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The Development of Regression Models to Estimate Routine Maintenance Costs for State Highway Infrastructure

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Abstract

Literature review indicates that most studies on pavement management have been on reconstruction and rehabilitation, but not on maintenance; this includes routine, corrective and preventive maintenance. This study developed linear regression models to estimate the total maintenance cost and component costs for labor, materials, equipment, and stockpile. The data used in the model development were extracted from the pavement and maintenance management systems of the Nevada Department of Transportation (NDOT). The life cycle maintenance strategies adopted by NDOT for five maintenance prioritization categories were used as the basis for developing the regression models of this study. These regression models are specified for each stage of life-cycle maintenance strategies. The models indicate that age, traffic flow, elevation, type of maintenance, maintenance schedule, life cycle stage, and the districts where maintenances are performed all are important factors that influence the magnitude of the costs. Because these models have embedded the road conditions into the life-cycle stage and type of maintenance performed, they can be easily integrated into existing pavement management systems for implementation.

Keywords

Highway Infrastructure Routine Maintenance, Regression Modeling

1. Introduction

Over the past decade or so, the population in Nevada has increased dramatically, especially within and near the urban areas. This increase has resulted in the need to expand Nevada's transportation system, particularly roadways. This expansion includes the construction of some new roadways; however, the greatest need involves improving nearly all existing major roadways. These improvements typically include additional lanes, turning lanes, sound walls, shoulder widening, upgrading older cross-section standards, adding guardrail, and more landscaping. New and improved existing roadways have to be maintained, which adds to the demand for maintenance manpower, equipment, and materials.

Estimating the demand on the maintenance resources is needed when the maintenance districts of the Nevada Department of Transportation (NDOT) submit their maintenance requests to headquarters. In turn, headquarters integrates the submissions and sends a request to state legislators for approval. Currently, NDOT's Maintenance Division is responsible for the following maintenance activities:

1) Flexible Pavement,
2) Rigid Pavement,
3) Miscellaneous Concrete,
4) Roadside Infrastructure,
5) Roadside Cleanup,
6) Roadside Facilities,
7) Roadside Appurtenances,
8) Traffic Services,
9) Snow and Ice Control,
10) Bridge, and
11) Stockpile Production.

Ideally, the funding decision depends on the additional number of positions needed and the funding increase for equipment and materials for all these maintenance activities over the life cycle of the highway system expansion. That decision could fully or partially meet the estimated demand for maintenance resources over the life cycles.

The objective of this research is to develop maintenance cost estimation models. These models estimate the total expected short-term and long-term maintenance burden required for NDOT. Short-term and long-term maintenance schedules for NDOT are shown in **Figure 1**. As can be seen in the figure, there is no preventive maintenance for maintenance prioritization Categories 1 and 2; on the other hand, there are more than one preventive maintenance activities between two constructions/rehabilitations for other prioritization categories.

In this study, linear regression models were developed for each individual stage of the life cycles in all these categories. These models estimated not only the annual maintenance costs, but also estimated the component costs for manpower, materials, equipment, and stockpile. With this objective in mind, this study included a literature review on estimating maintenance cost. Data also were collected on maintenance cost and road characteristics. These data were used to develop linear regression models.

This paper consists of seven sections. The first section provides an introduction on

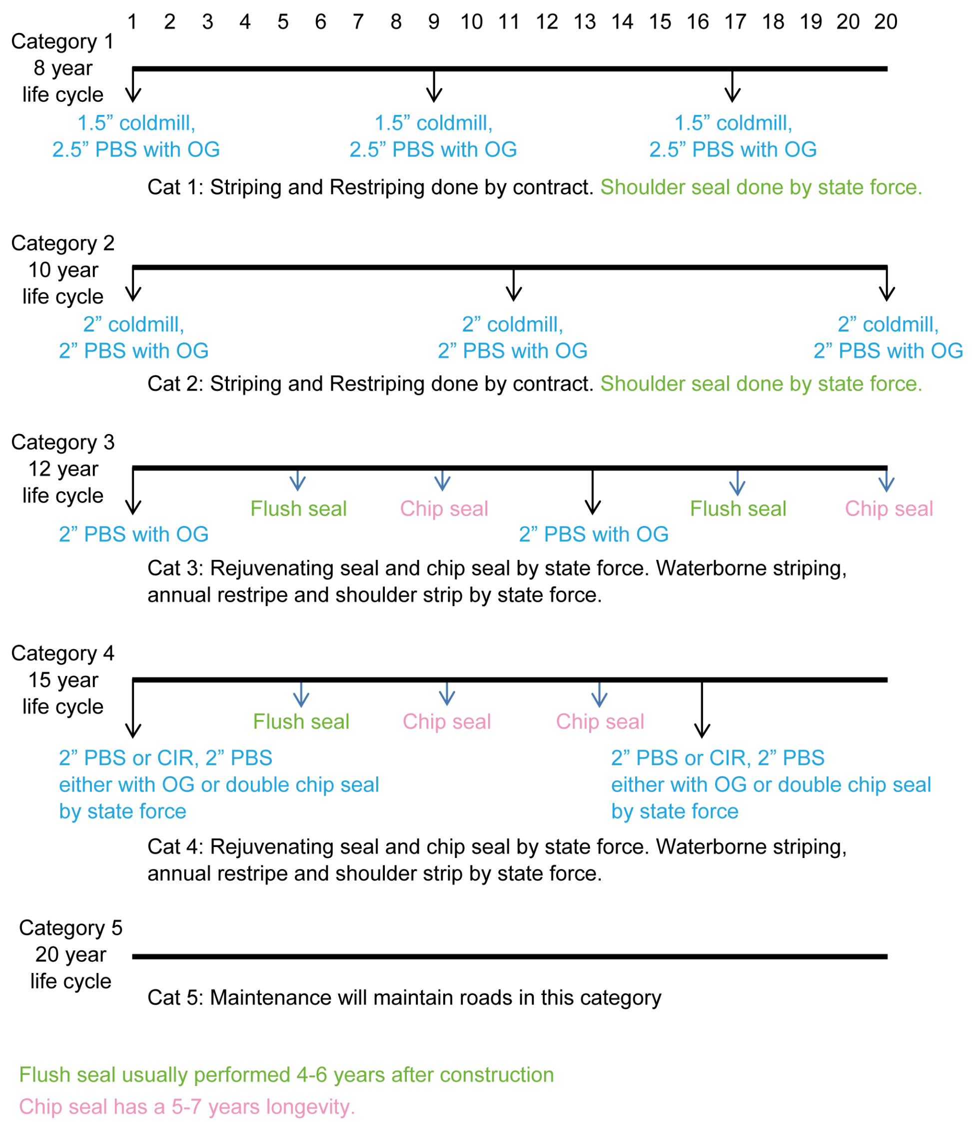

Figure 1. Life cycle of roads in NDOT.

the background and objective of the study. In the second section, a literature review is presented. The third section proposes a methodology on developing linear regression models. Section 4 describes the data collection process. In Section 5, the development of linear regression models for estimating annual maintenance costs is presented; this is followed by the last section, which summarizes the model development and identifies needs for future study.

2. Literature Review

According to [1], maintenance costs are incurred for maintenance activities that are triggered when pavement conditions reach a critical condition. Pavement deteriorates as more vehicles travel on it, and other environmental factors also affect it. The maintenance cost can be defined as the increase in the total maintenance costs resulting from an additional unit of traffic loading. The study in [1] classified maintenance, rehabilitation and reconstruction (MR&R) costs models into five approaches:

1) The pavement management system (PMS) direct approach,

2) The simple roughness approach,

3) The econometric approach,

4) The cost allocation approach, and

5) The perpetual overlay indirect approach.

Among these five approaches, the most relevant ones to this study are the PMS approach and the econometric approach. A PMS usually consists of a database that records the history of MR&R work on a roadway system and a pavement performance model that can estimate the roadway surface condition, given the MR&R history and future maintenance policies and traffic usage of that roadway segment. Optimal procedures usually are applied to search for the optimal MR&R schedule. As a product of the optimal procedure, maintenance costs can also be derived.

The econometric approach classified in [1] is to estimate a function that relates the total maintenance cost to influencing factors, such as traffic load, road geometry, pavement structure, and climate. It should be noted that there are only a few studies on estimating MR&R costs. However, the costs in these studies combined maintenance costs with rehabilitation and reconstruction costs. The most relevant study [2] used a regression modeling approach to study the impact of heavy trucks on maintenance cost. In their study, more than 1100 mile sections of highway were sampled randomly. Data including annual average daily traffic (AADT), maintenance cost, highway geometric information, and weather were collected from various sources and integrated into a single database, which was used to develop the regression model. The annual maintenance costs are related to AADTs of heavy trucks and passenger cars, age of pavement, pavement shoulder, temperature, maintenance location, the existence of a bridge, functional classification, and the district where a pavement section was located. It was found the maintenance cost incurred by heavy trucks was much higher than passenger cars; this has a significant implication to transportation policies, such as taxation.

In the 1990s, NDOT studied on various methods to estimate maintenance costs [3]. In that study, four techniques used in estimating maintenance costs were discussed ([3] [4]), which are:

1) Correlating annual maintenance costs to the present serviceability index (PSI) level,

2) Correlating annual maintenance costs to the probability of their occurrence,

3) Establishing an overall annual maintenance cost for each treatment, and

4) Establishing a fixed-period, cumulative, annual maintenance cost for each treatment.

The first technique correlates annual maintenance costs to pavement performance, represented as the PSI level. This technique was proposed based on the understanding that the costs of maintenance vary with the nature of maintenance activities that are triggered by the pavement conditions. Recognizing the fact that there is a time element involved in pavement performance—for example, not every maintenance activity occur every year—the maintenance costs fluctuate significantly between years. Therefore, the second method correlates the annual maintenance costs to the probability of the occurrence of maintenance activities. The third technique calculates the annual maintenance costs by considering the life of pavement after a certain treatment. The annual maintenance costs are the average of the total maintenance costs over the year before next maintenance treatment. By the fourth technique, the annual maintenance costs consider the time since the last pavement treatment.

In NDOT's study ([3] [4]), the last technique was adopted. Note that all four techniques are not regression models that can consider the different characteristics of pavement, such as traffic load and road functional classification, which are critical in determining the pavement conditions and the maintenance costs.

3. Methodology

In this study, regression models were developed for different maintenance costs, maintenance prioritization categories for various highway routes, and different life-cycle stages. The maintenance costs were broken down into manpower, materials, equipment, and stockpile costs.

In NDOT, the highway routes are classified into five maintenance prioritization categories, each with different maintenance strategies over their life cycles (see **Figure 1**) and road characteristics in terms of access control, traffic flow, etc. For the Category 1 routes, only one life-cycle stage is considered; it starts from reconstruction with "1.5" coldmill, 2.5" PBS with OG" and ends with another such reconstruction. Similar to the Category 1 route, only one life cycle stage is considered for Category 2 routes; it starts from and ends with "2" coldmill, 2.5" PBS with OG". There are three life cycle stages for Category 3: After reconstruction, After Flush Seal, and After Chip Seal. Category 4 has four life cycles, which are: After Reconstruction, After Flush Seal, After First Chip Seal, and After the Second Chip Seal. In other words, there is one more Chip Seal treatment for Category 4 routes than for Category 3 routes.

There is no clear maintenance treatment pattern that has been adopted for Category 5. In this study, three life cycle stages are proposed for Category 5 routes: Beginning Stage (1st Stage), Middle Stage (2nd Stage), and Last Stage (3rd Stage), where the middle stage can be employed repeatedly.

Linear regression models were developed for each life cycle stage of these five different maintenance prioritization categories. The models can be written as:

$$Y_i = \beta_1 + \beta_2 X_{2i} + \beta_3 X_{3i} + \cdots + \beta_k X_{ki} + \varepsilon_i, \quad \forall i.$$

The dependent variables Y_i are the maintenance costs for total maintenance cost and for man power, materials, equipment, and stockpile, separately. The X_i indicates the independent variables, which include age after the start of a life cycle stage, the pavement surface type, total traffic volume, truck flow volume, urban/rural area, and the elevation of a road segment.

4. Data Collection

The goal of data collection was to extract maintenance cost data, road section characteristics, and traffic flow data. The first step was to develop an inventory of roads maintained by NDOT that could be used as a population for sampling. In the second step, time-space diagrams were developed for the selected roads, in which the history of maintenance activities on each selected road could be presented. The third step utilized the time-space diagrams to identify the road sections that showed uniform maintenance treatments. The fourth step involved extracting maintenance cost data for selected road sections. In the last step, data on road characteristics were collected for the identified road sections.

NDOT uses a pavement management system database that contains a data item for each maintenance prioritization category. This data item is used to extract the road inventory data for every road of each county in Nevada. Note that one road could be divided into multiple sections, each with a different maintenance prioritization. Maintenance time-space diagrams present the maintenance tasks historically performed on a road. As shown in Figure 2, the x axis represents the years when maintenance occurred and the rehabilitation or reconstruction performed; the y axis indicates the locations where the maintenance activities happened on a road. Different colors are used to differentiate various maintenance tasks, which can be identified from NDOT's PMS and maintenance management database. The maintenance work performed by NDOT's work force that directly influence road performance is classified as: 1) Base & Surface Repair, 2) Hand Patching, 3) Machine Patching, 4) Maintenance Overlay, Inlay (Scheduled Betterment), 5) Roadway Capital Improvements (Scheduled Betterment), 6) Sand, 7) Fog/Flush, 8) Chip, 9) Scrub/Slurry, 10) Crack Filling, and 10) Cold Milling. From the colors, the road sections that experienced the same set of maintenance tasks historically can be easily distinguished. The time-space diagrams for prioritization Categories 3, 4 and 5 are presented with minor differences to distinguish them from those for Categories 1 and 2, because preventive maintenance tasks on these routes are different. These time-space diagrams were developed based on running an MS Excel program written using a Macro.

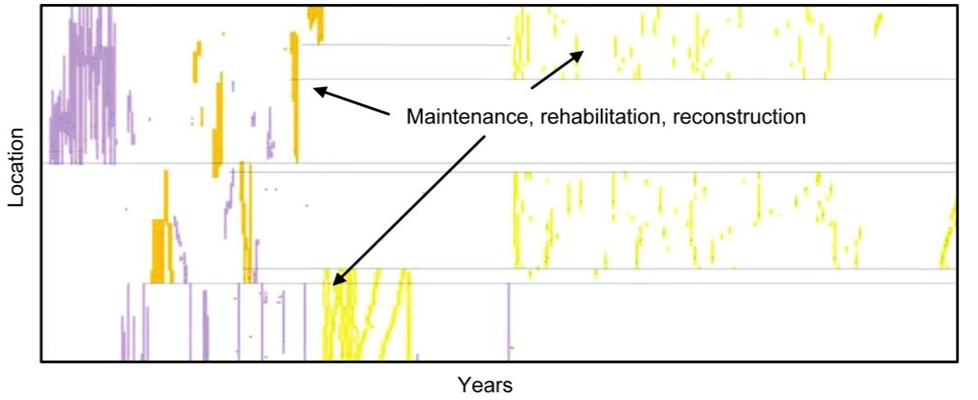

Figure 2. Time space diagram for US50 of Category 3 in Churchill county of Nevada.

The mile-by-mile traffic flow data available in the PMS database varies over a given road section. Thus, averaging has to be performed for the mile-by-mile traffic flow data. When the length of road section is great, the mile-by-mile midpoint elevations on the road section may vary; in that case, the average of these mile-by-mile midpoint evaluation data needs to be derived. Usually, however, road characteristics data for the most recent years have the complete mile-by-mile midpoint elevation data. Other road characteristics data—such as number of lane, type of road surface, and urban/rural—do not vary over the length of a road section; therefore, they can be collected by various methods. Maintenance cost data were extracted from the NDOT MMS database. To facilitate the data extraction, a Microsoft spreadsheet program was developed.

5. Maintenance Cost Model Development

5.1. Maintenance Prioritization Category 1

Linear regression models were developed for total maintenance cost and the component costs for labor, equipment, materials, and stockpiles. The results of these models are listed in Table 1. It can be seen from the table that the coefficient for the variable age is positive, which implies that the total maintenance cost increases with year. In the last year before a reconstruction, certain maintenance work may not be performed; thus, the coefficient for the last year indicator is negative. The coefficient for the factor "asphalt concrete" is positive, which indicates that the roads with an asphalt concrete surface incur more maintenance cost than rigid concrete pavement roads. The elevation of the road segment is also important to determine the amount of maintenance costs. The coefficient for the factor "elevation" is negative. This is because the data samples were from the Las Vegas area, where the roads of highways I-15 and US95 outside of the metropolitan area are at high elevations, and less maintained. The maintenance activities vary with the conditions of roads that are influenced by the amount of traffic rolling over them. The more vehicles travel on roads, the more deterioration results, which triggers more maintenance activities. The coefficient for "AADT" is positive, which is consistent with the study's expectations. From Table 1, it can be seen that these influencing factors show similar impacts on labor, materials, and equipment costs.

When the total maintenance cost was analyzed, it was shown that the maintenance cost in the year when a reconstruction happened was significantly less than previous years. This observation can be validated from the model for labor costs, which implies that those maintenance activities involving expensive equipment and materials were not performed in a year during which major construction was scheduled.

5.2. Regression Models for Roads in Prioritization Category 2

Table 1 also lists the results for linear regression models of roads in maintenance prioritization Category 2. From Figure 1, it can be seen that there is just one life cycle stage for the roads classified for Category 2. It starts right after the completion of a reconstruction, and ends at the next reconstruction. The results for the total cost in Table 1

Table 1. Regression models for road maintenance prioritization Categories 1 and 2.

Category 1				**Category 2**			
Total Cost				**Total Cost**			
Dependent Variable:		lntot		Dependent Variable:		lntot	
Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
one	8.20468	0.54838	14.96167	one	5.46705	0.44544	12.27327
age	6.28091e−002	1.25052e−002	5.02264	lyear	−0.53229	0.21494	−2.47648
lyear	−0.34813	0.20126	−1.72979	elev	4.81895e−004	9.19892e−005	5.23861
ac	0.95257	0.21990	4.33179	aadt	3.76878e−005	1.08794e−005	3.46415
elev	−9.52315e−004	1.69739e−004	−5.61045				
aadt	2.81009e−005	3.89760e−006	7.20981				
Number of Observations		201		Number of Observations		93	
Corrected R-squared		0.46536		Corrected R-squared			0.23575
Mean of Dependent Variable		7.88086		Mean of Dependent Variable		7.76939	
Labor Cost				**Labor Cost**			
Dependent Variable:		lnlabor		Dependent Variable:		lnlabor	
Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
one	7.65243	0.51194	14.94798	one	4.96110	0.38960	12.73369
age	5.84997e−002	1.16742e−002	5.01104	elev	3.95786e−004	8.00296e−005	4.94550
lyear	−0.33534	0.18788	−1.78483	urban	−0.32518	0.13213	−2.46100
ac	0.91071	0.20529	4.43621	aadt	4.40071e−005	9.81890e−006	4.48188
elev	−9.38479e−004	1.58459e−004	−5.92252				
aadt	2.58324e−005	3.63858e−006	7.09957				
Number of Observations		201		Number of Observations		93	
Corrected R-squared		0.46627		Corrected R-squared		0.25454	
Mean of Dependent Variable		7.23326		Mean of Dependent Variable		6.93872	
Category 1				**Category 2**			
Materials Cost				**Materials Cost**			
Dependent Variable:		lnma		Dependent Variable:		lnma	
Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
one	5.87373	0.75837	7.74515	one	2.52197	0.74212	3.39834
age	7.38305e−002	1.68890e−002	4.37151	lyear	−1.31390	0.35809	−3.66918

Continued

ac	1.02915	0.30212	3.40644	elev	8.60610e−004	1.53256e−004	5.61550
elev	−8.36852e−004	2.36656e−004	−3.53615	aadt	4.80663e−005	1.81253e−005	2.65190
aadt	3.46083e−005	5.37191e−006	6.44246				
Number of Observations		200		Number of Observations		93	
Corrected R-squared		0.37965		Corrected R-squared		0.28931	
Mean of Dependent Variable		6.20744		Mean of Dependent Variable		6.36397	
Equipment Cost				**Equipment Cost**			
Dependent Variable:		lneq		Dependent Variable:		lneq	
Indept Variable	Estimated Coefficient	Standard Error	t-Statistic	Indept Variable	Estimated Coefficient	Standard Error	t-Statistic
one	7.03420	0.59595	11.80334	one	4.25812	0.47823	8.90389
age	6.51333e−002	1.33239e−002	4.88845	lyear	−0.86702	0.23076	−3.75726
ac	0.92762	0.23842	3.89062	elev	4.30691e−004	9.87603e−005	4.36097
elev	−1.07228e−003	1.84905e−004	−5.79908	aadt	3.55617e−005	1.16802e−005	3.04463
aadt	2.61492e−005	4.23932e−006	6.16825				
Number of Observations		201		Number of Observations		93	
Corrected R-squared		0.43240		Corrected R-squared		0.22537	
Mean of Dependent Variable		6.41503		Mean of Dependent Variable		6.29168	

shows that the total cost each year did not change with time. It presents significant less cost than the previous year, when the road was under reconstruction. This observation is similar to that for the roads in Category 1. It implies that some maintenance work may not need to be performed when a road is scheduled for reconstruction. The coefficient for "elevation" is positive, which indicates that the roads at high elevation tend to cost more for maintenance, probably due to work in extreme weather conditions, such as snow, for which additional work (snow removal) has to be done.

The samples collected for Category 2 were from areas across the state, unlike the case for Category 1, in which samples were taken from Clark County only. The coefficient for traffic "AADT" is positive, which is consistent with the expectation that more traffic accelerates the deterioration of roads, and thus produces more conditions for maintenance. Similar patterns regarding the impact of influencing factors on total maintenance cost also can be found in the models for the component maintenance costs, except for stockpile cost.

5.3. Regression Models for the Roads in Prioritization Category 3

Three sets of linear regression models were developed, one set for each life cycle stage, as shown in Figure 1: after construction, after flush seal, and after chip seal.

The results in Table 2 for the life-cycle stage after reconstruction indicate that the coefficient for the last year's maintenance activities is positive. This observation is consistent with practice: more maintenance activities are reserved to be done at the time when a flush seal is performed. The maintenance cost between the reconstruction and flush seal can be viewed as constant over the years, because the coefficient for age is not significant.

The coefficient for elevation is positive, which makes sense because roads at higher elevations may have more chance of extreme weather as well as other road features that require maintenance (e.g., a guard rail). These observations also can be found in other maintenance cost components, including labor cost, equipment cost, and materials cost.

The results for the life-cycle stage Flush Seal indicates that only the variable representing the maintenance work when Chip Seal is performed is significant. This observation is consistent with practice, delaying maintenance work to be done when such a major preventive maintenance as Chip Seal is performed. This result also can be found in other maintenance cost components.

Table 2 shows the results for the life-cycle stage after Chip Seal, which ends at a reconstruction. The results indicate that the coefficient for the "maintenance cost at the year of reconstruction" is negative because some maintenance activities may be saved to be done at the time of major construction work. The coefficient for road elevation is positive, which is reasonable because more potential maintenance work could be created when a road is at a high elevation. Examples of such potential maintenance work include that for guard rails, slopes, and snow removal. Traffic has a positive coefficient, which is also consistent with expectations. These observations can be found in the results for maintenance cost components.

Based on the results for these three life cycle stages, it can be seen that the maintenance costs in the years when construction, flush seal, and chip are performed significantly vary from those of other years. They cost more or less than the regular year, depending upon the nature of the maintenance work. Elevation is an important influencing factor to the maintenance costs. Traffic is another factor that plays a significant role. Age, however, does not show a significant impact on the maintenance cost.

5.4. Regression Models for the Roads in Prioritization Category 4

For Category 4, four linear regression models were developed, one for each life-cycle stage as shown in Figure 1: after reconstruction, after flush seal, after first chip seal, and after the second chip seal. Each life-cycle stage starts at the next year after the major maintenance activities, and ends at the end when these major maintenance activities are performed. The results of the model are presented in Table 3.

The results on estimating total maintenance cost for the first life-cycle stage indicates that the coefficient for the "maintenance activities performed in the last year" is positive, which implies that more expenditure was incurred in the last year for flush seal, because a major preventive maintenance was preformed. Another significant variable is

Table 2. Regression models for the roads in prioritization Category 3.

	Total Cost				Labor Cost			
	Dependent Variable:		lntot		Dependent Variable:		lnlabor	
	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
Reconstruction	one	5.22175	0.60923	8.57101	one	6.22976	9.86522e−002	63.14873
	lyear	0.76511	0.24410	3.13439				
	elev	2.61157e−004	1.27936e−004	2.04131				
	Number of Observations		88		Number of Observations		198	
	Corrected R-squared		0.12134		Corrected R-squared		0.00000e+000	
					Durbin-Watson Statistic		0.85384	
	Mean of Dependent Variable		6.62413		Mean of Dependent Variable		6.22976	
	Total Cost				Labor Cost			
	Dependent Variable:		lntot		Dependent Variable:		lnlabor	
	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
Flush Seal	one	7.23358	8.94882e−002	80.83270	one	6.36667	7.74854e−002	82.16616
	lyear	1.35252	0.17832	7.58490	lyear	0.97188	0.15440	6.29458
	Number of Observations		135		Number of Observations		135	
	Corrected R-squared		0.29670		Corrected R-squared		0.22374	
	Mean of Dependent Variable		7.57421		Mean of Dependent Variable		6.61145	
	Total Cost				Labor Cost			
	Dependent Variable:		lntot		Dependent Variable:		lnlabor	
	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
Chip Seal	one	5.95503	0.46492	12.80873	one	5.37183	0.44704	12.01641
	lyear	0.52712	−0.18476	−2.85306	lyear	−0.48416	0.17765	−2.72532
	elev	2.29486e−004	8.29841e−005	2.76542	elev	1.51135e−004	7.97929e−005	1.89409
	aadt	5.97617e−004	1.41487e−004	4.22384	aadt	6.34517e−004	1.36046e−004	4.66399
	Number of Observations		87		Number of Observations		87	
	Corrected R-squared		0.19072		Corrected R-squared		0.21000	
	Mean of Dependent Variable		7.40151		Mean of Dependent Variable		6.47436	

Continued

	Material Cost				Equipment Cost			
	Dependent Variable:		lnma		Dependent Variable:		lneq	
	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
Reconstruction	one	2.76351	0.80326	3.44035	one	3.23098	0.68499	4.71685
	lyear	1.36009	0.32184	4.22592	elev	3.99350e−004	1.44481e−004	2.76404
	elev	4.61092e−004	1.68682e−004	2.73351				
	Number of Observations		88		Number of Observations		88	
	Corrected R-squared		0.21176		Corrected R-squared		7.09088e−002	
	Mean of Dependent Variable		5.24172		Mean of Dependent Variable		5.09624	
	Material Cost				**Equipment Cost**			
	Dependent Variable:		lnma		Dependent Variable:		lneq	
	Indept Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
Flush Seal	one	5.46978	0.17230	31.74660	one	6.13286	0.19015	32.25351
	lyear	1.81760	0.34332	5.29418	age	−0.13997	7.10209e−002	−1.97088
					lyear	1.07427	0.23502	4.57098
	Number of Observations		135		Number of Observations		135	
	Corrected R-squared		0.16785		Corrected R-squared		0.12471	
	Mean of Dependent Variable		5.92755		Mean of Dependent Variable		6.02601	
	Material Cost				**Equipment Cost**			
	Dependent Variable:		lnma		Dependent Variable:		lneq	
	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
Chip Seal	one	4.13053	0.70597	5.85082	one	4.00296	0.52272	7.65788
	age	0.11679	6.19514e−002	1.88524	lyear	−0.63538	0.20773	−3.05871
	lyear	−0.87590	0.27677	−3.16474	elev	3.50827e−004	9.33017e−005	3.76014
	elev	2.70935e−004	1.18212e−004	2.29195	aadt	5.96674e−004	1.59078e−004	3.75083
	aadt	6.77556e−004	1.99749e−004	3.39203				
	Number of Observations		87		Number of Observations		87	
	Corrected R-squared		0.15002		Corrected R-squared		0.20177	
	Mean of Dependent Variable		6.11288		Mean of Dependent Variable		6.01471	

Table 3. Linear regression models for the roads in prioritization Category 4.

Reconstruction				Flush Seal			
Total Cost				**Total Cost**			
Dependent Variable:		lntot		Dependent Variable:		lntot	
Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
one	6.84434	0.13647	50.15368	one	5.19255	0.79175	6.55835
lyear	0.79590	0.16331	4.87348	age	−0.20196	6.26297e−002	−3.22469
aadt	6.28703e−004	2.73911e−004	2.29528	lyear	2.09167	0.20415	10.24556
				dist1	0.37462	0.21830	1.71610
				dist2	0.84941	0.19924	4.26331
				elev	3.97635e−004	1.30377e−004	3.04989
				aadt	5.71083e−004	3.41515e−004	1.67221
				truck	6.07142e−003	−3.59775e−003	−1.68756
Number of Observations		97		Number of Observations		78	
Corrected R-squared		0.24126		Corrected R-squared		0.67316	
Mean of Dependent Variable		7.29449		Mean of Dependent Variable		7.68789	
Labor Cost				**Labor Cost**			
Dependent Variable:		lnlabor		Dependent Variable:		lnlabor	
Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
one	5.13562	0.33914	15.14314	one	2.38281	0.54250	4.39225
lyear	0.60321	0.16132	3.73924	lyear	1.25990	0.16808	7.49565
elev	1.84367e−004	6.63267e−005	2.77967	dist2	1.07410	0.16622	6.46196
aadt	5.36600e−004	2.70457e−004	1.98405	elev	6.78541e−004	9.43481e−005	7.19188
Number of Observations		97		Number of Observations		78	
Corrected R-squared		0.21081		Corrected R-squared		0.59666	
Mean of Dependent Variable		6.37113		Mean of Dependent Variable		6.72726	
Reconstruction				**Flush Seal**			
Material Cost				**Material Cost**			
Dependent Variable:		lnma		Dependent Variable:		lnma	
Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
one	5.59434	0.14065	39.77414	one	6.16959	0.28903	21.34551
lyear	1.20364	0.15429	7.80099	age	−0.29715	0.10351	−2.87087
dist1	−0.49562	0.16484	−3.00669	lyear	3.07651	0.34700	8.86597
aadt	7.02351e−004	2.64015e−004	2.66027	dist2	0.60091	0.25766	2.33222
Number of Observations		96		Number of Observations		78	
Corrected R-squared		0.47495		Corrected R-squared		0.51891	
Mean of Dependent Variable		6.07392		Mean of Dependent Variable		6.34646	

Continued

Equipment				**Equipment**			
Dependent Variable:		lneq		Dependent Variable:		lneq	
Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
one	5.76825	0.10346	55.75149	one	2.14434	0.76851	2.79024
lyear	0.51890	0.21725	2.38850	age	−0.25160	7.70902e−002	−3.26374
				lyear	1.53446	0.25827	5.94137
				dist1	0.70683	0.28343	2.49387
				dist2	1.20197	0.22563	5.32727
				elev	6.91082e−004	1.40269e−004	4.92683
Number of Observations		97		Number of Observations		78	
Corrected R-squared		4.67198e−002		Corrected R-squared		0.52516	
Mean of Dependent Variable		5.88594		Mean of Dependent Variable		6.15327	
Chip Seal-1				**Chip Seal-2**			
Total Cost				**Total Cost**			
Dependent Variable:		lntot		Dependent Variable:		lntot	
Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
one	6.91182	0.11215	61.63111	one	6.16464	0.61684	9.99388
lyear	1.81242	0.19820	9.14448	age	7.30700e−002	4.75945e−002	1.53526
dist1	0.31118	0.15951	1.95086	lyear	−0.51297	0.21971	−2.33473
				dist1	−0.35433	0.19684	−1.80010
				elev	1.73129e−004	7.67915e−005	2.25453
				aadt	1.51324e−003	7.35471e−004	2.05750
				truck	−1.29371e−002	6.05241e−003	−2.13752
Number of Observations		110		Number of Observations		89	
Corrected R-squared		0.44573		Corrected R-squared		0.24460	
Mean of Dependent Variable		7.41292		Mean of Dependent Variable		7.01842	
Labor Cost				**Labor Cost**			
Dependent Variable:		lnlabor		Dependent Variable:		lnlabor	
Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
one	5.64555	0.21227	26.59612	one	4.05502	0.47710	8.49922
lyear	1.29042	0.17225	7.49169	age	0.12064	4.42940e−002	2.72354
dist1	0.74466	0.23196	3.21034	lyear	−0.65300	0.20709	−3.15322
dist2	0.63657	0.23240	2.73915	elev	2.91755e−004	6.84721e−005	4.26093
				aadt	1.77472e−003	6.58573e−004	2.69479
Number of Observations		110		Number of Observations		89	
Corrected R-squared		0.36502		Corrected R-squared		0.24512	
Mean of Dependent Variable		6.51891		Mean of Dependent Variable		6.24271	

Continued

Chip Seal-1				Chip Seal-2			
Material Cost				**Material Cost**			
Dependent Variable:		lnma		Dependent Variable:		lnma	
Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
one	5.47692	0.13377	40.94294	one	5.70053	0.15453	36.88976
lyear	2.49629	0.29912	8.34551	dist1	−0.79064	0.23831	−3.31764
Number of Observations		110		Number of Observations		88	
Corrected R-squared		0.38643		Corrected R-squared		0.10315	
Mean of Dependent Variable		5.97618		Mean of Dependent Variable		5.36810	
Equipment				**Equipment**			
Dependent Variable:		lneq		Dependent Variable:		lneq	
Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
one	5.48704	0.13220	41.50479	one	3.50169	0.57218	6.11988
lyear	1.33063	0.23364	5.69523	age	0.13717	5.31210e−002	2.58223
dist1	0.32468	0.18803	1.72669	lyear	−0.76871	0.24836	−3.09514
				elev	3.18557e−004	8.21175e−005	3.87929
				aadt	1.34731e−003	7.89815e−004	1.70586
Number of Observations		110		Number of Observations		89	
Corrected R-squared		0.24098		Corrected R-squared		0.21175	
Mean of Dependent Variable		5.89780		Mean of Dependent Variable		5.71003	

traffic flow, which is consistent with expectation. These findings also can be found in the models for the four cost components: labor, equipment, materials, and stockpile.

For the second life-cycle stage starting after flush seal is performed, relatively more variables are identified as significant to the maintenance cost. It can be seen that the variable representing the last year is significant, which is reasonable. Traffic flow is also significant. Age is significant, but with a negative coefficient. If the life-cycle span is short and many maintenance activities are frequently reserved for the last year, it is possible that the maintenance cost appears to decline with year; this has been confirmed by respondents from some state DOT's Maintenance Divisions as part of the survey conducted in this study.

Where maintenance was performed is important. The results indicate that the maintenance—highly likely, chip seal—in Districts 1 and 2 in NDOT were more expensive than those in District 3 in NDOT; maintenance done in District 2 was more expensive than in District 1. Probably this is due to the fact that maintenance in District 2 was more complicated, involving more sophisticated technologies than in other districts. Another significant variable is elevation, the higher a road is located, the more expensive it is to maintain it; this is consistent with our expectations. These findings also can be found from the results for the four maintenance cost components.

The results for the third stage—starting from after a chip seal and ending at another chip seal—indicate that there are fewer significant variables. Whether or not a chip seal was performed in a year is important. The coefficient for the variable "last year", which is the year with a chip seal was performed, is positive. This is reasonable. In this life-cycle stage, District 1 showed the most costly maintenance. This observation may be relevant regarding what type of equipment is used for the second chip seal in various districts; this is because the results for the four cost components indicate that the material costs between Districts 1 and 2 are the same, statistically.

The results for the last life cycle stage are very different from those for the first three segments. Age is significant. The total maintenance cost increased each year, which is understandable. The coefficient for the maintenance cost incurred in the last year is negative, which implies that the "last year" maintenance less expensive because other maintenance tasks were saved to be done during the reconstruction in this year. Among the three districts, District 1 has the least cost. This observation is relevant to maintenance practice, probably regarding the type of materials used in different districts. This result also can be found from the data for the four cost components. Traffic flow AADT is significant, which is consistent with expectations

5.5. Regression Models for Roads in Prioritization Category 5

There is no clear definition in NDOT on the life cycle for routes in maintenance prioritization Category 5. For simplicity, this study proposes three stages for the life cycle of a Category 5 route. The first stage starts after the completion of reconstruction, such as "2" PBS with OG", and ends at a flush seal or a chip seal. The second stage starts after a flush seal or a chip seal and ends at the completion of another flush seal or chip seal. The third stage starts after a flush or a chip seal, and ends at a construction. The second stage could be repeated many times; this is different from the life-cycle stages for Category 4, in which the middle stages are each performed one time only.

The results for the first life-cycle stage in Table 4 show that age, the last maintenance, and elevation are significant factors influencing the maintenance cost each year. It is a natural expectation that total maintenance cost increases with year, because declining road conditions generate more maintenance work. The last year maintenance, which is either flush seal or chip seal, involves maintenance with more expensive materials or equipment. The elevation at which a road is located influences maintenance cost. The higher elevation at which a road is located, the more expensive it is to maintain. All these observations can be found in the models for the four maintenance cost components.

The results for the second life-cycle stage indicate that the last year maintenance and elevation of roads significantly influences maintenance costs. The impact of aging cannot be found in the result, probably due to the fact that the samples are a combination of life cycle stages that started or ended with flush seals or chip seals; these could be

Table 4. Linear regression models for the roads in prioritization Category 5.

	Total Cost				Labor Cost			
	Dependent Variable:		lntot		Dependent Variable:		lnlabor	
	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
1st Life Cycle Stage	one	4.73205	0.47258	10.01314	one	4.32551	0.42914	10.07945
	age	0.12385	4.50500e−002	2.74927	lyear	0.78063	0.15558	5.01760
	lyear	0.87737	0.17353	05.05593	elev	3.48566e−004	8.71128e−005	4.00132
	elev	3.91701e−004	9.00566e−005	4.34950				
	Number of Observations		159		Number of Observations		159	
	Corrected R-squared		0.30239		Corrected R-squared		0.20756	
	Mean of Dependent Variable		7.21153		Mean of Dependent Variable		6.21859	
	Total Cost				Labor Cost			
	Dependent Variable:		lntot		Dependent Variable:		lnlabor	
	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
2nd Life Cycle Stage	one	5.57972	0.24429	22.84037	one	4.64925	0.20747	22.40961
	lyear	1.35616	0.10931	12.40674	lyear	0.91641	9.28310e−002	9.87185
	elev	2.27820e−004	4.75289e−005	4.79329	elev	2.46666e−004	4.03643e−005	6.11100
	aadt	3.03482e−003	7.75647e−004	3.91263	aadt	2.35182e−003	6.58724e−004	3.57026
	Number of Observations		448		Number of Observations		448	
	Corrected R-squared		0.31453		Corrected R-squared		0.26197	
	Mean of Dependent Variable		7.38172		Mean of Dependent Variable		6.35050	
	Total Cost				Labor Cost			
	Dependent Variable:		lntot		Dependent Variable:		lnlabor	
	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
3rd Life Cycle Stage	one	7.31532	0.25695	28.47024	one	6.31538	0.25468	24.79744
	age	0.11737	8.69821e−002	1.34939	age	0.19669	7.89160e−002	2.49238
	lyear	0.59437	0.32084	1.85257				
	Number of Observations		94		Number of Observations		94	
	Corrected R-squared		6.75674e−002		Corrected R-squared		5.30684e−002	
	Mean of Dependent Variable		7.79547		Mean of Dependent Variable		6.86568	

Continued

	Material Cost				Equipment Cost			
	Dependent Variable:		lnma		Dependent Variable:		lneq	
	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
1st Life Cycle Stage	one	1.77701	0.86607	2.05181	one	2.45308	0.50058	4.90043
	age	0.25317	8.25596e−002	3.06651	lyear	0.88297	0.18148	4.86544
	lyear	1.22293	0.31802	3.84543	elev	6.22756e−004	1.01615e−004	6.12858
	elev	5.75305e−004	1.65039e−004	3.48586				
	Number of Observations		159		Number of Observations		159	
	Corrected R-squared		0.23406		Corrected R-squared		0.28343	
	Mean of Dependent Variable		5.60475		Mean of Dependent Variable		5.70657	
	Material Cost				Equipment Cost			
	Dependent Variable:		lnma		Dependent Variable:		lneq	
	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
2nd Life Cycle Stage	one	4.52583	0.18490	24.47656	one	4.29400	0.29732	14.44254
	lyear	2.38705	0.18875	12.64682	age	0.10612	3.07889e−002	−−3.44663
	aadt	5.12930e−003	1.33309e−003	3.84767	lyear	1.04501	0.13215	7.90795
					elev	2.52489e−004	5.38903e−005	4.68523
					aadt	2.04244e−003	8.90404e−004	2.29384
	Number of Observations		446		Number of Observations		448	
	Corrected R-squared		0.28976		Corrected R-squared		0.18172	
	Mean of Dependent Variable		5.74258		Mean of Dependent Variable		5.70223	
	Material Cost				Equipment Cost			
	Dependent Variable:		lnma		Dependent Variable:		lneq	
	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic	Indep Variable	Estimated Coefficient	Standard Error	t-Statistic
3rd Life Cycle Stage	one	6.20010	0.14017	44.23313	one	6.31784	0.16710	37.80960
	lyear	0.63605	0.27740	2.29287	lyear	0.78032	0.33069	2.35967
	Number of Observations		94		Number of Observations		94	
	Corrected R-squared		4.37733e−002		Corrected R-squared		4.68188e−002	
	Mean of Dependent Variable		6.36249		Mean of Dependent Variable		6.51707	

performed at different stages of road deterioration conditions. Traffic flow shows a positive impact. The results for the last life-cycle stage show that age and the last year maintenance (reconstruction) are significant factors. It is understandable that more maintenance is needed as roads age.

In the last year, when reconstructions were performed, some costs of these reconstructions were counted as maintenance equal to those for flush seals or chip seals. Thus, the last year maintenance becomes outstandingly expensive.

5.6. Annual Maintenance Costs for the Five Categories of Roads

The annual maintenance cost profiles for these five categories of roads are presented in Figure 3. For an asphalt roadway section in Category 1, the elevation is assumed to be 2400 ft, and the AADT is 27,000; the total maintenance costs for an eight-year life cycle can be calculated using the function coefficients given in Table 1. As shown in Figure 3, the total costs increase with year. The annual maintenance cost in the eighth year becomes lower than the linear trend because of the reconstruction done that year. For a road section in Category 2 with an assumed average elevation 3987 ft and an average AADT of 11,786, the profile of annual maintenance costs can be calculated using the coefficients in Table 1. It can be seen from Figure 3 that the maintenance costs are constant, and would drop in the last year. Given the 12-year life cycle presented in Figure 1 for the roads in Category 3, a road section is assumed to have an average elevation of 4900 ft and an average AADT of 800; the annual maintenance profile can be calculated using the coefficients in Table 2. The profile displayed in Figure 3 indicates that the annual maintenance costs jump when flush seal and chip seal are performed that year, and drop when there is a reconstruction. The jump in maintenance cost caused by chip seal is more than that by flush seal. Within each life cycle, the annual maintenance costs are constant.

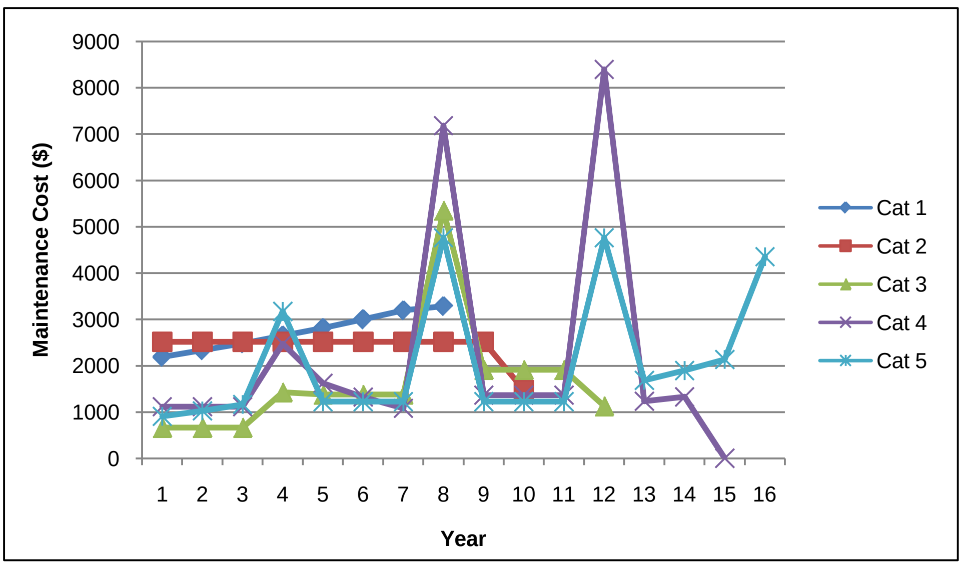

Figure 3. Comparison of annual maintenance cost profile for roads in five categories.

For a road section in Category 4, the profile of the annual maintenance cost is calculated using the values of the coefficients in Table 3. The road section is assumed to be located in District 1. Its elevation is 4700 ft, and it carries traffic with an AADT of 280. It can be seen from Figure 3 that the annual maintenance costs increase when there are flush seal and chip seals, and decrease when there is a reconstruction. The increase in cost with a flush seal is noticeably less than that with a chip seal. The first chip seal incurs less cost than the second one. When producing the annual maintenance profile for Category 5, the values of the coefficients in Table 4 are used. It is assumed that a road section has elevation 5000 ft, and has an AADT of 130. It can be seen from Figure 3 that the annual maintenance costs increase significantly during such events as flush seals, chip seals, and construction.

It is clear that the annual maintenance costs for Categories 1 and 2 are higher than that for the other three categories. Major preventive or reconstruction activities significantly influence the maintenance cost, and have to be considered when calculating the annual maintenance costs.

6. Conclusions and Future Study Needs

6.1. Conclusions

In this study, linear regression models were developed to estimate annual maintenance costs for highway maintenance. Consistent with the maintenance road classification adopted by NDOT, five prioritization categories of roads were considered for model development. Categories 1 and 2 each included only one life-cycle stage, spanning eight and ten years, respectively. Categories 3 and 4 include three and four life-cycle stages, respectively; each stage is associated with certain maintenance activities and has three to four years duration. At NDOT, there was no specific definition on the life cycle for Category 5; therefore, three stages were defined in this study. For each stage of the life cycles in these five categories of roads, linear regression models were developed. In addition to total maintenance cost, this study also developed linear regression models for four maintenance cost components: labor, equipment, materials, and stockpile.

Important influencing factors on annual maintenance costs were considered in this study: age of road, the type of maintenance activities in the last year of maintenance life cycle, elevation, district, and traffic. The results indicate that road age is a significant factor for some life cycle stages and some maintenance cost components. During the time period of a life-cycle stage, the annual maintenance cost may be kept the same. The maintenance activities in NDOT may have been scheduled by considering whether they are close to the time when a preventive maintenance or reconstruction is to be performed.

As reflected in the maintenance cost profile, the annual maintenance cost may decline with time and then jump up to a high level, indicating costs for prevention maintenance or construction activities. Flush seal and chip seal are two preventive maintenances performed by NDOT work forces. The costs incurred in these preventive maintenance activities are significantly higher than other routine and corrective maintenance. Thus, they were singled out in the cost estimation of this study by using indicator variables. Roadways with high elevation tend to be constructed with special safety features, such as guard rails, which would produce high maintenance costs. This perception was validated from the results of the models. Traffic flow deteriorates roads and generates the need for maintenance. Its impact on maintenance cost is also reflected in the model estimation results. Different districts may adopt different maintenance practices in terms of the materials and equipment used in their districts; this was observed from the models developed in this study.

It can be seen that the developed models uniquely integrate the life-cycle concept of pavement by developing different models for different stages in the life cycles. These life-cycle stages also represent the conditions of a road section. The practice of maintenance activities adopted in NDOT was fully considered in developing these models. The variables used in the models can be easily made available, and can provide the basis for the models to be incorporated into NDOT's pavement management and maintenance management systems for estimating future maintenance costs. NDOT could use these models to estimate the maintenance costs in order to submit cost requirements to the State of Nevada's legislation.

6.2. Future Study Needs

Sampling is a major issue for developing the regression models for some categories of road like Categories 1 and 2. With samples covering more areas in Nevada, useful variables such as district can be used, by which more accurate estimation of annual maintenance cost can be produced. The definition of life cycle influences the availability of sufficient samples. For example, the life cycle for Category 1 starts after a certain construction and ends at the same type of construction. This life cycle may be hard to find in the database. Certain approximation was used in this study to extract the samples for Category 1. This sampling may need to be revisited when the model is adopted by NDOT.

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