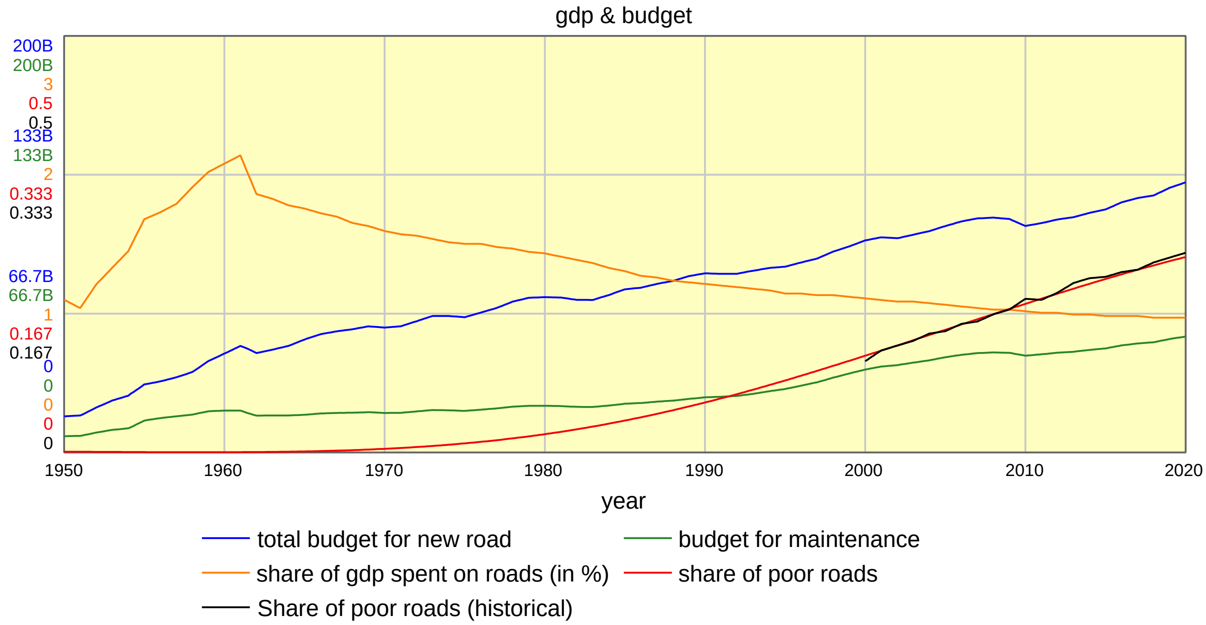

Figure 24: Base Run: share of roads in different condition

An interesting observation can be made immediately: incremental percentage of poor roads follows a somewhat s-shaped growth which is yet to satiate and will continue to grow. We can refer from the behavior graph that as the share of GDP spent on road infra decreases the share of poor roads starts to increase. Although there has been some biasness towards underfunding on maintenance activities, the overall maintenance fund has been increasing over the years.

As the initial value of good roads was way higher to begin with, the share of poor roads initially was low and even when there has been opening of new roads, the rate of opening roads hasn't been enough to compensate the roads becoming poor. Thus, the model still generates the growth in percentage of poor roads and, consequently, incremental maintenance backlog.

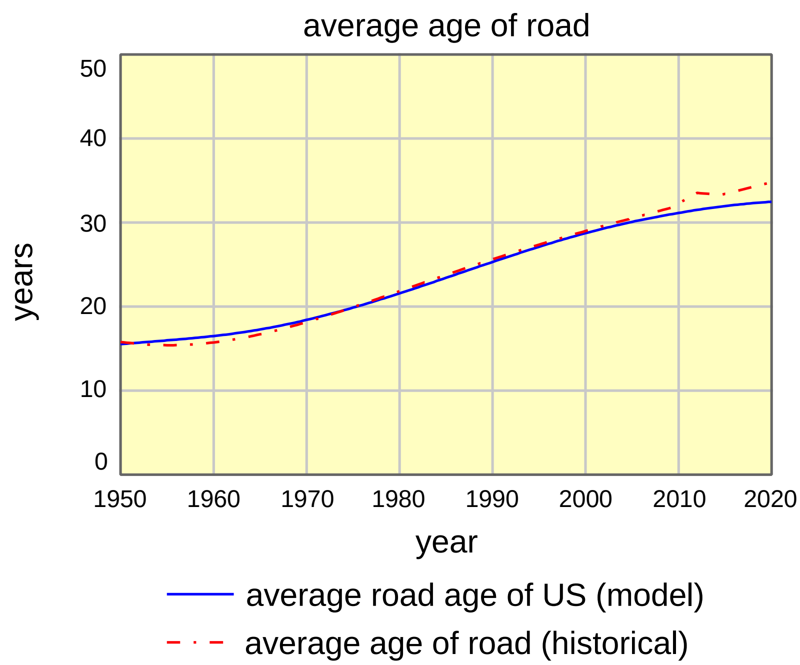

Figure 25: Base run: average age of road

The real reason for insufficient funding for maintenance is because of decreasing overall funding for road infrastructure has not been proportionately stable, if not higher. As discussed in hypothesis section under heading '**Cash-strapped highway trust fund (HTF)**' the users spending or contribution to highway trust fund has declined over the years leading to a decreasing transport spending as part of GDP even when the GDP was steadily growing. For now, an important observation is that funding for both new roads and maintenance have steady growth over the years.

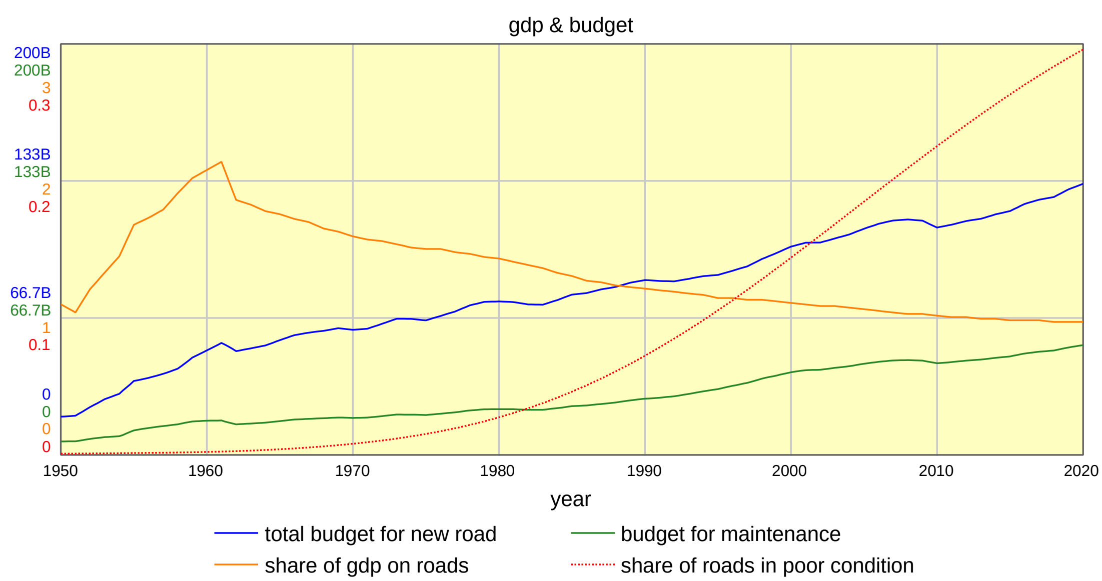

Figure 26: Base run: behavior of GDP and budget

Now to understand the underfunding on maintenance deeper the dynamics behind the decision making must be understood. The dynamics of those variables leading to bias towards funding of new roads is depicted in figure below.

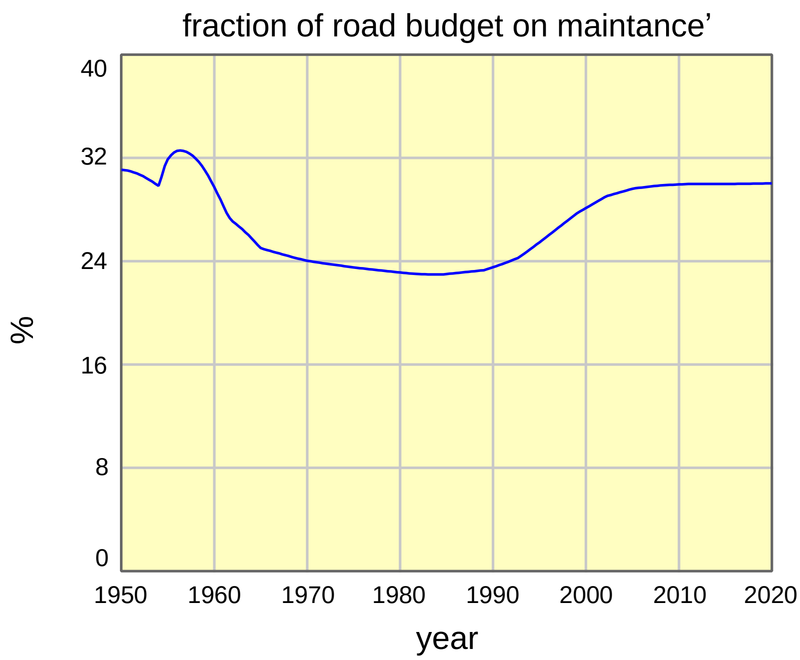

Figure 27: Base run: decision on budget allocation for new roads

As the Figure demonstrates, initially there had been growth in prioritization for funding for maintenance as the publicity loop became weaker due to lesser construction of new roads when compared to 1950. However, if we consider a smoothed graph, we will notice that the maintenance fund decreased from 30% of overall road budget to as low as 20% by 1990. There was however an increase in maintenance fund from 20% back to 30%.

Now, referring to the graph representing decision on budget allocation for new roads, we can see that the behavior of decision-making process is not varying by a big margin. After initial instability, the reinforcing loops dominates and gives a steady increase towards decision for higher budget for new roads. As the poor roads continue to increase, the balancing loops starts to dominate after around 20 years, causing increase in demand for maintenance and thus resulting in steady decrease in demand for new roads. If we consider the overall duration of simulation till 2020, the interaction of decision-making factors results a steady behavior not much different from the equilibrium dynamics.

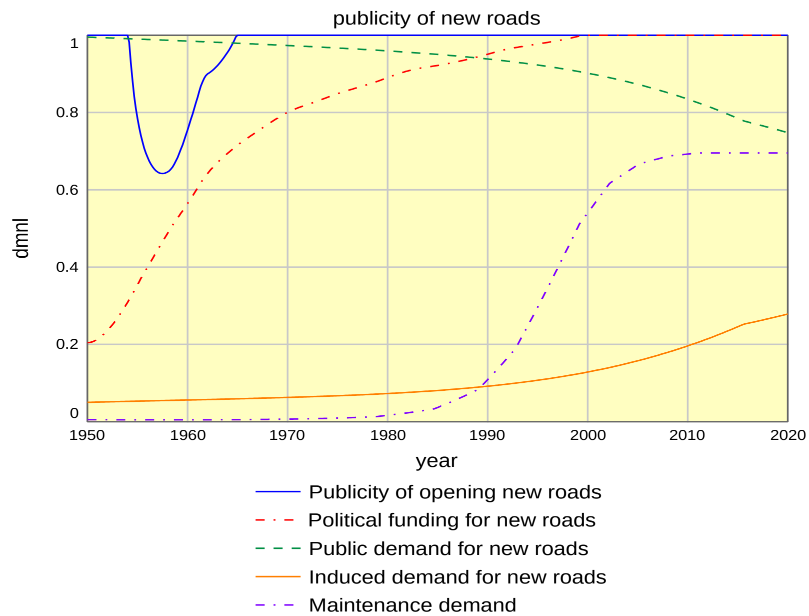

Figure 28: Base run: factors affecting decision for new road

Initially, the length of good roads was high and there was no pressure from public to change the perception. The graph showing the publicity effect explains how there was steady decrease in the publicity. The reason behind the dip was that the opening of new roads was not as high as early 50's. During 1955 the new roads opening was lower than the public reference of a good development whose value is assumed to be 10000 miles per year and thus the publicity effect dived, and it took almost 8 years to increase and public reference as good development giving the maximum reinforcement towards decision factor.

On the other hand, the approval for new roads was on increasing trend giving an incremental assurance of political funding and higher approval of new roads in following years caused reinforcing feedback loop to function allowing the effect to reach maximum by year 1985. The other reinforcing loop is one caused by the perceived need to build more roads when there is an increase in share of poor road. The perceived need for new road start with very low value which is corresponding to the initial share of poor roads which is low initially and as the share of poor roads increase, the perceived need for new roads grows steadily as shown in graph below.

'Public demand for new roads' depends on the type of reporting done (as explained in section 2.4 (Feedback Perspective). Based on the comprehensive assessment report by 'American Society of Civil Engineers. (2021)', we assumed that the information available publicly, insists on need for higher maintenance budget and following the assumption the effect of public participation on demand for new roads shows a decreasing trend. As the share of poor roads increase, the media coverage of the issue increase and that increases the public curiosity and understanding of issue based of publicly available information. Public participation increases the poll pressure on government. Assuming normal pressure from roads issues on poll to be 50%, the demand for new roads follows a decreasing behavior over time. In other words, public starts to support demand for maintenance of existing roads rather than building new roads. Finally, coming to the demand for new road as an effect of additional maintenance needs, it shows a somewhat S-shaped decay in demand for new roads.

This is explained by the fact that additional maintenance needs increase with increasing travel time on poor roads. Travel time on poor road increases when the percentage of poor roads increases. The S-shaped decay is explained by the fact that demand for maintenance would not increase increasingly when the increase in additional maintenance cost is low however as soon as additional maintenance cost goes over affordable cost the demand for maintenance needs increases increasingly thus increasing the demand of maintenance. The demand for maintenance is anchored to the fraction of overall population who feels the heat of affordability. As the percentage of population affected by additional maintenance cost nears maximum the demand for maintenance increases decreasingly, conversely the demand for new roads decreases decreasingly giving S-shaped decay.

4.1 Base Run (Simulated till 2050)

While simulating the model in 'as-it-is' scenario up until 2050, we get yet another interesting behavior. We can see that the problem of increasing cover of poor roads continue to grow and peaks in 2040 with nearly 30% of overall road in bad state i.e., nearly 1/3rd of total US road in bad state. Post 2040 the share of poor roads falls to 26% which is still higher than what it is at the current moment.

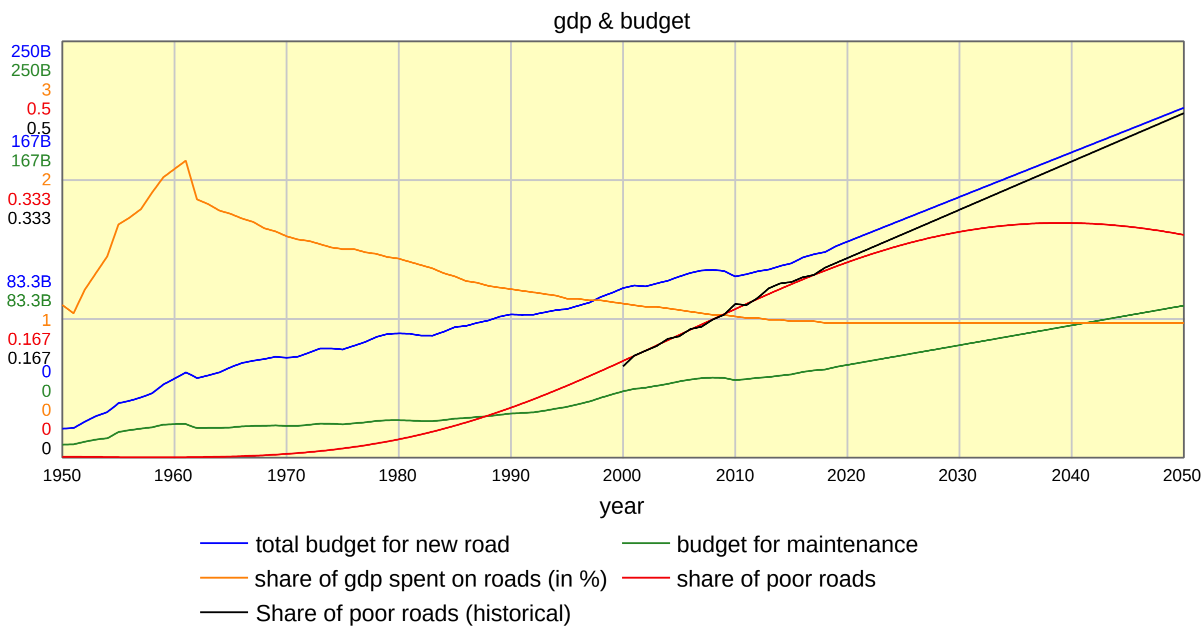

Figure 29: Base run: simulation extended till 2050

The influencing factor here being the increase in budget for building new roads. With the GDP assumed to grow at same rate, even if the budget allocation remains as it is, the actual roads being constructed will be higher and the stock of good roads will start to grow. Similarly rate of natural retirement will deplete the stock of poor roads and the percentage of poor roads will fall to 26%.

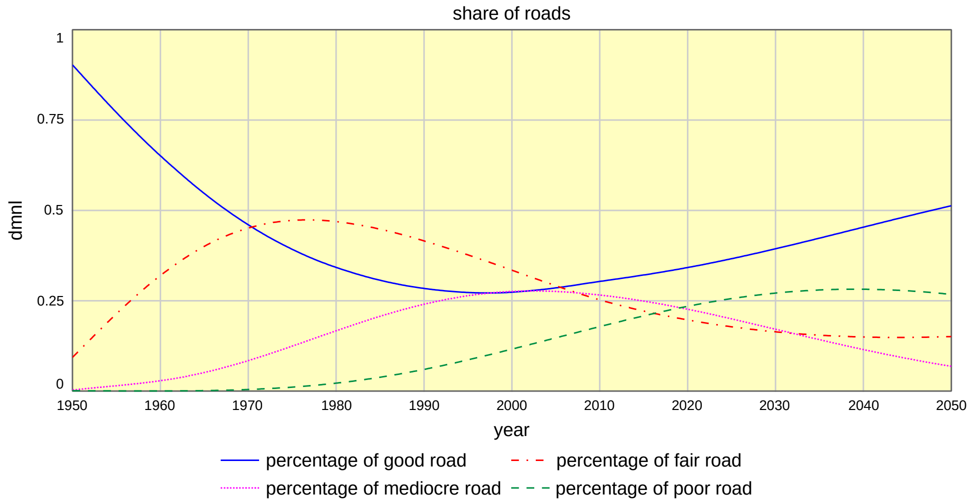

Figure 30: Base run: extended till 2050

After referring to the simulation run till 2050 one could argue that there is no need for policy interventions as the problematic behavior disappears partially over some period of time however while making that conclusion one must realize that the exogenous parameter such as GDP, Share of GDP spent on roads, cost of maintenance and building new roads has been considered to remain as it is over model run time which may not be realistic. Below shared are the results from 4 different scenario analysis i.e.,

Scenario 1: While running simulation having two exogeneous parameters; gdp *and share of gdp spent on road* as continuous. Meaning the both the gdp and share of gdp spent on road would remain same as that of year 2020.

Scenario 2: While running simulation having *gdp as* continuous *and share of gdp spent on road* as extrapolated. Meaning the *gdp* would remain same as that of year 2020 while *share of gdp spent on road* would follow behavior with respect to previous history.

Scenario 3: While running simulation having *gdp as* extrapolated *and share of gdp spent on road* as continuous. Meaning the *gdp* would follow behavior with respect to previous history while and *share of gdp spent on road* would remain same as that of year 2020.

Scenario 4: While running simulation having two exogeneous parameters; gdp *and share of gdp spent on road* as extrapolated. Meaning both the gdp and share of gdp spent on road would follow behavior with respect to previous history.

The results shared below shows that scenario 3 and 4 follows the same behaviour. In this case the total road length increases from 4.05 million miles in 2020 to 4.48 million miles in 2050. However, when the gdp was kept constant i.e., scenario 1 and 2 the total road length increased from 4.05 million miles in 2020 to 4.26 million miles in 2050.

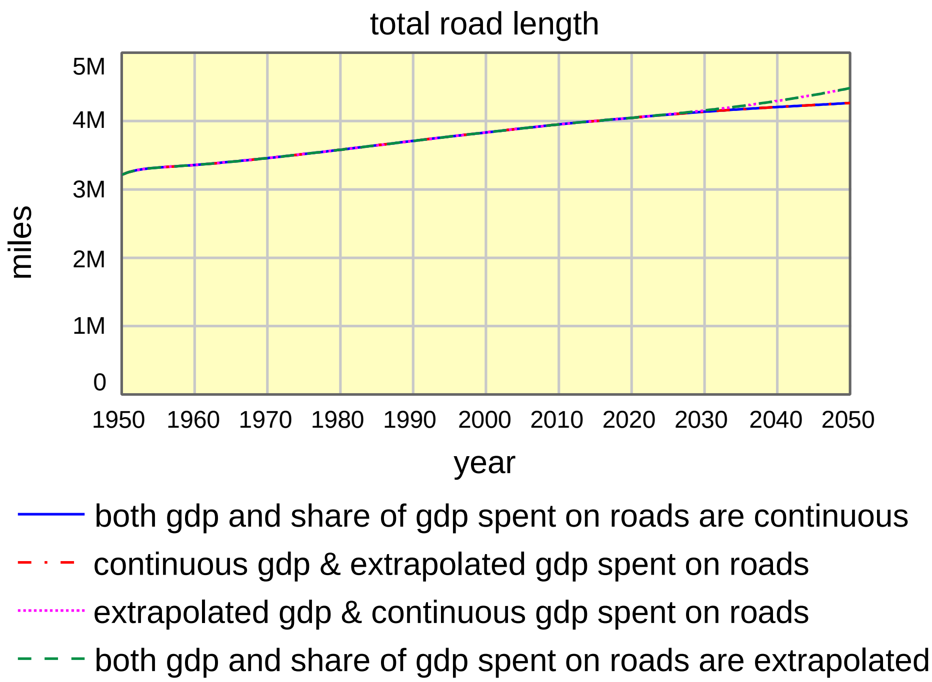

Figure 31: scenario analysis 1

Similar was the case with share of poor roads, scenario 3 and 4 follows the same behaviour. In this case the share of poor roads increased from 23% in 2020 to 26% in 2050. However, when the gdp was kept constant i.e., scenario 1 and 2 the the share of poor roads increased from 23% in 2020 to 29% in 2050.

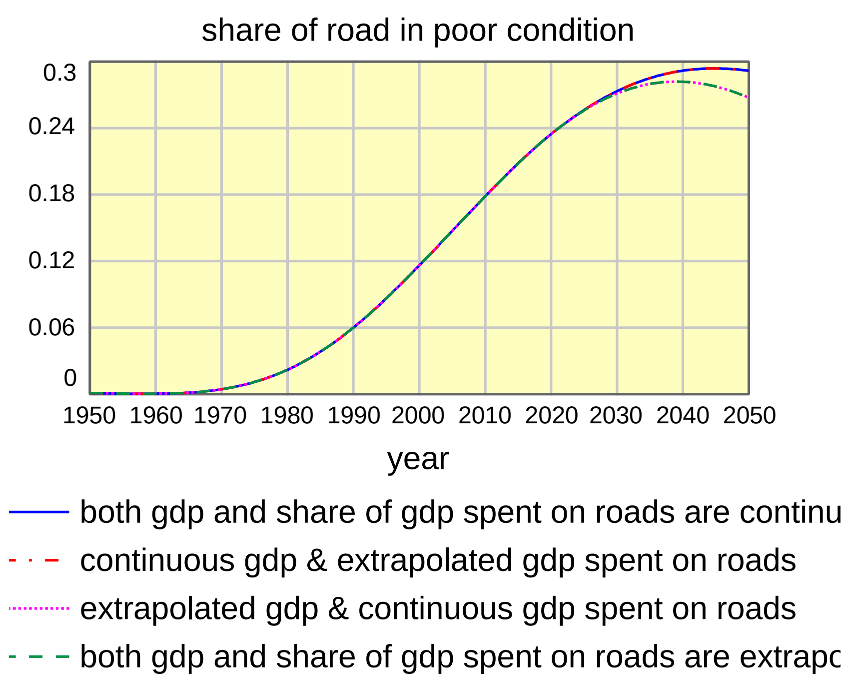

Figure 32: scenario analysis 2

Chapter 5. Policy Suggestions

As discussed earlier, incorporating the economics of highway trust fund and interaction on highway trust fund and overall GDP was not included in the boundary of this project however we did validate that the decreasing share of overall GDP invested on road could be because of the decreasing contribution from users' fee to the highway fund. By the 1980s, the relationship between the amount of money paid by drivers and the amount spent on highways had begun to weaken and since 2005, the bottom has fallen out of the "users pay" model of transportation finance in the United States (Dutzik, T., et. al., 2015)citing this one of the policies could be as follows-

Tax Adjustment

Tax-rate adjustments to make up for revenue lost due to weakening of user fees. The fuel efficiency could be determined by dividing miles driven by vehicle category by the total amount of fuel consumed by that category and comparing the quotient to the previous year. Although fuel-economy standards for new vehicles are to rise over the next few years, the average efficiency of the entire vehicle fleet will rise slowly because of the large number of older vehicles on the road. Second policy could be to introduce

Vehicle Miles Traveled Charges (VMT)

Economists have long favored mileage-based user charges as an alternative source of highway funding (Sorensen, P., et. al., 2012). Under the user charge concept, motorists would pay fees based on distance driven and, perhaps, on other costs of road use, such as wear and tear on roads, traffic congestion, and air pollution. The funds collected would be spent for surface transportation purposes. And finally, a policy of accelerated retirement.

Accelerated retirement of poor roads

This policy might need one time funding from the government and lot of scenario analysis and feasibility analysis need to be carried out to weigh cost-benefit ratio. However, this could be a suitable alternative to reduce the cover of poor roads and eventually get rid of huge backlog of maintenance cost. This policy was chosen for the analysis as the rate of retirement was inside the boundary of analysis and the analysis could be done easily by considering policy period.

While considering Policy Period of 10 years:

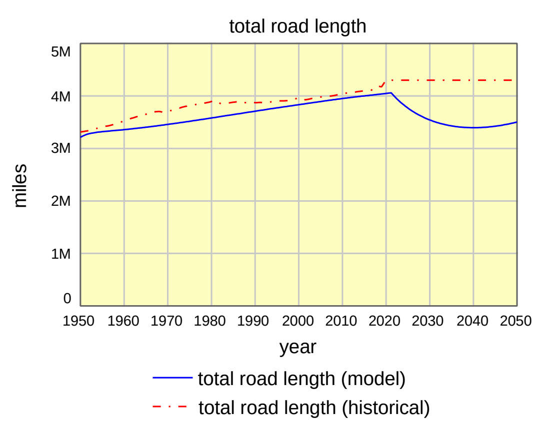

Figure 33: Policy scenario analysis

Results shared above shows that the overall length of road will be reduced from 4.5 million miles in 2020 to 3.5 million miles in 2050 which is still higher than 3.2 million miles in 1950.

Share of roads in poor condition follows decreasing trend as expected. The result shows that the share of poor roads falls from 23% in 2020 to 5% in 2050. The result comes at the cost of total length or roads however it would still mean that the roads condition would improve.

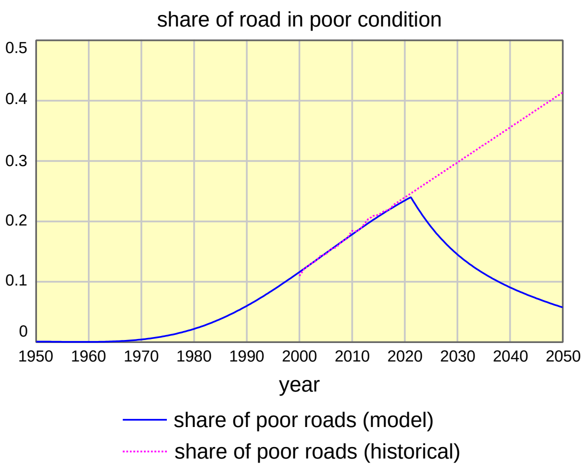

Figure 34: Policy scenario analysis

Now let's see the behaviour of maintenance backlog. Result shows that the maintenance backlog would no longer grow, and it would stagnate at the level corresponding to 2050

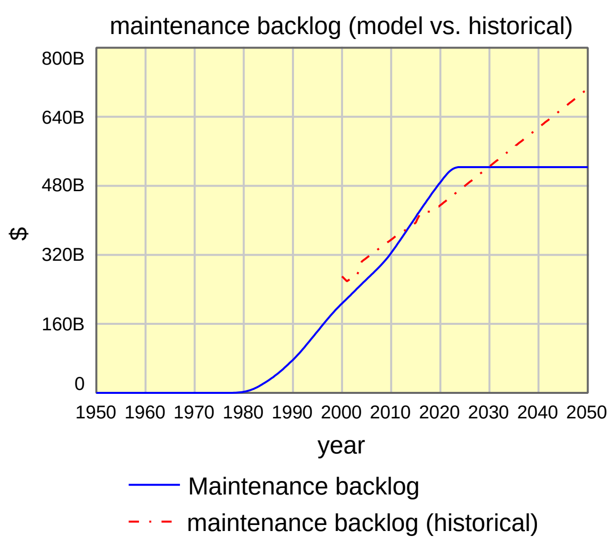

Figure 35: Policy scenario analysis

While considering Policy Period of 20 years:

Results shared below shows that the overall length of road will be reduced from 4.5 million miles in 2020 to 3.72 million miles in 2050 which is still higher than 3.2 million miles in 1950.

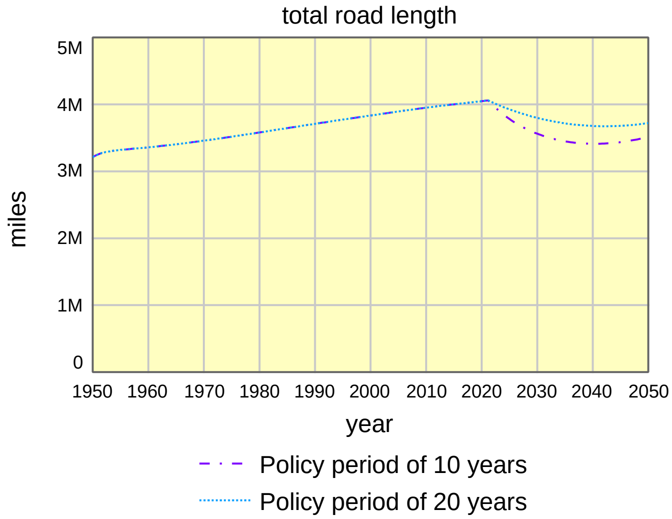

Figure 36: Policy scenario analysis

Share of roads in poor condition follows decreasing trend as expected. The result shows that the share of poor roads falls from 23% in 2020 to 11% in 2050.

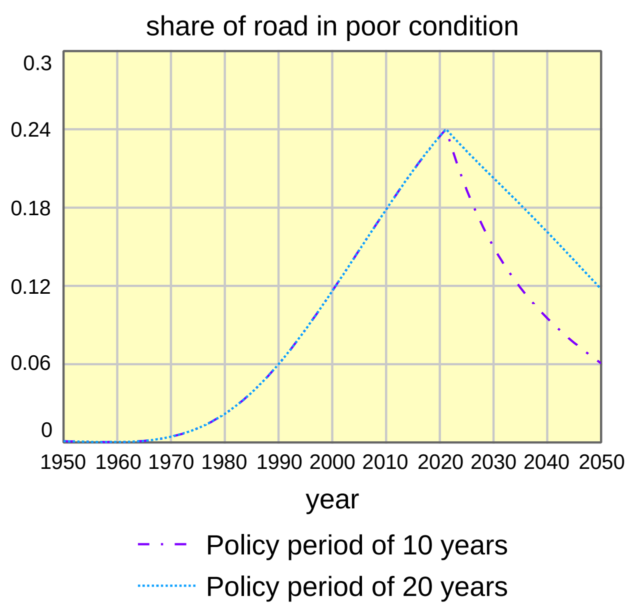

Figure 37: Policy scenario analysis

Thus, it is very easy to conclude that lesser the policy period more aggressive will be the results and longer the policy period more realistic will be the results.

Although a very basic policy scenario analysis is performed as part of this research, a more detailed policy feasibility analysis and implementation analysis must be done. The policy analysis and implementation feasibility of this thesis could be a potential project for model based policy implementation course.

Conclusions

Even though this project started having engineering perspectives of roads degradation due to increasing traffic and maintenance needs in center, we realized the aspect chosen to be addressed specifically by this project is its close interconnection with the foregone roadways growth in USA.

In other words, in accordance with the formulated problem definition, research objectives and research questions, condition of road, maintenance needs and ageing of road infrastructure are indispensably interconnected as the dynamics of the one changes the dynamics of the other. Thus, in this project both the condition of road and the ageing chain of road were considered to be equally important.

Although all the underlying hypothesis holds true when it comes to decision making process; the problem of increasing cover of poor roads and sky-rocketing maintenance backlog is not because of underspending caused by biasness towards new roads. Although the biasness exist it is not to the extent to cause such major funding gap.

The gap is explained by the fact that the average age of roads in US has been increasing causing increase in maintenance demands and thus the maintenance budget has not been enough to fill the gap. The average age of U.S. highways and streets is almost 34 years, the oldest in records dating back to 1925, according to *Bureau of Economic Analysis* figures, as government spending on new civil projects lags. What's worse, in the last five years through 2015, the average age of roadways has increased by the most since 1946. The model as well as the historical behavior confirms the same.

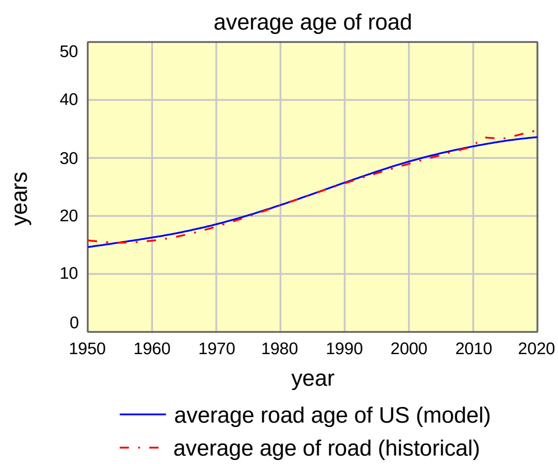

Figure 31: Behavior: Average age of US road

Similar is the case of increasing share of poor roads in the US. Because there had been mega expansion of highway network and construction of roads in 50's, the aging has caused all those roads to become mediocre or poor and the new road construction has not been done to the par with 50's, increasing the share of poor roads in the US. Below graph plotted, shows the relationship between 'share of gdp spent on roads' and the 'share of poor roads.' As the US government started to cut the share of road infrastructure spending as a share of the economy, the cover of poor roads started to grow. Share of poor roads, which was less than 10% till 1990 increased nearly up to 25%. Spending by the government on road transportation dropped from its high of 2.2 percent of the nation's gross domestic product (GDP) in the late 1960s to less than 1 percent in 2020. Falling federal spending on infrastructure is exacerbating the problem.

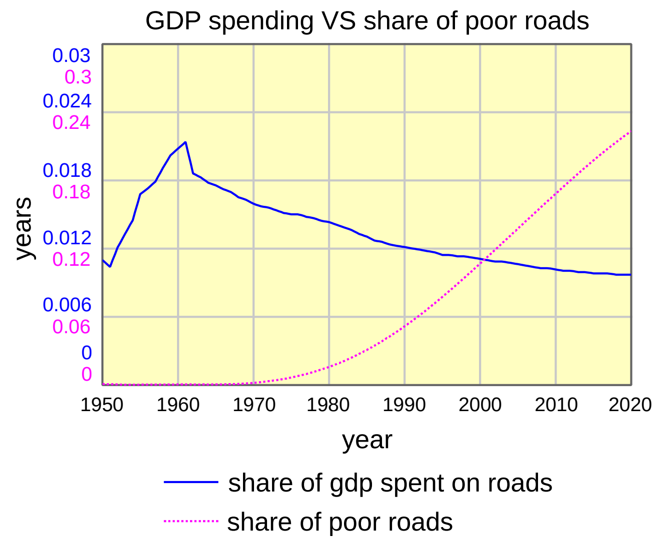

Figure 32: GDP spending VS. share of poor roads

Referring to all the above analysis and results it can be concluded that the research objectives has been met and we have found answers to all the research question listed in section 1.3.

Limitations and Further Work

This study contributes to the literature in several different ways. First, it presents an SD model that allows researchers to analyze the development of road networks in a global and integrated way. Whereas the literature offers multiple examples of SD models within the road infrastructure sector, this study provides a simulation tool capable of recreating the feedback mechanisms associated with the evolution of the road network condition, considering the budgetary decision making processes and interventions, and describing the role played by the interaction of general public, politicians and construction and maintenance stakeholders.

Since the model employs traditional system dynamics formulations, it can be adapted to reflect the specific conditions of any road network worldwide with the help of further studies. Future studies can strengthen this contribution by exploiting the design and engineering perspectives of road infrastructure.

Although the study has addressed the interaction of feedback loops related to decision making of budget allocation, it has some limitations imposed by its scope and assumptions, as discussed in previous sections. For instance, the SD model is based on ageing chain mechanisms. It does not incorporate variables related to climatic factors, vehicle data, and geotechnical conditions. Similarly, the policy structure and policy scenario analysis could be done to assess the feasibility and applicability of the suggested policies.

Further research is required in multiple fields to overcome the limitations in this study. In order to improve the decision-making processes associated with road network preservation, it is necessary to integrate experts from various areas, such as paving engineering, infrastructure systems management, highway economics and interaction with overall economy of the country. In this way, a model that analyzes all the involved sectors at the same level of detail, understands all the factors that affect the deterioration phenomena, and includes user costs in the analysis could be developed. Also, understanding the dynamics in the economic sector could achieve a better quantification and evaluation of costs. Finally, running optimization simulations to construct concrete framework for designing effective maintenance policy would increase applicability of the SD approach for operational and tactical decision.

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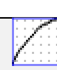
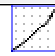
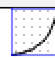
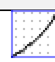
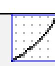
Appendix A. Model Documentation

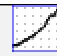
The following pages provide the complete model documentation generated by the Stella software, used for the model construction. The documentation includes all the equations, units, initial and parameter values, graphical functions specifications and notes on sources for estimated values, functioning of switches, etc. We hope this documentation would be sufficient for better understanding of the model and potential reproduction by an interested reader.

	Parameter	Equation	Properties	Units	Documentations
	fair(t)	fair(t - dt) + (good_roads_becoming_fair - fair_roads_becoming_mediocre - maintenance_of_fair_road) * dt	INIT fair = 300000 {value calibrated to fit reference mode calculated value is 312975 miles}	mile	The International Roughness Index (IRI) measures the cumulative deviation from a smooth surface in inches per mile. Roads with IRI between 95 to 130 qualifies for fair road. Source: https://www.fhwa.dot.gov/policy/2015cpr/chap3.cfm
	good(t)	good(t - dt) + (opening_of_new_roads + reopening + maintenance_of_poor_road + maintenance_of_mediocre_road + maintenance_of_fair_road - good_roads_becoming_fair) * dt	INIT good = 2900000 {value calibrated to fit reference mode calculated value is 3312975 miles }	mile	The International Roughness Index (IRI) measures the cumulative deviation from a smooth surface in inches per mile. Roads with IRI < 95 qualifies for good road. Source: https://www.fhwa.dot.gov/policy/2015cpr/chap3.cfm
	information_publicly_available(t)	information_publicly_available(t - dt) + (related_issues_reporting) * dt	INIT information_publicly_available = 0.1	dmnl	Information publicly available in forms of research report, news report and any other form of print or TV media. It is assumed that information publicly available is only 10%
	Maintenance_backlog(t)	Maintenance_backlog(t - dt) + (deferred_maintenance) * dt	INIT Maintenance_backlog = 0	$	The maintenance backlog is a time indicator that represents all the maintenance work required that has not yet been completed. Maintenance backlog quantifies the amount of money (in $) needed to perform pending maintenance actions.
	mediocre(t)	mediocre(t - dt) + (fair_roads_becoming_mediocre - mediocre_roads_turning_poor - maintenance_of_mediocre_road) * dt	INIT mediocre = 10000	mile	The International Roughness Index (IRI) measures the cumulative deviation from a smooth surface in inches per mile. Roads with IRI between 130 to 170 qualifies for mediocre road. Source: https://www.fhwa.dot.gov/policy/2015cpr/chap3.cfm
	poor(t)	poor(t - dt) + (mediocre_roads_turning_poor - Natural_retirement - Accelarated_road_retirements - maintenance_of_poor_road) * dt	INIT poor = 2975	mile	The International Roughness Index (IRI) measures the cumulative deviation from a smooth surface in inches per mile. Roads with IRI > 170 qualifies for mediocre road. Source: https://www.fhwa.dot.gov/policy/2015cpr/chap3.cfm
	public_interest_on_budget_allocation_for_roads(t)	public_interest_on_budget_allocation_for_roads(t - dt) + (net_change_in_public_interest) * dt	INIT public_interest_on_budget_allocation_for_roads = 0.1	dmnl	
	roads_under_construction(t)	roads_under_construction(t - dt) + (new_lane_miles_approved - opening_of_new_roads) * dt	INIT roads_under_construction = 100000 {1000000	mile	Stock of roads under construction refers to the roads which were approved to be under construction. Section 7 of the Federal-Aid Highway Act of 1944 directed designation of a 40,000-mile National System of Interstate Highways which were mostly unpaved and were

					approved for construction. Based on the available report, we have assumed that total roads under construction in US in 1950 to be 100000 miles Source: https://www.fhwa.dot.gov/infrastructure/50interstate.cfm
	Accelarated_road_retirements	poor//policy_time_to_retire_roads		miles/year	Policy intervention to retire the poor roads before the natural retirement
	deferred_maintenance	((required_maintenance_expenditure)-required_maintenance_expenditure)*0+ IF budget_for_maintenance>required_maintenance_expenditure THEN 0 ELSE required_maintenance_expenditure-budget_for_maintenance		$/year	Deferred maintenance refers to the maintenance cost that were put on hold annually due to lack of maintenance funds. In other words, it is difference between required maintenance expenditures and actual budget for maintenance.
	fair_roads_becoming_mediocre	MAX(fair_road_condition_inspection_delay, 0)		miles/year	The rate at which fair roads deteriorate to mediocre following aging and deterioration
	good_roads_becoming_fair	MAX(good_road_condition_inspection_delay, 0)		miles/year	The rate at which good roads deteriorate to fair following aging and deterioration
	maintenance_of_fair_road	budget_for_maintenance*percentage_of_maintenance_budget_on_fair_and_mediocre_roads/maintenance_cost_for_fair_road		miles/year	Rate of maintenance of fair roads to good roads
	maintenance_of_mediocre_road	budget_for_maintenance*percentage_of_maintenance_budget_on_fair_and_mediocre_roads/maintenance_cost_for_mediocre_roads		miles/year	Rate of maintenance of mediocre roads to good roads
	maintenance_of_poor_road	IF poor_roads_available_for_maintenance<actual_road_to_be_maintained THEN 0 ELSE actual_road_to_be_maintained {MAX((budget_for_maintenance/maintenance_cost_for_poor_roads)*percentage_of_maintenance_budget_on_poor_roads, 0)		miles/year	Rate of maintenance of poor roads to good roads
	mediocre_roads_turning_poor	MAX(DELAYN(mediocre/service_life_of_mediocre_road, 10, 2, INIT(mediocre/service_life_of_mediocre_road)), 0)		miles/year	The rate at which mediocre roads deteriorate to poor following aging and deterioration
	Natural_retirement	poor/service_life_of_poor_road {IF poor=0 THEN 0 ELSE MAX(DELAYN(poor/service_life_of_poor_road, 10, 2, INIT(poor/service_life_of_poor_road)), 0) {(poor/Time_as_old)		miles/year	Rate at which roads retire following the aging mechanism
	net_change_in_public_interest	(gap_of_public_participation*informed_public_with_issues_clarity)/time_taken_to_change_public_interest		dmnl/year	The rate at which public interest develops towards participation is based on awareness level of general public
	new_lane_miles_approved	new_lane_miles		miles/year	
	opening_of_new_roads	roads_under_construction/time_to_commission		miles/year	The rate at which new roads from under construction get commissioned for public use
	related_issues_reporting	effect_of_increasing_poor_roads_on_media_interest*research_reporting_and_press_coverage		dmnl/year	
	reopening	(Natural_retirement+Accelarated_road_retirements)*fraction_of_retired_roads_reopen		miles/year	Rate of rehabilitation of roads which are retiring due to deterioration of roads exceeding acceptable limit
	actual_road_to_be_maintained	(budget_for_maintenance*percentage_of_maintenance_budget_on_poor_roads)/maintenance_cost_for_poor_roads		miles/year	
	additional_maintenance_cost_per_mile	0.5		$/mile	
	assurance_for_new_road_based_on_rel	GRAPH(relative_political_funding) Points: (0.00, 0.000), (1.00, 0.204704191101), (2.00, 0.373647966026), (3.00, 0.51307842386),		dmnl	The cost of political campaigns has been increasing over the years hence the

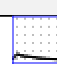
	ative_political_funding	(4.00, 0.628151338387), (5.00, 0.723121805124), (6.00, 0.801501583626), (7.00, 0.866188953175), (8.00, 0.919575883568), (9.00, 0.963636483909), (10.00, 1.000)			assurance for new road is based on relative political funding.
	average_additional_cost	distance_driven_on_bad_roads*additional_maintenance_cost_per_mile		$/year	
	average_age_of_fair_roads	30		year	The average age of good, fair, mediocre and poor roads were based on Ruiz et. al., 2020 but the initialisation value was calculated using partial-calibration method (Homer, 1983)
	average_age_of_good_roads	15		year	The average age of good, fair, mediocre and poor roads were based on Ruiz et. al., 2020 but the initialisation value was calculated using partial-calibration method (Homer, 1983)
	average_age_of_mediocre_roads	40		year	The average age of good, fair, mediocre and poor roads were based on Ruiz et. al., 2020 but the initialisation value was calculated using partial-calibration method (Homer, 1983)
	average_age_of_poor_roads	60 {70		year	The average age of good, fair, mediocre and poor roads were based on Ruiz et. al., 2020 but the initialisation value was calculated using partial-calibration method (Homer, 1983)
	"average_age_of_road_(historical)"	GRAPH(TIME) Points: (1950.00, 15.79), (1952.69230769, 15.4884090909), (1955.38461538, 15.3969482517), (1958.07692308, 15.5159050699), (1960.76923077, 15.8346762339), (1963.46153846, 16.3347671877), (1966.15384615, 16.9924016234), (1968.84615385, 17.7807607726), (1971.53846154, 18.6718724564), (1974.23076923, 19.6381698554), (1976.92307692, 20.6537399596), (1979.61538462, 21.6952816586), (1982.30769231, 22.7427934327), (1985.00, 23.7800106061), (1987.69230769, 24.7946121212), (1990.38461538, 25.7782167959), (1993.07692308, 26.7261890231), (1995.76923077, 27.6372738743), (1998.46153846, 28.5130815667), (2001.15384615, 29.3574412539), (2003.84615385, 30.1756441029), (2006.53846154, 30.9735956149), (2009.23076923, 31.7568971521), (2011.92307692, 33.5298766317), (2014.61538462, 33.294588345), (2017.30769231, 34.0498018648), (2020.00, 34.79)		year	https://www.bloomberg.com/news/articles/2018-01-30/america-s-highways-and-byways-are-rapidly-getting-older
	average_age_relative_to_age_of_good_roads	average_road_age_of_US/service_life_of_good_road		dmnl	The ratio of average age of road in the US to that of age of good road, if the ratio is equal to or less than 1 that would mean the maintenance cost is lower however as the ratio increases the maintenance cost is bound to increase
	average_distance_per_trip	40*365 {40 miles/trip 40*365 miles/year}		miles/year	https://www.bts.gov/statistical-products/surveys/national-household-travel-survey-daily-travel-quick-facts
	average_maintenance_cost_per_public_mileage	10500		$/mile/year	Cost incurred to repair unit mile of public road. Value calibrated to match the reference mode.
	average_road_age_of_US	(good*average_age_of_good_roads+fair*average_age_of_fair_roads+mediocre*average_a		year	Mathematical average age of total road length in US.

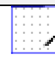
		ge_of_mediocre_roads+poor*average_age_of_poor_roads)/(good+fair+mediocre+poor)			
	budget_dependent_on_decision	0.6*total_road_budget		$/year	
	budget_for_maintenance	minimum_share_for_maintenance*total_road_budget+ (budget_dependent_on_decision-(budget_dependent_on_decision*share_of_budget_allocation_for_new_roads)) {total_road_budget*decision_factor		$/year	Actual budget available for carrying out maintenance of roads in the US every year.
	demand_for_new_road	1-effect_of_increasing_maintenance_cost_on_maintenance_demand		dmnl	
	distance_driven_on_bad_roads	average_distance_per_trip*share_of_poor_roads		miles/year	
	effect_of_average_road_age_on_maintenance_expenditures	GRAPH(average_age_relative_to_age_of_good_roads) Points: (0.500, 0.100), (0.750, 0.528789745102), (1.000, 1.000), (1.250, 1.61390488918), (1.500, 2.2938078746), (1.750, 3.08375569172), (2.000, 4.000)		dmnl	Average road age has an impact on maintenance expenditures of the road. The value of this graphical integration has been based research done by Kahn, M. E., & Levinson, D. M. (2011), the cost of maintenance rises to 2-folds (4 times) when the age of infrastructure rises by 1-fold (2 times).
	effect_of_increasing_maintenance_cost_on_maintenance_demand	GRAPH(relative_increase_in_maintenance_cost_due_to_driving_on_poor_road) Points: (0.0, 0.004684995647), (20.0, 0.0125903469735), (40.0, 0.0331981112243), (60.0, 0.0834420454155), (80.0, 0.188258994959), (100.0, 0.3500), (120.0, 0.511741005041), (140.0, 0.616557954585), (160.0, 0.666801888776), (180.0, 0.687409653027), (200.0, 0.695315004353)		dmnl	
	effect_of_increasing_poor_roads_on_media_interest	GRAPH(share_of_poor_roads) Points: (0.000, 0.012), (0.100, 0.029), (0.200, 0.052), (0.300, 0.087), (0.400, 0.121), (0.500, 0.179), (0.600, 0.237), (0.700, 0.312), (0.800, 0.457), (0.900, 0.694), (1.000, 1.000)		dmnl	This is based on a basic assumption that the share of poor roads increases the media interest to report about the issue and grab both public's and government's attention.
	effect_of_perceived_increase_in_poor_roads_on_demand_for_new_roads	effect_of_perceived_need_for_more_roads*(informed_public_with_issues_clarity)		dmnl	The perceived need for new roads also depends on media reporting and people reading those news. The effect of induced demand for new road and public awareness combined together determines the overall demand
	effect_of_perceived_need_for_more_roads	GRAPH(perceived_poor_roads) Points: (0.000, 0.5000), (0.200, 0.53060351228), (0.400, 0.564425624043), (0.600, 0.601804838351), (0.800, 0.643115258945), (1.000, 0.688770334399), (1.200, 0.739226996053), (1.400, 0.794990231137), (1.600, 0.856618136849), (1.800, 0.924727505984), (2.000, 1.0000)		dmnl	As the poor roads increase there is an induced demand for more new roads and hence public starts to raise voice for more new roads
	effect_of_public_interest_on_supportive_poll	effect_of_perceived_increase_in_poor_roads_on_demand_for_new_roads*public_interest_on_budget_allocation_for_roads		dmnl	
	effect_of_public_participation_on_demand_for_new_road	1-pressure_on_gov_to_change_perception		dmnl	Public participation determines the decision making process as government is wary of vote bank. This is defined as Power politics.
	effect_of_publicity_on_approval_of_new_roads	GRAPH(publicity_of_new_roads) Points: (0.000, 0.000), (0.100, 0.0612070245601), (0.200, 0.128851248086), (0.300, 0.203609676702), (0.400, 0.28623051789), (0.500, 0.377540668798), (0.600, 0.478453992107), (0.700, 0.589980462274),		dmnl	

		(0.800, 0.713236273698), (0.900, 0.849455011967), (1.000, 1.000)			
	fair_road_condition_inspection_delay	DELAYN(fair/service_life_of_bad_road, 10, 2, INIT(fair/service_life_of_bad_road))		miles/year	Delay in inspection and checks to ascertain the condition of road
	fraction_of_retired_roads_reopen	0		dmnl	
	gap_of_public_participation	ideal_public_participation-public_interest_on_budget_allocation_for_roads		dmnl	gap between ideal participation (100%) and the current level of public participation
	gdp	GRAPH(TIME) Points: (1950.00, 2.29e+12), (1951.00, 2471371428570), (1952.00, 2572114285710), (1953.00, 2690814285710), (1954.00, 2680914285710), (1955.00, 2857357142860), (1956.00, 2926771428570), (1957.00, 2987800000000), (1958.00, 2974514285710), (1959.00, 3151514285710), (1960.00, 3248285714290), (1961.00, 3330800000000), (1962.00, 3513028571430), (1963.00, 3674214285710), (1964.00, 3873400000000), (1965.00, 4116357142860), (1966.00, 4383142857140), (1967.00, 4538371428570), (1968.00, 4734400000000), (1969.00, 4901285714290), (1970.00, 4948428571430), (1971.00, 5065100000000), (1972.00, 5298457142860), (1973.00, 5587114285710), (1974.00, 5667285714290), (1975.00, 5649285714290), (1976.00, 5836085714290), (1977.00, 6117928571430), (1978.00, 6431000000000), (1979.00, 6690828571430), (1980.00, 6766714285710), (1981.00, 6854828571430), (1982.00, 6863142857140), (1983.00, 6970914285710), (1984.00, 7382857142860), (1985.00, 7792000000000), (1986.00, 8084571428570), (1987.00, 8360357142860), (1988.00, 8673742857140), (1989.00, 9010928571430), (1990.00, 9266571428570), (1991.00, 9361442857140), (1992.00, 9487000000000), (1993.00, 9787985714290), (1994.00, 10100571428600), (1995.00, 10451285714300), (1996.00, 10767485714300), (1997.00, 11192328571400), (1998.00, 11684171428600), (1999.00, 12209900000000), (2000.00, 12759571428600), (2001.00, 13166557142900), (2002.00, 13321400000000), (2003.00, 13586742857100), (2004.00, 13999457142900), (2005.00, 14514642857100), (2006.00, 14998000000000), (2007.00, 15391485714300), (2008.00, 15622400000000), (2009.00,		$/year	The current base year for GDP calculations is 2012. The period from which the weights for a measurement series are derived. https://www.thebalance.com/us-gdp-by-year-3305543

		15542771428600), (2010.00, 15264714285700), (2011.00, 15630114285700), (2012.00, 15881685714300), (2013.00, 16226800000000), (2014.00, 16530742857100), (2015.00, 16949142857100), (2016.00, 17449085714300), (2017.00, 17748700000000), (2018.00, 18159542857100), (2019.00, 18693771428600), (2020.00, 19092000000000)			
	good_road_condition_inspection_delay	DELAYN(good/service_life_of_good_road, 10, 2, INIT(good/service_life_of_good_road))		miles/year	Delay in inspection and checks to ascertain the condition of road
	ideal_public_participation	1		dmnl	The most favorable situation for any country is to have 100% of public participation in decision making process related to public infrastructure
	informed_public_with_issues_clarity	information_publicly_available		dmnl	Information is available is co-related to awareness of informed public
	"maintenance_backlog_(historical)"	GRAPH(TIME) Points: (1950.00, NaN), (1951.00, NaN), (1952.00, NaN), (1953.00, NaN), (1954.00, NaN), (1955.00, NaN), (1956.00, NaN), (1957.00, NaN), (1958.00, NaN), (1959.00, NaN), (1960.00, NaN), (1961.00, NaN), (1962.00, NaN), (1963.00, NaN), (1964.00, NaN), (1965.00, NaN), (1966.00, NaN), (1967.00, NaN), (1968.00, NaN), (1969.00, NaN), (1970.00, NaN), (1971.00, NaN), (1972.00, NaN), (1973.00, NaN), (1974.00, NaN), (1975.00, NaN), (1976.00, NaN), (1977.00, NaN), (1978.00, NaN), (1979.00, NaN), (1980.00, NaN), (1981.00, NaN), (1982.00, NaN), (1983.00, NaN), (1984.00, NaN), (1985.00, NaN), (1986.00, NaN), (1987.00, NaN), (1988.00, NaN), (1989.00, NaN), (1990.00, NaN), (1991.00, NaN), (1992.00, NaN), (1993.00, NaN), (1994.00, NaN), (1995.00, NaN), (1996.00, NaN), (1997.00, NaN), (1998.00, NaN), (1999.00, NaN), (2000.00, 2.7e+11), (2001.00, 258526315789), (2002.00, 267105263158), (2003.00, 270715170279), (2004.00, 304334365325), (2005.00, 312941176471), (2006.00, 321513931889), (2007.00, 330030959752), (2008.00, 338470588235), (2009.00, 346811145511), (2010.00, 3.55e+11), (2011.00, 3.64e+11), (2012.00, 3.72e+11), (2013.00, 3.78e+11), (2014.00, 3.85e+11), (2015.00, 3.95e+11), (2016.00, 4.18e+11), (2017.00, 4.2e+11), (2018.00, 4.2e+11), (2019.00, 4.26e+11), (2020.00, 4.35e+11)		$	
	maintenance_cost_for_fair_road	1e6		$/mile	
	maintenance_cost_for_mediocre_roads	2e6		$/mile	
	maintenance_cost_for_poor_roads	3000000		$/mile	
	maintenance_period	1		year	

	minimum_share_for_maintenance	0.1		dmnl	This is the minimum share of total money allocated for maintenance irrespective of budget allocation decision making discussion/debate
	minimum_share_for_new_roads	0.3		dmnl	
	new_lane_cost	5e6		$/mile	Cost of building a new road source: https://www.artba.org/about/faq/#:~:text=Construct%20a%20new%204%2Dlane,per%20mile%20in%20urban%20areas
	new_lane_miles	total_budget_for_new_road/new_lane_cost		miles/year	Total lane miles that could be build based on available budget
	normal_pressure_from_road_issues_on_poll	1		dmnl	Maximum pressure that can be created on the government to change decision following the people's will
	normal_share_of_roads_in_poor_condition	0.1		dmnl	Although not normal but for the purpose of simulation it has been assumed that people do not really worry until the cover of poor road is 10% of all the total roads.
	"opening_of_new/replaced_roads"	opening_of_new_roads+reopening		mile/year	
	perceived_political_funding	SMTHN(political_funding, time_to_perceive_funding_benefits, 2, 18000)		$/year	Time taken to realize the benefit of political funding and the use of those funds in electoral campaigns
	perceived_poor_roads	SMTHN(poor_roads_relative_to_normal_share_of_poor_roads, time_to_perceive_need_of_new_roads, 2, 0)		dmnl	Public awareness about increasing poor road follows an information delay
	percentage_of_fair_road	fair/total_road_length		dmnl	
	percentage_of_good_road	good/total_road_length		dmnl	
	percentage_of_maintenance_budget_on_fair_and_mediocre_roads	0.4		dmnl	
	percentage_of_maintenance_budget_on_poor_roads	0.2		dmnl	
	percentage_of_mediocre_road	mediocre/total_road_length		dmnl	
	percentage_of_poor_road	poor/total_road_length		dmnl	
	policy_time_to_retire_roads	0		year	Suggested time period to retire the roads in poor condition to achieve desired percentage of poor roads
	political_funding	share_of_profit_as_political_funding		$/year	Political funding rewarded to government making decision in favor of new roads construction.
	poor_roads_available_for_maintenance	IF poor/maintenance_period<0 THEN 0 ELSE poor/maintenance_period		miles/year	
	poor_roads_relative_to_normal_share_of_poor_roads	share_of_poor_roads/normal_share_of_roads_in_poor_condition {SMTHN(share_of_roads_in_poor_condition, 2, 3, 0.15)		dmnl	
	pressure_on_gov_to_chan	MIN(effect_of_public_interest_on_supportive_poll, normal_pressure_from_road_issues_on_poll)		dmnl	

	ge_perception				
	profit_for_construction_company	new_lane_miles*profit_per_lane_mile		$/year	Total profit made by construction company
	profit_per_lane_mile	1000		$/mile	Assumed profit per lane mile. Sensitivity test has been conducted on this variable to see if there is any major deviation of behavior of key parameter.
	public_reference_as_good_development	10000		mile/year	
	publicity_of_new_roads	("opening_of_new/replaced_roads"/public_reference_as_good_development)		dmnl	
	relative_increase_in_maintenance_cost_due_to_driving_on_poor_road	average_additional_cost/INIT(average_additional_cost)		dmnl	
	relative_political_funding	perceived_political_funding/INIT(perceived_political_funding)		dmnl	ratio of political funding with respect to initial value of political funding
	required_maintenance_expenditure	average_maintenance_cost_per_public_mileage*effect_of_average_road_age_on_maintenance_expenditures*total_road_length		$/year	The cost required to repair total length of road based on average maintenance cost per mile of road. Note: The actual maintenance cost could be different for roads with different age group.
	research_reporting_and_press_coverage	0.1		dmnl/year	The extent by which research reporting is being carried out. The assumption is of 10%
	service_life_of_bad_road	30		year	Period until when the fair road remains in fair condition until it degrade to mediocre
	service_life_of_good_road	30		year	Period until when the newly constructed road remains in good condition until it degrade to fair
	service_life_of_mediocre_road	25		year	Period until when the mediocre road remains in mediocre condition until it degrade to poor
	service_life_of_poor_road	50		year	Period after which poor road deteriorates and retires
	share_of_budget_allocation_for_new_roads	(assurance_for_new_road_based_on_relative_political_funding+effect_of_publicity_on_approval_of_new_roads+demand_for_new_road+effect_of_perceived_increase_in_poor_roads_on_demand_for_new_roads+effect_of_public_participation_on_demand_for_new_road)/5		dmnl	share of budget allocated for new roads. The value represents dynamics of all the interacting variables available
	share_of_budget_on_maintenance	(budget_for_maintenance/total_road_budget)*100		dmnl	
	share_of_budget_on_new_roads	total_budget_for_new_road/total_road_budget		dmnl	
	share_of_gdp_spent_on_roads	"share_of_gdp_spent_on_roads_(in_%)"/100		dmnl	
	"share_of_gdp_spent_on_roads_(in_%)"	GRAPH(TIME) Points: (1950.00, 1.10), (1951.00, 1.04), (1952.00, 1.21), (1953.00, 1.33), (1954.00, 1.45), (1955.00, 1.68), (1956.00, 1.73), (1957.00, 1.79), (1958.00, 1.91), (1959.00, 2.02), (1960.00, 2.08), (1961.00, 2.14), (1962.00, 1.861), (1963.00, 1.827), (1964.00, 1.78), (1965.00, 1.757), (1966.00, 1.723), (1967.00, 1.699), (1968.00, 1.653), (1969.00, 1.63), (1970.00, 1.595), (1971.00, 1.572), (1972.00, 1.561), (1973.00,		dmnl	The share of total GDP used to construct, maintain and rehabilitate roads in USA. Federal, state, and local tax revenues support upkeep of most roads, which are generally free to drivers. Source:

		1.538), (1974.00, 1.514), (1975.00, 1.503), (1976.00, 1.503), (1977.00, 1.48), (1978.00, 1.468), (1979.00, 1.445), (1980.00, 1.434), (1981.00, 1.41), (1982.00, 1.387), (1983.00, 1.364), (1984.00, 1.329), (1985.00, 1.306), (1986.00, 1.272), (1987.00, 1.26), (1988.00, 1.237), (1989.00, 1.225), (1990.00, 1.214), (1991.00, 1.202), (1992.00, 1.191), (1993.00, 1.179), (1994.00, 1.168), (1995.00, 1.145), (1996.00, 1.145), (1997.00, 1.133), (1998.00, 1.133), (1999.00, 1.121), (2000.00, 1.11), (2001.00, 1.098), (2002.00, 1.087), (2003.00, 1.087), (2004.00, 1.075), (2005.00, 1.064), (2006.00, 1.052), (2007.00, 1.04), (2008.00, 1.029), (2009.00, 1.029), (2010.00, 1.017), (2011.00, 1.006), (2012.00, 1.006), (2013.00, 0.994), (2014.00, 0.994), (2015.00, 0.983), (2016.00, 0.983), (2017.00, 0.983), (2018.00, 0.971), (2019.00, 0.971), (2020.00, 0.971)			https://en.wikipedia.org/wiki/Transportation_in_the_United_States
	share_of_poor_roads	(poor)/total_road_length		dmnl	The fraction of roads in poor condition out of total road length of the country
	"share_of_poor_roads_(historical)"	GRAPH(TIME) Points: (1950.00, NaN), (1951.00, NaN), (1952.00, NaN), (1953.00, NaN), (1954.00, NaN), (1955.00, NaN), (1956.00, NaN), (1957.00, NaN), (1958.00, NaN), (1959.00, NaN), (1960.00, NaN), (1961.00, NaN), (1962.00, NaN), (1963.00, NaN), (1964.00, NaN), (1965.00, NaN), (1966.00, NaN), (1967.00, NaN), (1968.00, NaN), (1969.00, NaN), (1970.00, NaN), (1971.00, NaN), (1972.00, NaN), (1973.00, NaN), (1974.00, NaN), (1975.00, NaN), (1976.00, NaN), (1977.00, NaN), (1978.00, NaN), (1979.00, NaN), (1980.00, NaN), (1981.00, NaN), (1982.00, NaN), (1983.00, NaN), (1984.00, NaN), (1985.00, NaN), (1986.00, NaN), (1987.00, NaN), (1988.00, NaN), (1989.00, NaN), (1990.00, NaN), (1991.00, NaN), (1992.00, NaN), (1993.00, NaN), (1994.00, NaN), (1995.00, NaN), (1996.00, NaN), (1997.00, NaN), (1998.00, NaN), (1999.00, NaN), (2000.00, 0.0896), (2001.00, 0.0925), (2002.00, 0.0983), (2003.00, 0.1040), (2004.00, 0.1127), (2005.00, 0.1156), (2006.00, 0.1243), (2007.00, 0.1272), (2008.00, 0.1358), (2009.00, 0.1416), (2010.00, 0.1445), (2011.00, 0.1532), (2012.00, 0.1618), (2013.00, 0.1734), (2014.00, 0.1792), (2015.00, 0.1908), (2016.00, 0.1965), (2017.00, 0.1994), (2018.00, 0.2081), (2019.00, 0.2139), (2020.00, 0.2197)		dmnl	
	"share_of_poor_roads_(historical)_1"	GRAPH(TIME) Points: (1950.00, NaN), (1951.00, NaN), (1952.00, NaN), (1953.00, NaN), (1954.00, NaN), (1955.00, NaN), (1956.00, NaN), (1957.00, NaN), (1958.00, NaN), (1959.00, NaN), (1960.00, NaN), (1961.00, NaN), (1962.00, NaN), (1963.00, NaN), (1964.00, NaN), (1965.00, NaN), (1966.00, NaN), (1967.00, NaN), (1968.00, NaN), (1969.00, NaN), (1970.00, NaN), (1971.00, NaN), (1972.00, NaN), (1973.00, NaN), (1974.00, NaN), (1975.00, NaN), (1976.00, NaN), (1977.00, NaN), (1978.00, NaN), (1979.00, NaN), (1980.00, NaN), (1981.00, NaN), (1982.00, NaN), (1983.00, NaN), (1984.00, NaN), (1985.00, NaN), (1986.00, NaN), (1987.00, NaN), (1988.00, NaN), (1989.00, NaN), (1990.00, NaN), (1991.00, NaN), (1992.00, NaN), (1993.00,		dmnl	

		NaN), (1994.00, NaN), (1995.00, NaN), (1996.00, NaN), (1997.00, NaN), (1998.00, NaN), (1999.00, NaN), (2000.00, 0.1096), (2001.00, 0.1225), (2002.00, 0.1283), (2003.00, 0.1340), (2004.00, 0.1427), (2005.00, 0.1456), (2006.00, 0.1543), (2007.00, 0.1572), (2008.00, 0.1658), (2009.00, 0.1716), (2010.00, 0.1845), (2011.00, 0.1832), (2012.00, 0.1918), (2013.00, 0.2034), (2014.00, 0.2092), (2015.00, 0.2108), (2016.00, 0.2165), (2017.00, 0.2194), (2018.00, 0.2281), (2019.00, 0.2339), (2020.00, 0.2397)			
	share_of_profit_allocated_for_political_funding	0.01		dmnl	
	share_of_profit_as_political_funding	profit_for_construction_company*share_of_profit_allocated_for_political_funding		$/year	
	time_taken_to_change_public_interest	5		year	
	time_to_commission	2		year	Time to commission new road, assumed value of 2 years to fit the historical behaviour of total road length
	time_to_perceive_funding_benefits	5		year	
	time_to_perceive_need_of_new_roads	2		year	Time taken to realize the degrading condition of road.
	total_budget_for_new_road	(minimum_share_for_new_roads*total_road_budget)+budget_dependent_on_decision*share_of_budget_allocation_for_new_roads {total_road_budget-budget_for_maintenance		$/year	
	total_road_budget	gdp*share_of_gdp_spent_on_roads		$/year	
	total_road_length	fair + good + mediocre + poor		mile	Sum of the functional roads in different condition
	"total_road_length_(historical)"	GRAPH(TIME) Points: (1950.00, 3312975), (1951.06060606, 3326510), (1952.12121212, 3343170), (1953.18181818, 3366190), (1954.24242424, 3394561), (1955.3030303, 3418214), (1956.36363636, 3429801), (1957.42424242, 3453118), (1958.48484848, 3478787), (1959.54545455, 3510660), (1960.60606061, 3545693), (1961.66666667, 3573046), (1962.72727273, 3599581), (1963.78787879, 3620457), (1964.84848485, 3644069), (1965.90909091, 3689666), (1966.96969697, 3697950), (1968.03030303, 3704914), (1969.09090909, 3684085), (1970.15151515, 3710299), (1971.21212121, 3730082), (1972.27272727, 3758942), (1973.33333333, 3786713), (1974.39393939, 3806883), (1975.45454545, 3815807), (1976.51515152, 3838146), (1977.57575758, 3857356), (1978.63636364, 3867167), (1979.6969697, 3884761), (1980.75757576, 3917496), (1981.81818182, 3859837), (1982.87878788, 3852473), (1983.93939394, 3865894), (1985.00, 3879617), (1986.06060606, 3891464), (1987.12121212, 3863912), (1988.18181818, 3877941), (1989.24242424, 3873992), (1990.3030303, 3870744), (1991.36363636, 3876865), (1992.42424242, 3866926), (1993.48484848, 3883920), (1994.54545455, 3901081),		mile	

		(1995.60606061, 3905211), (1996.66666667, 3906595), (1997.72727273, 3912344), (1998.78787879, 3934264), (1999.84848485, 3960500), (2000.90909091, 3920968), (2001.96969697, 3932017), (2003.03030303, 3951101), (2004.09090909, 3963265), (2005.15151515, 3981671), (2006.21212121, 3990899), (2007.27272727, 3997456), (2008.33333333, 4011628), (2009.39393939, 4033011), (2010.45454545, 4048518), (2011.51515152, 4059352), (2012.57575758, 4067396), (2013.63636364, 4083768), (2014.6969697, 4094447), (2015.75757576, 4092730), (2016.81818182, 4115462), (2017.87878788, 4194257), (2018.93939394, 4171417), (2020.00, 4300000)			

Total	Count	Including Array Elements
Variables	109	109
Sectors	6	
Stocks	8	8
Flows	14	14
Converters	87	87
Constants	33	33
Equations	68	68
Graphicals	13	13
Macro Variables	43	

Run Specs	
Start Time	1950
Stop Time	2050
DT	1/6
Fractional DT	True
Save Interval	0.166666666667
Sim Duration	1.5

Time Units	year
Pause Interval	0
Integration Method	Euler
Keep all variable results	True
Run By	Run
Calculate loop dominance information	True
Exhaustive Search Threshold	1000