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Development of a Statistical Model to Predict Materials' Unit Prices for Future Maintenance and Rehabilitation in Highway Life Cycle Cost Analysis

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MTI MINETA TRANSPORTATION INSTITUTE

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MINETA TRANSPORTATION INSTITUTE

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REPORT 20-53

DEVELOPMENT OF A STATISTICAL MODEL TO PREDICT MATERIALS' UNIT PRICES FOR FUTURE MAINTENANCE AND REHABILITATION IN HIGHWAY LIFE CYCLE COST ANALYSIS

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16. Abstract

The main objectives of this study are to investigate the trends in primary pavement materials' unit price over time and to develop statistical models and guidelines for using predictive unit prices of pavement materials instead of uniform unit prices in life cycle cost analysis (LCCA) for future maintenance and rehabilitation (M&R) projects. Various socio-economic data were collected for the past 20 years (1997–2018) in California, including oil price, population, government expenditure in transportation, vehicle registration, and other key variables, in order to identify factors affecting pavement materials' unit price. Additionally, the unit price records of the popular pavement materials were categorized by project size (small, medium, large, and extra-large). The critical variables were chosen after identifying their correlations, and the future values of each variable were predicted through time-series analysis. Multiple regression models using selected socio-economic variables were developed to predict the future values of pavement materials' unit price. A case study was used to compare the results between the uniform unit prices in the current LCCA procedures and the unit prices predicted in this study. In LCCA, long-term prediction involves uncertainties due to unexpected economic trends and industrial demand and supply conditions. Economic recessions and a global pandemic are examples of unexpected events which can have a significant influence on variations in material unit prices and project costs. Nevertheless, the data-driven scientific approach as described in this research reduces risk caused by such uncertainties and enables reasonable predictions for the future. The statistical models developed to predict the future unit prices of the pavement materials through this research can be implemented to enhance the current LCCA procedure and predict more realistic unit prices and project costs for the future M&R activities, thus promoting the most cost-effective alternative in LCCA.

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EXECUTIVE SUMMARY

Pavement Life Cycle Cost Analysis (LCCA) is a practice to help pavement designers make better decisions by balancing initial construction costs and projected future costs of a project. The future costs may include maintenance and rehabilitation (M&R) costs as well as work zone traffic delay throughout the life cycle of a project.

LCCA has been used in California since 2007 to compare the cost-effectiveness of design alternatives such as pavement materials and cross-sections for Caltrans highway projects. The cost calculation module of the existing Caltrans LCCA software, *RealCost 2.5CA*, requires a unit price per material to calculate the cost of future M&R projects. Caltrans' LCCA procedure manual guides users to default to the statewide uniform unit prices or find the relevant unit prices from the Caltrans historical contract cost database. However, materials' unit prices may vary over time given the project size or due to additional factors. The unit price entered by a user to calculate the future Maintenance and Rehabilitation (M&R) project cost for a long-term LCCA period—typically 50–60 years—without considering unit price variability may result in inaccurate results.

Many state transportation agencies maintain construction cost data through public access webpages with unit price information made available for the past several years to several decades. This information is useful for contractors who prepare project bid documents and for pavement designers who compare design alternatives. Information in these resources provided useful guidance during this research and the authors' development of statistical models for LCCA unit price estimates in California.

The main objective of this research was to develop statistical models and guidelines for using predictive unit prices of pavement materials instead of uniform unit prices in LCCA for future M&R activities. Developing predictive unit prices for future M&R activities as an alternative method to the standard conception of unit pricing is a key contribution of the research. The research investigated the trends in the primary pavement materials' unit price and various California socio-economic parameters over time. The primary pavement materials' unit prices in the past 20 years (1999–2018) were collected from the Caltrans Construction Contract Cost database and trends were explored by geographical region (California districts), climate regions, as well as project size, to identify any differences related to such factors. The results showed no significant price differences by geographical or climate region, but differences were observed by project size. The unit prices of each pavement material were categorized into four project sizes (small, medium, large, and extra-large projects), and the annual average unit prices were calculated in each category. The project size was used as a binomial independent variable, and the unit prices were used as the dependent variable in multiple regression models. For most pavement materials, the unit price was lower in large-sizes projects as compared to small-sized projects, therefore the addition of project size as an independent variable resulted in better prediction results in multiple regression models.

The research also investigated socio-economic parameters related to highway construction in order to identify factors that affect and can help predict future prices of pavement materials. Various socio-economic data describing California were collected, and after correlation analysis, four representative socio-economic parameters were selected: national crude oil price, California population, total number of the vehicles registered in California, and state budget expenditure in transportation. Data on these socio-economic variables were collected for the past 20 years (1997–2018), and their future values were predicted for a 50-year LCCA period using ARIMA time series models. The ARIMA model captured and smoothed the unique decline phenomenon of three socio-economic parameters, all except population, during the U.S. economic recession (approximately 2008–2012), and it predicted future values. The values of socio-economic variables (both current and predicted) were used as independent variables in multiple regression models to estimate each pavement material item's unit price for the future M&R activities in the life cycle analysis period.

Using the pavement materials' unit prices from a Caltrans database as well as the socio-economic data collected, multiple regression models were developed to estimate the annual unit prices of each pavement material for the next 50 years (2020–2069). The R-squared values for different variables were in the range of 0.5 and 0.9 indicating that the models were able to explain at least half or more of the variation in the response variables representing a good set of results. Although some of the predictions were realistic and reasonable, others were not considered satisfactory possibly due to a small number of years of past data or a small number of projects in certain size categories. For example, HMA-O's unit price was recorded for only four years from 2015 to 2018. Due to the lack of unit price information, the average unit price was not available in some project categories during the data collection period. The authors recommend using the latest unit prices of the materials having a lack of information instead of using the predicted unit prices in the model that might be biased. Conversely, the authors recommend the use of future unit prices predicted in the statistical models by project size of the pavement material items used in a large number of projects in the past years, such as Rowadway Excavation, Class 2 Aggregate Base, HMA-A, RHMA, JPCP, and LCB. These models were verified using the unit prices gathered from the recent pavement projects in the state.

The predicted future values of pavement materials' unit prices were used in a case study to compare the differences in the results obtained from using uniform unit prices in the current LCCA procedure. The NPVs of the life cycle agency costs calculated by the model-predicted unit prices were higher than those calculated with the uniform unit prices for two alternatives: HMA-A with a 20-year design life and JPCP with a 40-year design life. In the case study, JPCP with a 40-year design life was more cost-effective than HMA-A with 20-year design when the authors calculated the life cycle costs for both alternatives using the future unit prices predicted by the models developed in this study.

In LCCA, long-term prediction must take account of uncertainties due to the unexpected economic trends and industry demand and supply conditions. Economic recessions and a global pandemic are examples of unexpected events which can have a significant influence on variations in material unit prices and project costs in the future. Nevertheless, the data-driven scientific approach described in this research reduces the risk associated with such uncertainties and enables practicable predictions for the future. The models developed in this research can be implemented to enhance California's current LCCA procedure to predict more realistic unit prices and project costs for future M&R activities, thus aiding in the selection of the most cost-effective alternatives within an LCCA framework.

I. INTRODUCTION

BACKGROUND

Pavement life cycle cost analysis (LCCA) is a practice to help pavement designers make better decisions by balancing initial construction costs and projected future costs of a project. The future costs may include maintenance and rehabilitation (M&R) costs and work zone traffic delay throughout the life cycle of a project.[1] In 2002, the Federal Highway Administration (FHWA) first published an LCCA primer to provide background knowledge and demonstrations for transportation officials, and that was followed by an LCCA software tool in 2004 called *RealCost (version 2.5)* to support practitioners performing LCCA for highway projects.[2,3]

LCCA has been used in California since 2007 to compare the cost-effectiveness of design alternatives such as paving materials and cross-sections for Caltrans highway projects.[4, 5] According to the Caltrans Highway Design Manual (HDM) Topics 612 and 619, Caltrans pavement engineers evaluate the cost-effectiveness of alternative pavement designs for new construction, reconstruction, and rehabilitation of highways.[6] To support the project engineers, Caltrans published the Life Cycle Cost Analysis Procedure Manual in 2007, which was updated in 2013. Additionally, an online training course was developed and is available on the Caltrans LCCA website.[4]

The cost calculation module of the existing Caltrans LCCA software, *RealCost 2.5CA*, requires a unit price per material to calculate the cost of future M&R projects. Caltrans' LCCA procedure manual guides users to defer to the statewide uniform unit prices as a default or to find the relevant unit prices from the Caltrans historical contract cost database.[1] However, materials' unit prices may vary over time given the project size or due to additional factors. Entering a unit price to calculate the future M&R project cost for a long-term LCCA period (typically 60 years) without considering unit price variability may yield inaccurate results.[7]

RESEARCH OBJECTIVE AND TASKS

The objective of this research was to investigate the trends in pavement materials' unit prices due to various factors (project size, climate region, and other socio-economic variables) and develop statistical models to predict material and construction-related unit price inputs for future M&R projects to support LCCA for California highway projects. Developing the future predictive unit prices as an alternative method to the standard conception of future uniform unit pricesis a key contribution of this study. The study results will enhance the accuracy and practicality of the highway LCCA results with the aim of enabling practitioners to select cost-effective material and construction alternatives. In view of the objectives, the following list of tasks were completed in this research.

Task 1: Development of Research Framework and Literature Review

A review of the published research, state Department of Transportation resources, and tools related to state-of-the-art practices used to estimate materials and construction costs for highway maintenance and rehabilitation projects was conducted. Various sources of data were also identified to be used in subsequent tasks in this research.

Task 2: Data Collection and Analysis

The materials and construction costs of California highway projects were collected from the Caltrans contractor cost database and the Integrated Maintenance Management System (IMMS) database.[8] Additional data on various factors that may impact materials' unit price were also collected from several sources. All data were integrated in a database at a local server and analyzed using open-source software tools.

Task 3: Model Development

The unit cost estimate models were developed from the collected data using appropriate statistical methods (categorical analysis, cluster analysis, and multiple linear/non-linear regression). Various models were developed and tested to identify the most relevant model in this research.

Task 4: Model Validation and Case Study

The statistical models developed in this research was applied to a recent Caltrans project as a case study to evaluate model effectiveness and the sensitivity of model output. The future unit prices predicted by the statistical models were used in the project cost calculation for the future M&R activities and compared with the project costs calculated by the standard concept of the uniform unit prices for the future M&R activities.

Task 5: Documentation and Final Report

A final report was prepared documenting all findings of the research and final recommendations to Caltrans.

II. LITERATURE REVIEW

LITERATURE ON UNIT PRICE ESTIMATION AND MATHEMATICAL MODELS

The process for estimating pavement project cost usually consists of many individual elements combined to obtain the final cost output. Although the methods used throughout the United States vary, there are certain elements and variables that are common to most, if not all, methods. In general, the engineer determines the unit price basis based on the proposed scope for the project considering the following factors:

- Geographic location (e.g., urban/rural, state location, district),
- Similarity of recent construction projects,
- Inflation (adjustments of past prices to reflect the current year),
- Reliability of recent construction cost data,
- Recent trends in cost of materials, labor, and equipment,
- Anticipated difficulty of construction,
- Project size relative to size of previous projects,
- Proposed project schedule,
- Anticipated construction staging,
- Right-of-way,
- Railroads,
- Utilities,
- Expected environmental problems (e.g., hazardous wastes, wetlands), and
- Engineering judgment.

Several research studies have been conducted to explore pavement cost estimate approaches and methodologies in the past two decades. Gransberg and Molenaar developed the life cycle cost award algorithms for a design/build highway pavement project in 2003.[9] The study goal was to design best-value award algorithms based on the best sustaining lifespan to procure pavement versus conventional lowest bid awards. Gransberg and Molenaar analyzed the existing design/build award methods to identify the potential for applying awards based on the life cycle award algorithms (LCAA).[9] In addition to the initial capital cost, the algorithm proposed a new requirement applicable among design/builders to consider maintenance, repair, and rehabilitation costs.

The analysis focused on two cases: one was administered through the Florida Department of Transportation (FDOT) and the other through the Washington State Department of Transportation (WSDOT). The FDOT case was based on literature in FDOT's design/build policy documentation[10] considering proposals, costs, and scheduling corresponding with technical scores, all applicable to best-value award algorithms. The WSDOT case was based on an urban freeway project in Vancouver, Washington, State Route 500: the "Thurston Way Interchange Project." This was WSDOT's first design/build project, with grade-separated structures, on/off ramps, and realignment. Eight 12-ft lanes were analyzed based on AASHTO 1993 definitions. Design alternatives were referenced from the existing state manuals and material costs for LCAA.[9] To eliminate external variables, the researchers assumed that the projects were purely pavement construction projects excluding non-pavement related projects like drainage or traffic signage projects.. Only pavement structure from the sub-grade up was included in the analysis, and the subgrade was assumed to be the same for all alternatives. Cost was analyzed by life cycle unit of cost per centerline-mile to evenly account for construction work zones and roadway curvatures. The work zone was assumed to be one mile in length, and it was assumed that no more than half of the available lanes were closed at any given time per requests for proposals (RFPs) traffic control requirements.[9]

Gransberg and Molenaar found four different categories of best-value award algorithms in state highway design/build RFPs.

- Meets technical criteria-low bid;
- Adjusted bid;
- Adjusted score; and
- Weighted criteria.

Several other states (Arizona, Indiana, South Carolina, Texas, and Washington) also had a specified formula and score consideration for the award algorithms, as summarized in Table 1.

Table 1. Example of Best-Value Award Algorithm from Typical Agencies[9]

Agency	Formula with Agency Name for Award Method	Award Algorithm
Arizona DOT (AZDOT 1997)	Adjusted price = price proposal - quality value	Adjusted bid
Indiana DOT (INDOT 1998)	Low bid - fully qualified Fully qualified = score ≥ 75	Meets technical criteria - low bid
Federal Highway Administration (FHWA 2001)	Adjusted score = technical score x 10,000 / price proposal + contract administrative cost[†] [†]Contract administrative cost = daily administrative cost x proposed schedule days	Adjusted score
South Carolina DOT (SCDOT 1996)	Composite score = price proposal/technical score	Adjusted bid
Texas Turnpike Authority (TTA 2001)	Price score = (lowest proposed price / price$_i$) x Wt$_{price}$ Technical score = (tech score$_i$ / high tech score) x W$_{tech}$	Weighted criteria
Washington DOT (WSDOT 1999)	Best-value score Technical score x 10,000,000 / lump sum price	Adjusted score

Gransberg and Molenaar's study concluded that the best-value award algorithm can be skewed based on cost, time, or quality. It is possible to use LCAA, but the processes must be followed through thoughtfully to prevent bias towards other factors that may affect contractors and owners alike.

Tighe presented the guidelines for a probabilistic pavement life cycle cost analysis procedure.[11] Tighe's guidelines followed the same principles as discussed in the LCAA developed by Gransberg.[9] Specifically, for Tighe's LCAA, it was recommended that constant dollars and real discount rates be used, thus eliminating estimates and premiums for both cost and discount rates. Pavement cost estimates were determined by the availability of data from previous construction and maintenance projects. The initial construction, major maintenance, rehabilitation, and salvage values were used for the LCAA. Initial construction included material costs with pavement design. Maintenance costs were categorized as routine maintenance, such as pothole repair or drainage improvements, and major maintenance such as structure and surface improvements. Rehabilitation cost was determined from pavement performance prediction, and salvage value was included at the end of service life to calculate salvage values of the material. For the cost variation analysis, the goodness of fit test was utilized to examine the distribution of the data across the material types and costs. Costs from bidders were also compiled based on bidding prices and were analyzed graphically to observe the most common pricing for the specific material per unit weight. Depending on the data spread, either a log normal or a normal distribution was applied to fully quantify the material's statistical behavior. For the pavement thickness variation, it was suggested that a best fit distribution should be utilized given limited information in the prior literature.[11]

Tighe's guidelines followed an in-depth mathematical model based on the Monte Carlo simulation to better simulate the true probability distribution for a certain frequency for each material usage. Tighe suggested that for the overall analysis of pavement LCCA, a log normal distribution should be used for most of the components relating to the material's cost and cost of construction, thus better quantifying the variations and statistical spread with varying bidding and economic changes.[11]

Swei et al. presented a parametric approach to estimate expected cost and cost variation in infrastructure construction by utilizing a probabilistic LCCA procedure.[12] The study utilized fifteen different pavement bid items across five American states and specifically investigated the bias and heteroscedasticity in what were then current cost-estimation procedures. Several methods were utilized, including multiple linear regression, reiteration of data, logarithmic, transformation, and other approaches, as summarized in Table 2. The mathematical functional forms were then applied to each individual state and its corresponding bid datasets.

Table 2. Summary of the Structural form for the Three Approaches to Model Variation in Bid Unit-Price Data[12]

Approach	Model Type	Functional Form
1.	Log Reciprocal Power	$P_i = \beta_o + \beta_q LN(\chi_{i,q}) + u_i$ $\frac{1}{P_i} = \beta_0 + \beta_q \chi_{i,q} + u_i$ $LN(P_i) = \beta_0 + \beta_q LN(\chi_{i,q}) + u_i$
2.	Box–Cox transformation (λ)	$P_i^{(\lambda_1)} = \beta_0 + \beta_q \chi_{i,q}^{(\lambda_2)} + u_i$
3.	Box–Cox transformation (λ), district variation (d), and number of bidders (b)	$P_i^{(\lambda_1)} = \beta_0 + \beta_q \chi_{i,q}^{(\lambda_2)} + \sum_{l=1}^{L} \beta_{d_l} \chi_{i,d_l} + \beta_b \chi_{i,b} + u_i$

Notes:

P_i: Bid unit, i.e., price for i^{th} sample

$\chi_{i,q}$: Bid quantity

χ_{i,d_l}: Dummy variable for l^{th} district within a state

$\chi_{i,q}$: Number of bidders for a project

λ_1, λ_2: Optimal data transformations for bid unit price and quantity

Conclusively, Swei and colleagues found that current methods of LCCA result in biased estimates, but applying principles of maximum likelihood can reduce the bias naturally present in material and construction costs.[12]

REVIEW OF UNIT PRICE DATA SOURCES FROM VARIOUS STATE TRANSPORTATION AGENCIES

A detailed review of unit price database from nine state transportation agencies was conducted in order to understand the information being utilized by those agencies in their respective processes. Table 3 provides a list of the data sources from each of the nine state transportation agencies. Many agencies maintain this information through public access webpages with unit price information for the past several years to decades available. This information is useful for contractors who prepare project bid documents and for pavement designers who compare design alternatives. Information in these resources provided useful guidance and ideas during this research in order to identify critical socio-economic factors to help develop statistical models for California LCCA unit price estimates.

Table 3. Pavement Unit Price Information by State

State	Source, Format, Description, and Link
California	DOT website, web interface, downloadable to csv files https://sv08data.dot.ca.gov/contractcost/
Colorado	Item Unit Costs by Projects,2015 Cost Data, Data source: DOT website; pdf file https://www.codot.gov/business/eema/documents/2015/2015-cdb-1st-qtr/view
Connecticut	CTDOT English Bid Item List (Unit Prices), December 2018 Data source: DOT website; Excel sheet https://www.ct.gov/dot/cwp/view.asp?a=3198&q=459664
Florida	Bridge construction and demolition unit price per square feet Data from April 2014, Data source: DOT website; pdf file http://www.dot.state.fl.us/planning/policy/costs
Kentucky	Average Unit Bid Prices, Data from 2016, 2017, and 2018 Data source: DOT website; Excel sheets https://transportation.ky.gov/Construction-Procurement/Pages/Average-Unit-Bid-Prices.aspx
New York	US Customary Contracts Let April 1, 2016 to March 31, 2017 Weighted Average Unit Price Report, By Item, Region and Quarter Data source: DOT website; Excel sheet, Microsoft Word and pdf files https://www.dot.ny.gov/divisions/engineering/design/dqab/waipr
Texas	Average Low Bid Unit Prices – Construction and Maintenance, March 2019 Highway Cost Index Report, April 2019 Data source: DOT website; Excel sheet, text document, and pdf file https://www.txdot.gov/business/letting-bids/average-low-bid-unit-prices.html
West Virginia	Highway Construction Unit Prices (2016, 2017, 2018), DOT website; text document https://transportation.wv.gov/highways/contractadmin/Lettings/Pages/AverageUnitBidPrices.aspx
Wisconsin	Average Unit Price List, December 2018, Cost Index Data, July 2016 Data source: DOT website; Excel sheet and pdf file https://wisconsindot.gov/Pages/doing-bus/eng-consultants/cnsltrsrces/tools/estimating/est-guidance.aspx

III. DATA COLLECTION AND ANALYSIS

In view of the literature and considering the research objectives, the research team investigated various sources of information related to Caltrans highway projects and maintenance costs to obtain pavement construction cost data. Caltrans maintains the Integrated Maintenance Management System (IMMS) database which includes the project date, location, size, cost, material quantity and unit price, and equipment quantity and unit price for past projects completed on the California highway system. Additionally, Caltrans' Contractor Cost database[8] and Annual Contract Cost Data Books[13] contain information on contractors' bid costs per item for all projects which can be filtered by district, year, minimum and maximum price, and quantity. Data on California Highway Capital Maintenance (CAPM) and Rehabilitation (REHAB) projects completed in the past 20 years were collected from these sources for use in this research.

Relevant data were exported and integrated into a new local database on a local server with additional socio-economic parameters. Data on the socio-economic parameters collected and utilized in this research included gasoline/diesel price, population, crude oil price, annual state budget in construction, the number of vehicles registered in California, annual vehicle miles traveled (VMT) in California, consumer price index, etc., details of which are provided in subsequent sections.

CALIFORNIA PAVEMENT CONSTRUCTION COST DATA

Caltrans annually publishes a Contractor Cost Data Book, which summarizes the cost by item for highway construction projects. Caltrans also maintains the online contractor cost data through a publicly accessible website which is manually updated biweekly from the contractors' bid documents.[8] The cost data are available from 1993 to present by item, district, and bid rank. As of April 2019, 2,686 construction items were recorded and listed in the construction cost database. Additionally, a total of 2.5 million records were included in the contractor cost database.

In the present research, 116,000 records of the pavement-related item costs were imported into the local server database to develop cost estimate models for major pavement-related items. The records include material item description, unit, district, quantity, unit price, total item price, year, and contract number.

MAJOR AND MINOR ITEMS FOR PAVEMENT MAINTENANCE AND REHABILITATION ACTIVITY

Table 4 displays information on pavement- and non-pavement-related items priced by unit collected from nine different states, including major and minor items. This research focused on the major items related to pavement maintenance and rehabilitation projects in LCCA, such as concrete paving, asphalt overlay, aggregate base, and subbase.

Table 4. Pavement- and Non-Pavement-Related Items in Highway Construction

Category	Item Description
Major Items (Pavement-related)	concrete paving, widening, shoulders, bituminous paving, widening shoulder, aggregate base, subbase, surface patching, cold milling, hauling, traffic control, seal coat, storm sewers, concrete structures, etc.
Major Items (Non-pavement-related)	cofferdams, concrete box culverts, piling, sweeping, structure removal, hauling, earth excavation, borrow embankment, etc.
Minor Items (Pavement-related)	pavement marking, driveway pavement, bridge deck overlay, bridge approach pavement, etc.
Minor Items (Non-pavement-related)	lighting, traffic signals, signing, weed spraying, crack routing, landscaping, pipe culverts, pipe underdrains and pipe drains, manholes, catch basins, inlets, curb and gutter, sidewalk, electrical maintenance, reinforcing steel, soil stabilization, anchors and tiebacks, fencing, railroad track construction, bearing, deck grooving, etc.

In view of the information gathered from other states, the primary pavement materials for both rigid and flexible pavements used in calculation of the future maintenance and rehabilitation activities in Caltrans LCCA were identified and are listed in Table 5.

Table 5. List of Primary Pavement Items used in Future M&R in LCCA

Pavement Item Description	Unit	Number of Projects	Data Period
Roadway Excavation	CY	4,151	1999–2018
Class 1 Aggregate Subbase (C1AS)	CY	29	1999–2018
Class 2 Aggregate Subbase (C2AS)	CY	210	1999–2018
Class 2 Aggregate Base (C2AB)	CY	800	2012–2018
Class 3 Aggregate Base (C3AB)	CY	160	2012–2018
Hot Mix Asphalt, Type A (HMA-A)	Ton	2,415	2008–2018
Hot Mix Asphalt, Open Graded (HMA-O)	Ton	57	2015–2018
Rubberized Hot Mix Asphalt, Gap Graded (RHMA)	Ton	681	2008–2018
Rubberized Hot Mix Asphalt, Open Graded (RHMA-O)	Ton	66	2015–2018
Jointed Plain Concrete Pavement (JPCP)	CY	200	2009–2019
Jointed Plain Concrete Pavement, Rapid Setting Concrete (JPCP-RSC)	CY	89	2014–2018
Lean Concrete Base (LCB)	CY	501	1999–2018
Lean Concrete Base, Rapid Setting Concrete (LCB-RSC)	CY	105	2013–2018

As an example of changes of material unit prices over time, Figure 1 shows the average unit price change of jointed plain concrete pavement (JPCP) by project size in each district over time. The discussion about determining the project sizes is described in the later section (Chapter IV). The unit price of the primary pavement items listed in Table 5 are shown by project size in Appendix C.

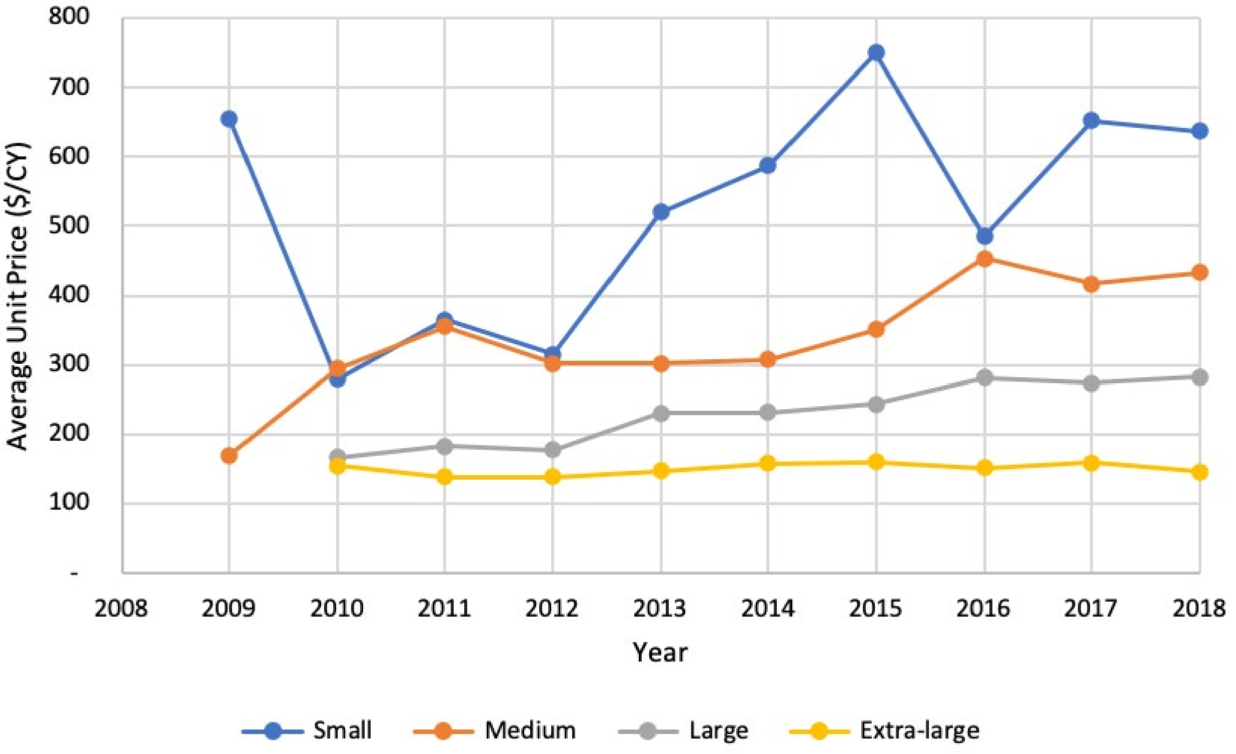

Figure 1. Unit Price Changes of Jointed Plain Concrete Pavement (JPCP) by Project Size in 2009–2018

SOCIO-ECONOMIC PARAMETERS

Three major components of pavement-related materials are asphalt, concrete, and aggregates; the unit prices of the materials are associated with socio-economic parameters that are directly linked with material production and raw materials. For example, consider crude oil price for asphalt binders and industry cement price for cement mix. Transportation and labor costs are related to consumer price index, inflation rate, and gasoline/diesel price. Considering this information and in view of the literature, data related to the following selected socio-economic parameters were collected from multiple sources for review in this research.

- Gasoline/diesel price
- Population
- Crude oil price
- Annual construction budget
- Vehicle registration and vehicle miles traveled
- Consumer price index

- State expenditure in transportation
- Inflation rate, industry cement price, etc.

State Annual Gas Prices

The state annual gas price represents the cost of gasoline per gallon for each type of fuel grade, including diesel cost, which was obtained from the U.S. Energy Information Administration indexed by state.[14] The dataset contained monthly and annual gas prices, both of which show similar trends. As shown in Table 6 and Figure 2, from 1994 until 2002, gas prices were generally flat with little variation, after which the cost gradually continued to increase until 2008. From 2008 to 2009, the cost dropped, corresponding with the 2008 recession. From 2009 to 2012, the price continued to increase, and from 2012 to 2016, it dropped back to values equivalent to the lowest price seen during the 2008 recession. From 2016 to present, the prices have resumed an almost linear increase. Both the monthly and annual gas prices display minimal variation among the different grades of fuel and are almost equal in terms of behavior across time. Changes of gas prices influence on vehicle miles traveled, pavement damages, and material' unit prices directly or indireclty.

Table 6. State Annual Gas Price

Year	CA All Grades All Formulations Gasoline Retail Prices ($/gal)	CA Regular All Formulations Gasoline Retail Prices ($/gal)	CA Midgrade All Formulations Gasoline Retail Prices ($/gal)	CA Premium All Formulations Gasoline Retail Prices ($/gal)	CA No. 2 Diesel Retail Prices ($/gal)	CA No. 2 Diesel Ultra Low Sulfur Retail Prices ($/gal)
1995	1.260	1.215	1.325	1.410	1.295	
1996	1.357	1.312	1.425	1.505	1.441	
1997	1.391	1.345	1.461	1.543	1.383	
1998	1.220	1.174	1.281	1.377	1.184	
1999	1.419	1.373	1.478	1.580	1.348	
2000	1.714	1.669	1.771	1.870	1.672	
2001	1.677	1.632	1.736	1.836	1.543	
2002	1.561	1.514	1.622	1.724	1.450	
2003	1.878	1.831	1.940	2.040	1.657	
2004	2.166	2.120	2.227	2.327	2.099	
2005	2.517	2.473	2.574	2.672	2.608	
2006	2.855	2.809	2.913	3.013	2.922	
2007	3.124	3.077	3.185	3.285	3.094	
2008	3.561	3.512	3.624	3.727	3.925	3.925
2009	2.725	2.678	2.785	2.888	2.607	2.607
2010	3.138	3.091	3.200	3.302	3.157	3.157
2011	3.863	3.817	3.924	4.026		4.084
2012	4.081	4.034	4.141	4.244	4.230	4.230
2013	3.933	3.886	3.994	4.098	4.126	4.126
2014	3.794	3.745	3.857	3.963	4.004	4.004
2015	3.221	3.169	3.288	3.401	3.015	3.015
2016	2.782	2.727	2.855	2.970	2.654	2.654
2017	3.080	3.023	3.158	3.274	3.067	3.067
2018	3.551	3.483	3.656	3.769	3.874	3.874

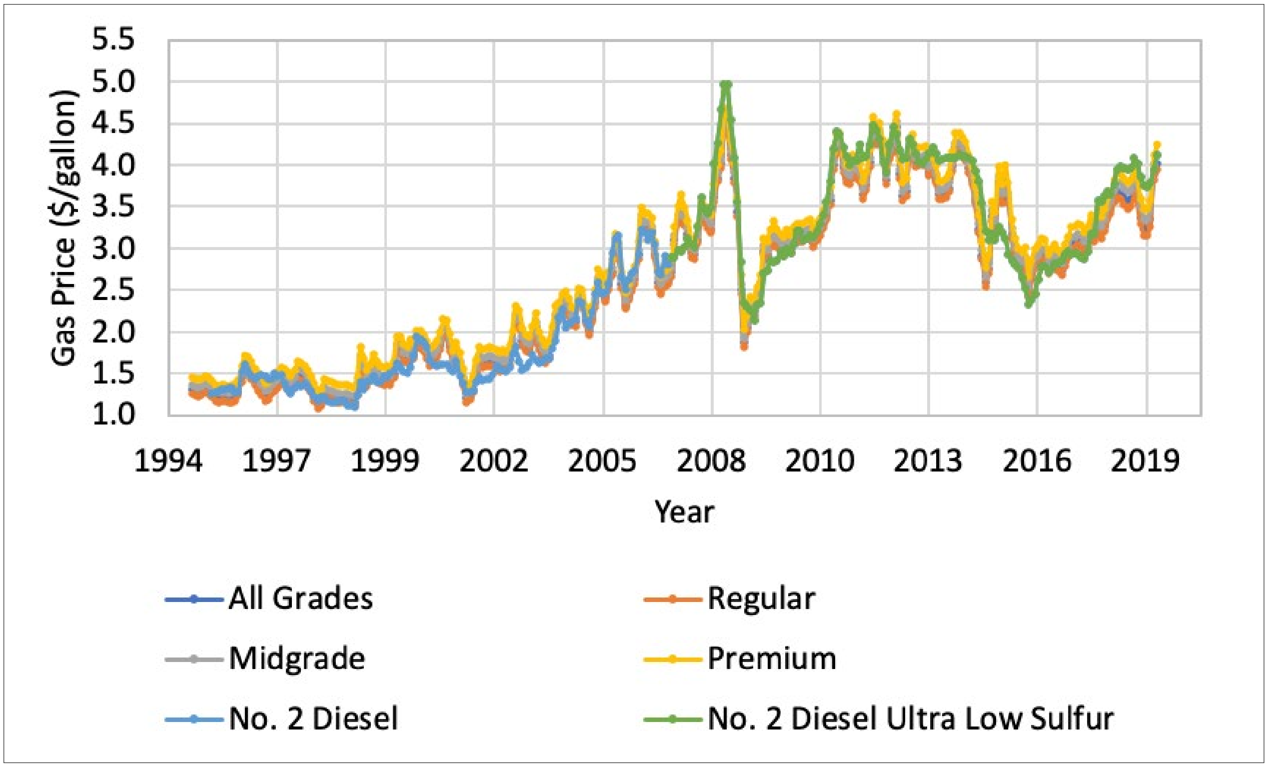

Figure 2. California Gas Prices

Crude Oil Prices

Table 7 and Figure 3 show the yearly average national crude oil prices (both imported and domestic sources) in the United States from 1986 to 2019. The data were retrieved from the United States Energy Information Administration, Independent Statistics and Analytics.[14] General trends display an almost constant price for crude oil from 1986 to 1999 with an approximate spot price of $20 per barrel, whereas from 2000 to 2008, the spot price continually increased linearly to $100. From 2008 to 2009, the price dropped to the 2006 value of $61, showcasing the effects of the 2008 recession. From 2009 to 2011, the price increased again nearly to 2008 values and remained relatively constant from 2011 to 2014. Afterwards, the price dropped to a 2005 value of approximately $50 per barrel by 2015. From 2015 to present, the price has increased linearly.

Table 7. National Crude Oil Price

Year	National Average ($/barrel) Crude Oil Prices	% Change
1986	15.04	
1987	19.17	4.13
1988	15.98	-3.19
1989	19.64	3.66
1990	24.47	4.83
1991	21.5	-2.97
1992	20.56	-0.94
1993	18.45	-2.11
1994	17.19	-1.26
1995	18.44	1.25
1996	22.11	3.67
1997	20.61	-1.50
1998	14.45	-6.16
1999	19.26	4.81
2000	30.3	11.04
2001	25.95	-4.35
2002	26.12	0.17
2003	31.12	5.00
2004	41.44	10.32
2005	56.49	15.05
2006	66.02	9.53
2007	72.32	6.30
2008	99.57	27.25
2009	61.65	-37.92
2010	79.4	17.75
2011	94.87	15.47
2012	94.11	-0.76
2013	97.91	3.80
2014	93.26	-4.65
2015	48.69	-44.57
2016	43.14	-5.55
2017	50.88	7.74
2018	64.94	14.06

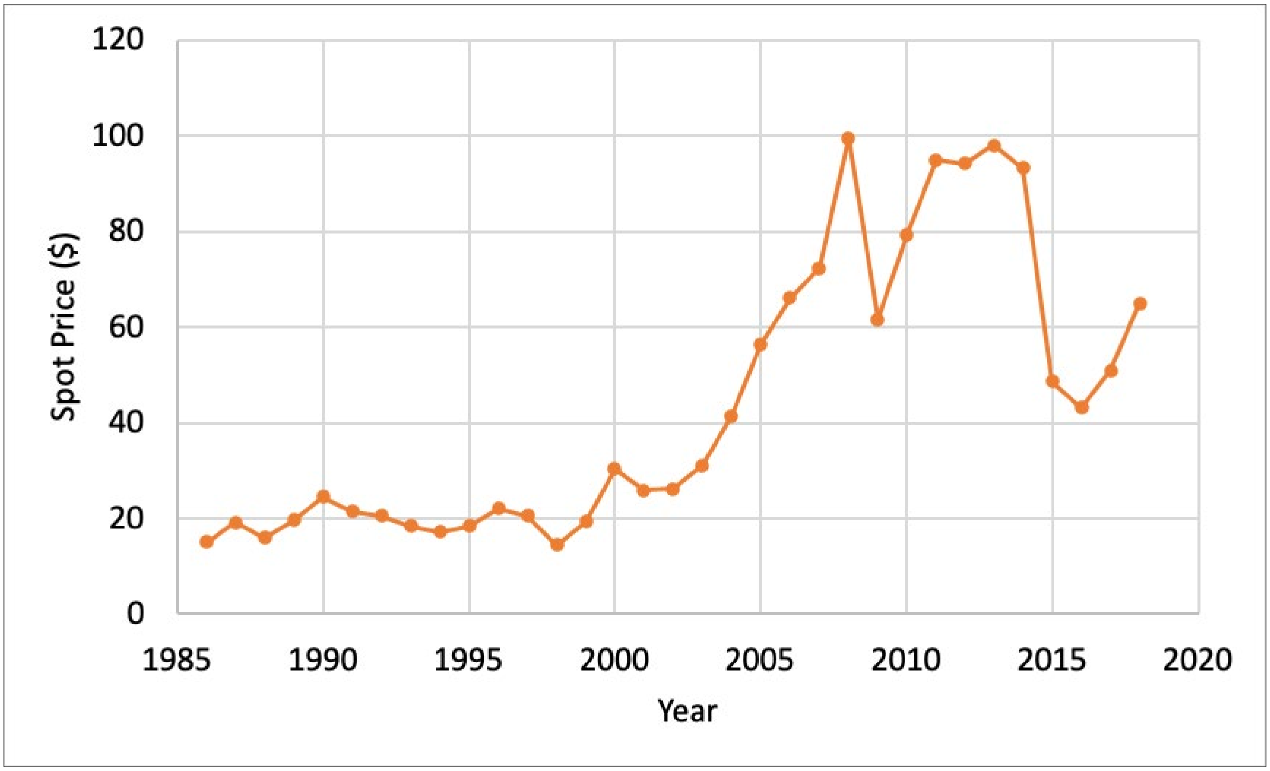

Figure 3. Annual National Crude Oil Prices

California Vehicle Miles Traveled (VMT)

The value of California Vehicle Miles Travelled (VMT) represents the cumulative total amount of vehicle miles travelled throughout the State of California's roadway networks, including minor and major roadways, arterials, and connectors. The values serve as a representative behavioral indicator of all vehicle miles travelled, including by all public/commercial and privately-owned vehicles. The data were retrieved from the Bureau of Transportation Statistics (BTS) of U.S. Department of Transportation.[15] Additionally, data were also sourced from the Federal Highway Administration, specifically the Office of Highway Policy Information. BTS's database only has VMT data up until 2013, but both data sources had identical values for the VMT and this combination was deemed sufficient to use as data for the analysis. Trends in the data, as illustrated in Table 8, show a continual growth from 1997 until 2004, where the VMT stagnated up through 2008. Similarly, from 2008 until 2011, the VMT gradually decreased corresponding with the 2008 recession. After 2011, the CA VMT almost linearly increases until the present day.

Table 8. California Vehicles Miles Travelled (VMT)

Year	CA VMT (Millions)	CA VMT Per Capita	VMT Change	Per Capita Change
1997	279,096	8,591	NA	NA
1998	290,630	8,810	11,534	219
1999	300,066	9,053	9,436	243
2000	306,649	9,018	6,583	-35
2001	NA	NA	NA	NA
2002	320,942	9,179	NA	NA
2003	323,592	9,165	2,650	-14
2004	328,917	9,250	5,325	85
2005	329,267	9,199	350	-51
2006	327,478	9,102	-1,789	-97
2007	328,312	9,057	834	-45
2008	327,286	8,904	-1,026	-153
2009	324,486	8,779	-2,800	-125
2010	322,849	8,647	-1,637	-132
2011	320,784	8,512	-2,065	-135
2012	326,272	8,577	5,488	65
2013	329,534	8,576	3,262	-1
2014	332,857	8,588	3,323	12
2015	335,539	8,587	2,682	-2
2016	340,115	8,648	4,576	61
2017	343,862	8,681	3,747	33

California Vehicle Registration

The California Vehicle Registration metric represents the cumulative total number of vehicles actively registered in the State of California, including both private/commercial and public vehicles. Data range from 1997 to 2017. The values serve to represent the economic trends within California and the number of vehicles operating on California's roadway network. Data were retrieved from the U.S. Department of Transportation's Federal Highway Administration.[15] General trends as presented in Table 9 show a gradual increase in vehicle registration numbers from 1997 till 2006. There is a visible decrease in both truck (private/commercial) as well as auto (private/commercial) registrations from 2009 to 2013, corresponding with the 2008 recession. Since 2013, these numbers have steadily increased (nearly linearly), although they have not matched the total number of vehicles registered in 2007.

Table 9. California Vehicle Registration

Year	Total Vehicle Registration (Private, Public, and Commercial)
1997	24,944,976
1998	25,600,250
1999	26,362,468
2000	27,697,923
2001	28,780,056
2002	29,618,605
2003	30,248,069
2004	31,399,596
2005	32,487,477
2006	33,182,058
2007	33,935,386
2008	33,483,061
2009	34,433,206
2010	31,014,128
2011	29,176,697
2012	27,702,150
2013	28,074,977
2014	28,686,646
2015	29,424,012
2016	30,221,033
2017	30,795,141
2018	31,022,328

Population

The population dataset represents the State of California’s total population estimates from 1970 to 2018. The numbers serve as representative values of the population based on local county estimates, including the once per decade census counts. Data were retrieved from the State of California’s Department of Finance website and included demographic data and forecasting estimates.[16] Table 10 and Figure 4 show the general trends for the total population estimate in the State of California, revealing steady linear growth from 1970 to present. However, a very slight tapering of the rate of change can be seen relative to the entire data trend from 1970 to 2018.

Table 10. California Population Growth

Year	California Population	Year	California Population
1970	20,039,000	1995	31,711,849
1971	20,346,000	1996	31,962,949
1972	20,585,000	1997	32,452,789
1973	20,869,000	1998	32,862,965
1974	21,174,000	1999	33,418,578
1975	21,538,000	2000	34,095,209
1976	21,936,000	2001	34,512,742
1977	22,352,000	2002	34,938,290
1978	22,839,000	2003	35,388,928
1979	23,257,000	2004	35,752,765
1980	23,782,000	2005	35,985,582
1981	24,278,000	2006	36,246,822
1982	24,805,000	2007	36,552,529
1983	25,337,000	2008	36,856,222
1984	25,816,000	2009	37,077,204
1985	26,402,000	2010	37,318,481
1986	27,052,000	2011	37,678,534
1987	27,717,000	2012	38,045,271
1988	28,393,000	2013	38,425,695
1989	29,142,000	2014	38,756,940
1990	29,828,496	2015	39,076,128
1991	30,458,613	2016	39,328,337
1992	30,987,384	2017	39,610,556
1993	31,314,189	2018	39,825,181
1994	31,523,690		

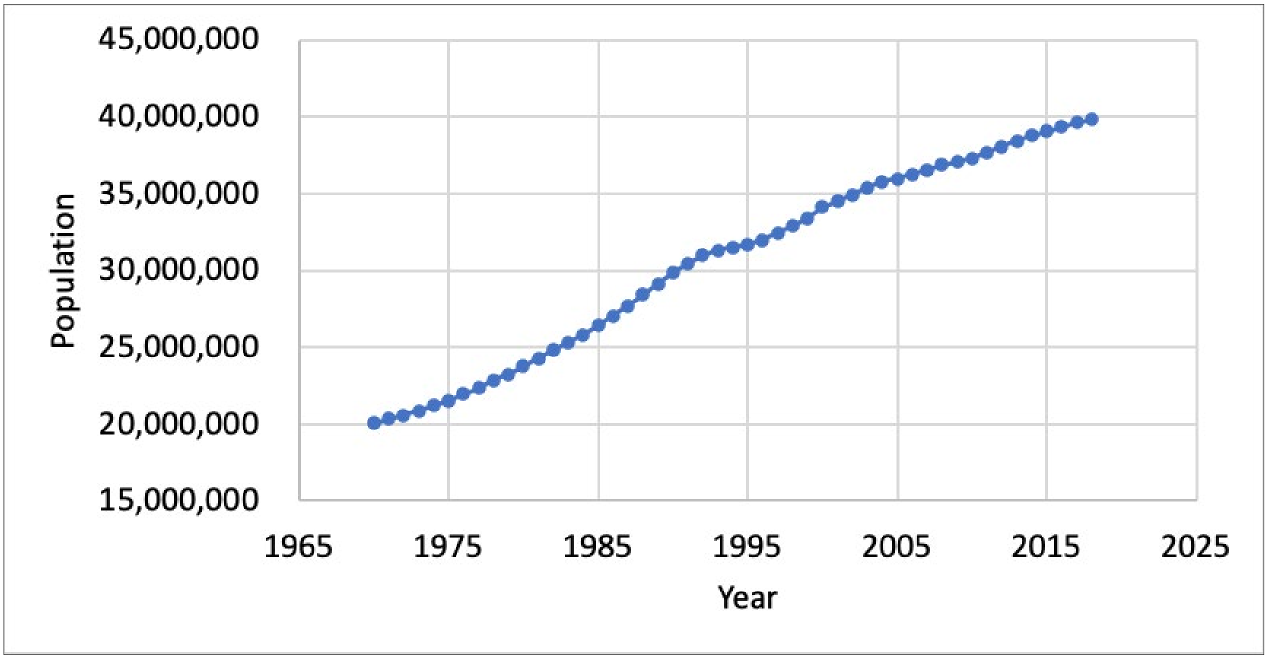

Figure 4. California Population Growth (1970–2018)

Inflation

The inflation dataset showcases the inflation specific to the State of California from 1955 to 2018. The dataset is separated into three sections based on California Gross Domestic Product (GDP), Personal Consumer Index (CPI), and State and Local Purchases Index. The values serve as a representative of behavior of the State of California's economic growth and general trends across each individual year. The data were obtained from the State of California's Department of Finance.[17] Table 11 shows the GDP index, personal consumption expenditures index, and state and local purchase index in California from 1980 to 2018. Table 11 shows an almost linear growth in inflation from 1980 to 2018. The only visible discrepancy is a slight stagnation of growth immediately after 2008, indicative of the 2008 economic recession.

Table 11. Changes of Inflation Rates

Year	CA GDP Index	CA Personal Consumption Expenditures Index	CA State and Local Purchases Index
1980	42.27	41.26	30.08
1981	46.27	44.96	33.23
1982	49.13	47.46	35.40
1983	51.06	49.47	36.96
1984	52.90	51.34	38.54
1985	54.57	53.13	40.11
1986	55.67	54.29	41.27
1987	57.05	55.96	43.20
1988	59.06	58.15	44.64
1989	61.37	60.69	46.75
1990	63.67	63.36	49.15
1991	65.83	65.47	50.95
1992	67.33	67.22	52.69
1993	68.92	68.89	54.00
1994	70.39	70.33	55.39
1995	71.87	71.81	56.87
1996	73.18	73.35	58.18
1997	74.45	74.62	59.47
1998	75.28	75.22	60.63
1999	76.37	76.34	63.01
2000	78.08	78.24	66.03
2001	79.79	79.74	68.28
2002	81.05	80.79	69.82
2003	82.56	82.36	72.05
2004	84.78	84.41	75.37
2005	87.42	86.81	79.61
2006	90.07	89.17	83.62
2007	92.49	91.44	88.13
2008	94.29	94.18	92.56
2009	95.00	94.09	92.05
2010	96.11	95.71	94.67
2011	98.12	98.13	97.74
2012	100.00	100.00	100.00
2013	101.76	101.35	103.28
2014	103.68	102.87	105.67
2015	104.79	103.13	105.75
2016	105.94	104.24	105.97
2017	107.95	106.07	109.16
2018	110.38	108.23	113.01

State Budget Transportation Expenditure

The California Budget Transportation Expenditure represents the State of California's budget allocated towards transportation-related projects and agencies. The data selected are specific only to California-funded projects and exclude all federally funded or partially funded projects. Table 12 shows the California expenditures in transportation from 1989 to 2018 The data were obtained from the California's Legislative Analyst's Office, Nonpartisan Fiscal and Policy Advisor.[18] General trend in Table 12 shows a significant amount of unpredictability in funding which fluctuates greatly across each year. Funding prior to 1990 was substantially low, with a gradual increase in funding from 1990 to 2000. From 2000 onward, the funding amounts fluctuate significantly, with the year of 2012 resulting in negative funding of 100 million. Since 2012, funding has gradually continued to increase.

Table 12. California Budget Transportation Expenditure

Fiscal Year	State Expenditure Transportation
1989–1990	$12,460,000
1990–1991	$5,978,000
1991–1992	$36,270,000
1992–1993	$67,751,000
1993–1994	$93,850,000
1994–1995	$149,903,000
1995–1996	$173,078,000
1996–1997	$199,170,000
1997–1998	$222,035,000
1998–1999	$259,744,000
1999–2000	$288,993,000
2000–2001	$360,420,000
2001–2002	$255,717,000
2002–2003	$189,737,000
2003–2004	$193,084,000
2004–2005	$347,468,000
2005–2006	$340,382,000
2006–2007	$349,855,000
2007–2008	$1,039,000
2008–2009	$232,433,000
2009–2010	$365,332,000
2010–2011	$59,045,000
2011–2012	$131,470,000
2012–2013	-$114,165,000
2013–2014	-$6,107,000
2014–2015	$115,255,000
2015–2016	$178,929,000
2016–2017	$224,626,000
2017–2018	$241,488,000

California Minimum Wage

The California minimum wage dataset represents the State's minimum wage from 1916 to 2018. The values serve as a representative of the labor cost throughout California for each given year. The dataset does not represent prevailing minimum wage, instead only displaying the state-mandated minimum wage. The data were obtained from the State of California's Department of Industrial Relations.[19] The general trend in Table 13 shows an almost exponential growth in minimum wage values across each year.

Table 13. California Minimum Wage

Effective Date (mm/dd/yyyy)	New Minimum Wage	Old Minimum Wage	Amount of Wage Increase	Percent Increase
01/01/1980	$3.10	$2.90	$0.20	6.90
01/01/1981	$3.35	$3.10	$0.25	8.06
07/01/1988	$4.25	$3.35	$0.90	26.87
10/01/1996	$4.75	$4.25	$0.50	11.76
03/01/1997	$5.00	$4.75	$0.25	5.26
09/01/1997	$5.15	$5.00	$0.15	3.00
03/01/1998	$5.75	$5.15	$0.60	11.65
01/01/2001	$6.25	$5.75	$0.50	8.70
01/01/2002	$6.75	$6.25	$0.50	8.00
01/01/2007	$7.50	$6.75	$0.75	11.10
01/01/2008	$8.00	$7.50	$0.50	6.70
07/01/2014	$9.00	$8.00	$1.00	12.50
01/01/2016	$10.00	$9.00	$1.00	11.10
01/01/2017	$10.50	$10.00	$0.50	5.00
01/01/2018	$11.00	$10.50	$0.50	4.88

IV. MODEL DEVELOPMENT

Pavement cost data obtained from Caltrans resources and data on various socio-economic parameters as described in the previous chapter were incorporated into a local database for subsequent analysis. Several steps were undertaken in the analysis of data to develop a statistical model for predicting pavement material unit price, details of which are presented in the subsequent section.

VARIATION IN PAVEMENT MATERIAL UNIT PRICE BY GEOGRAPHICAL LOCATION

To explore any variation in the materials' unit prices by geographic location, the research team selected the two most important pavement materials: Joint Plain Concrete Pavement (JPCP) for rigid pavement and hot mix asphalt Type A (HMA-A) for flexible pavement. JPCP and HMA-A are the most commonly used pavement materials in California highway construction. JPCP was used in 200 projects from 2009–2019, and HMA-A was used in 2,415 projects from 2008–2018. Both materials were used in California highway construction before 2008, but it was not possible to match the material items before 2008, since these material items' codes were changed in the Caltrans construction cost database system in 2008.

The unit price of JPCP was analyzed for various districts in California using ANOVA. The results of that analysis are presented in Table 14. The null hypothesis was that the unit price of JPCP is similar in different districts and any differences are not statistically significant by geographic location. The ANOVA results show a P-value of 0.596, which indicates that the null hypothesis cannot be rejected; hence there is no statistically significant variation in the unit price of JPCP by geographic location (districts) in California. Similarly, the ANOVA result for HMA-A data shows a P-value of 0.124, thus confirming no statistically significant variation in unit price of HMA-A by geographic location (districts) in California.

Caltrans Highway Design Manual (HDM) contains information on pavement material selection and cross-section design by climate region. Caltrans' pavement climate region map defines nine climate regions in the California highway network according to the climate conditions and locations (North Coast, Central Coast, Inland Valley, Low Mountain, High Mountain, Desert, High Desert, South Coast, and South Mountain).[6] The unit price data for JPCP and HMA-A were analyzed by climate region to explore any differences in price. The null hypothesis was that JPCP and HMA-A cost are similar with no statistically significant differences by climate region. The ANOVA test result as presented in Table 14 shows a P-value of 0.176 for JPCP, which means the null hypothesis cannot be rejected; hence there is no statistically significant variation in the unit price of JPCP by climate region in California. Similarly, the ANOVA result listed in Table 14 for HMA-A data shows a P-value of 0.158, thus confirming no statistically significant variation in the unit price of HMA-A by climate region in California.

Given the abovementioned ANOVA test results, it can be concluded that there is no statistically significant variation in the unit price of JPCP and HMA-A by geographic location and climate region in California. Therefore, the variables were not separated by these factors for use in the development of the statistical models.

Table 14. ANOVA Test Results of District and Climate variables for JPCP and HMA in 2018

Variable	Type	Df	Sum Sq.	Mean Sq.	F-value	P-value
District	JPCP	7	425,567	60,795	0.801	0.596
District	HMA-A	11	2,817,603	256,146	1.517	0.124
Climate	JPCP	5	541,890	108,378	1.701	0.176
Climate	HMA-A	7	1,815,015	259,288	1.526	0.158

CORRELATION IN SOCIO-ECONOMIC VARIABLES

In order to select the most critical socio-economic parameters as described in the previous chapter, the research team conducted a correlation analysis amongst the socio-economic variables. According to the correlation analysis results as presented in Table 15, crude oil price showed a strong correlation with gasoline and diesel price, and so the crude oil price variable was selected to represent gasoline prices and diesel prices in this research.

The California population showed a strong correlation with three parameters: vehicle miles traveled, consumer price index (CPI), and minimum wage. Therefore, the California population variable was selected and the other variables were dropped from subsequent analysis.

Two parameters, state expenditure in transportation and total vehicle registration, showed less correlation with other variables and thus were considered separately as the independent variables in this research.

In summary, four variables—crude oil price, population, state expenditure in transportation, and annual vehicle registration—were selected as the independent variables to represent corresponding socio-economic parameters to develop the statistical models in this research.

Table 15. Correlation Analysis Results for the Socio-Economic Parameters

Variable	Gasoline	Diesel	Crude Oil	Population	Expenditure	Total Vehicle	VMT	CPI	Wage
Gasoline	1.00	0.99	0.93	0.88	-0.47	-0.66	0.69	0.89	0.75
Diesel	0.99	1.00	0.94	0.85	-0.46	-0.54	0.66	0.86	0.71
Crude Oil	0.93	0.94	1.00	0.76	-0.04	-0.25	0.53	0.78	0.58
Population	0.88	0.85	0.76	1.00	0.45	-0.54	0.90	0.99	0.94
Expenditure	-0.47	-0.46	-0.04	0.45	1.00	0.53	-0.17	0.37	-0.09
Total Vehicles	-0.66	-0.54	-0.24	-0.54	0.53	1.00	-0.08	-0.44	-0.12
VMT	0.69	0.66	0.53	0.90	-0.18	-0.09	1.00	0.87	0.87
CPI	0.89	0.86	0.78	0.99	0.38	-0.44	0.87	1.00	0.97
Wage	0.75	0.71	0.58	0.94	-0.09	-0.12	0.87	0.97	1.00

TIME-SERIES ANALYSIS OF SOCIO-ECONOMIC VARIABLES

In order to predict the future cost of each of the four selected socio-economic variables, time-series analysis was conducted for the next 50 years of the LCCA period from 2020 to 2069. The Autoregressive Integrated Moving Average (ARIMA) modeling approach was implemented using the R programming language to develop the predictive model of each of the four socio-economic variables. Several ARIMA models were developed with varying modelling parameters, and the best model was selected by minimizing the Akaike Information Criteria (AIC) values. The ARIMA model for each variable calculated the coefficients of three regressive parameters and the coefficients of the moving average of point values for one, two, and three years to filter out a unique type of finite impulse value for certain year. The coefficients of the autoregressive 1, 2, 3, the moving average 1, 2, 3, the log likelihood, and Akaike Information Criteria (AIC) values of the ARIMA model of each variable are shown in Table 14. The model with the lower AIC value has relatively better goodness of fit than the model with the light AIC value. The authors found the best model structure (the autoregressive and the moving average) having the lowest AIC value for each variable.

Using the ARIMA models, the future point values of each variable were predicted for a 50-year LCCA period starting from 2020. Figures 5 through 8 show the past values and the future predicted values of each socio-economic variable used in this research. Figures 5 through 8 also show a simple linear graph using past data extended into the future to show a predicted line for comparison purposes. For three variables, crude oil, vehicle registration, and state expenditure in transportation, the ARIMA models fit well and smoothen the sharp decreases of the values due to the U.S. economic recession in 2008 (population did not decrease during the recession). The simple linear graph does not reflect the trend possibly affected by the sudden variation due to the 2008 U.S. economic recession and showed a large gap between the past values and the future predicted values. In Figures 5 through 8, the differences of the predicted values between the simple linear regression models and the ARIMA models become larger as the prediction moves to a further future.

The predicted values of each variable from 2020 to 2069 were populated from the corresponding ARIMA model and are presented in Appendix B.

Table 16. The Results of the ARIMA Models

Variables	Coefficient AR1	Coefficient AR2	Coefficient AR3	Coefficient MA1	Coefficient MA2	Coefficient MA3	Log Likelihood	AIC
Crude Oil	-1.71	-0.97	-0.21	0.72	-0.88	-0.81	-132.06	278.12
Population	0.15	-0.03	-0.47	0.03	-0.05	0.92	-597.22	1208.43
Vehicle Registration	0	0	0	-0.56	-0.13	0	-158.43	322.87
State Expenditure in Transportation	-0.39	-0.26	-0.13	-1.80	0.80	0	-436.83	885.66

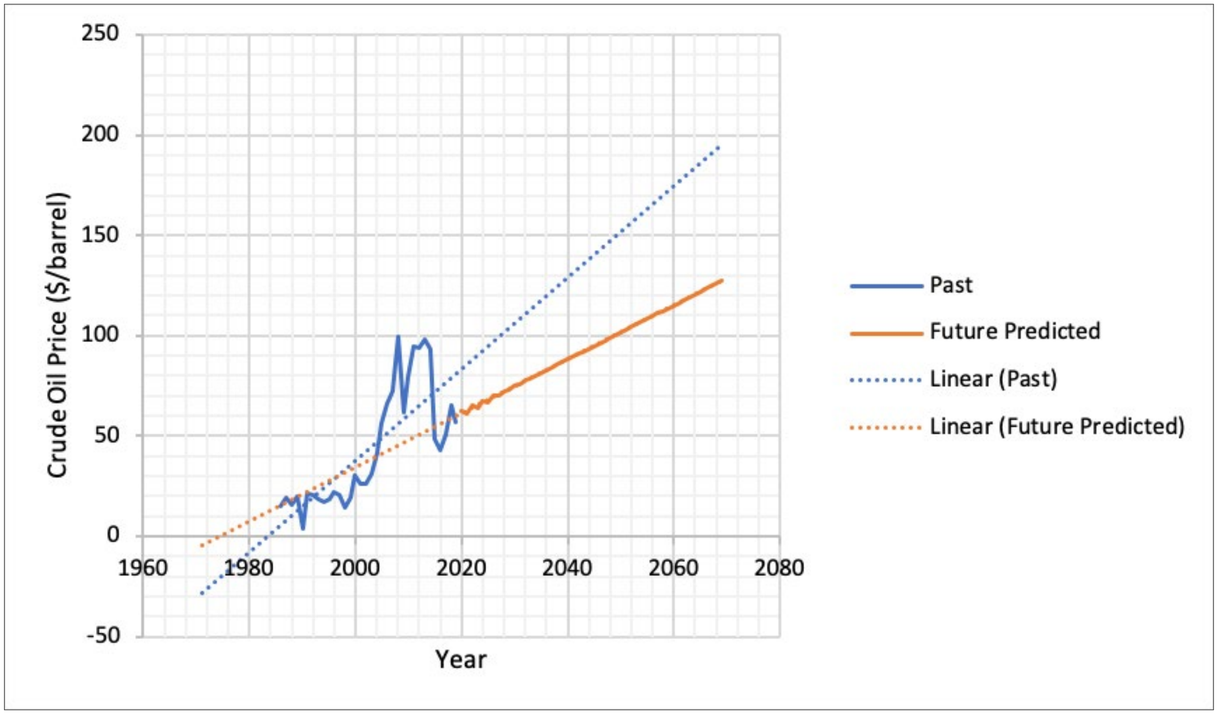

Figure 5. The Past and the Future Predicted Values of Crude Oil

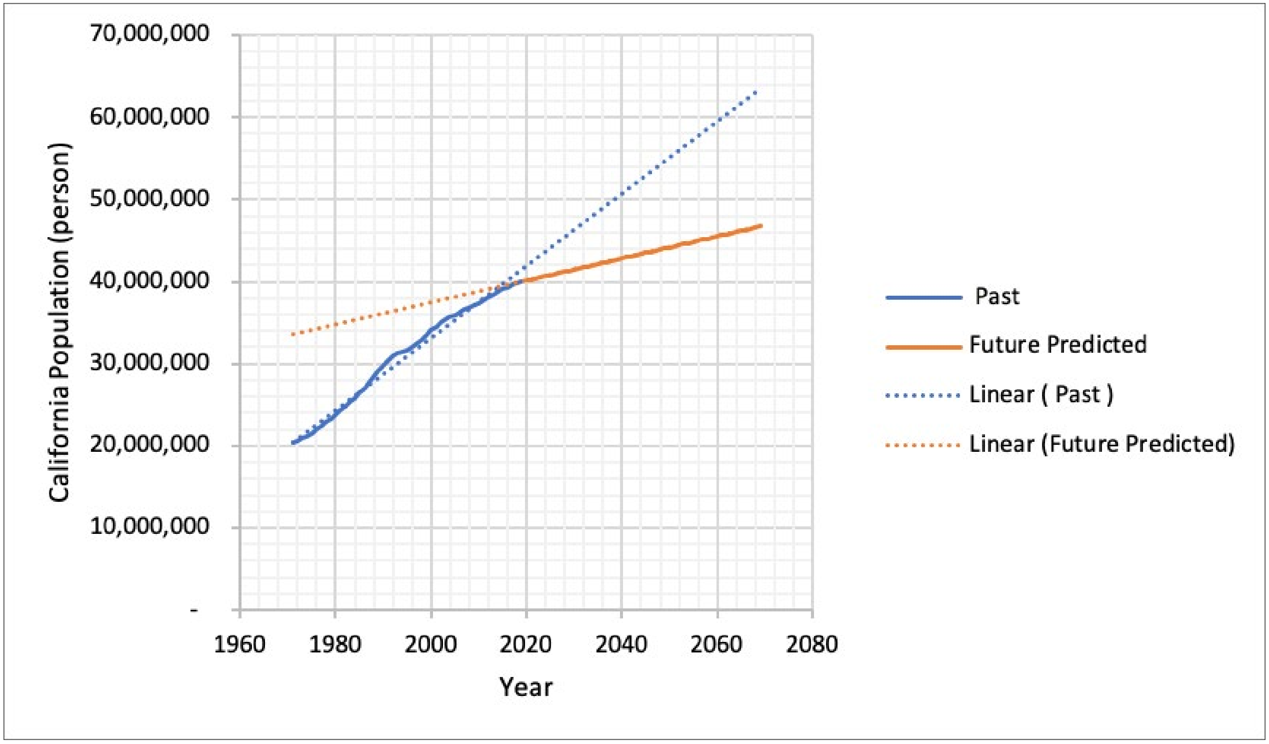

Figure 6. **The Past and the Future Predicted Values of California Population**

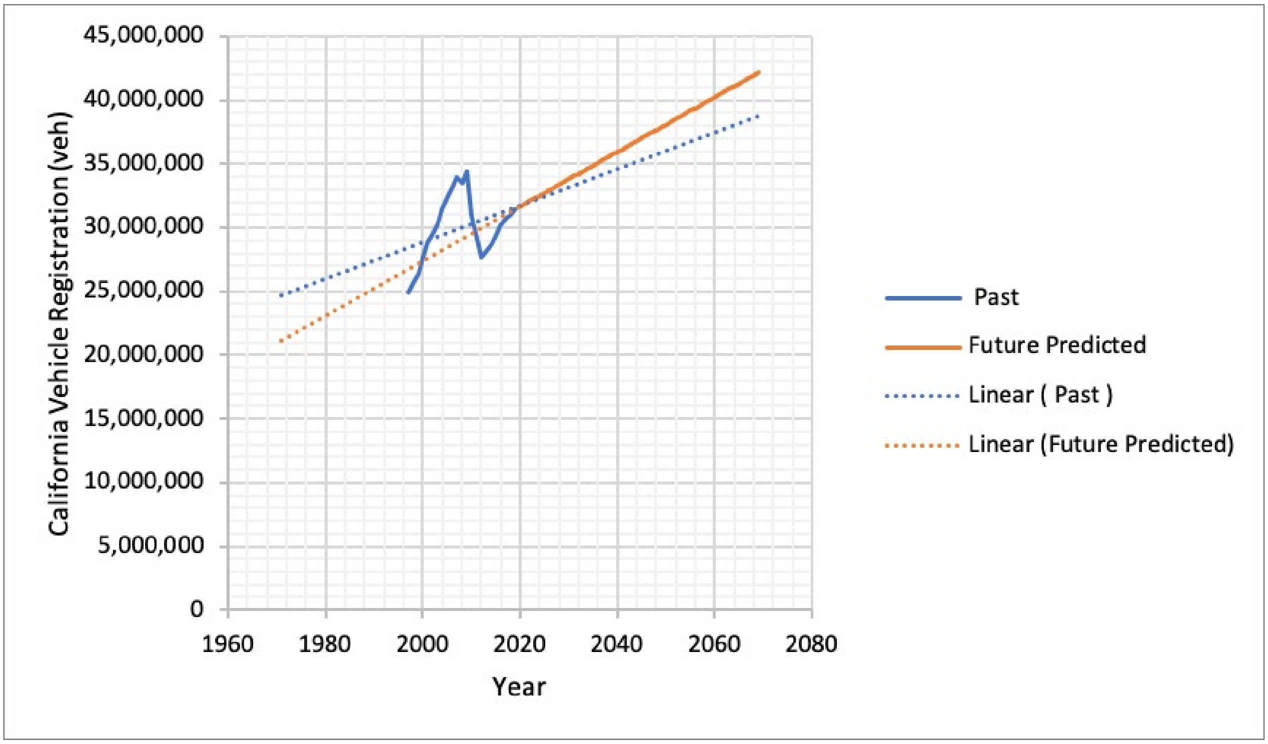

Figure 7. **The Past and the Future Predicted Values of California Vehicle Registration**

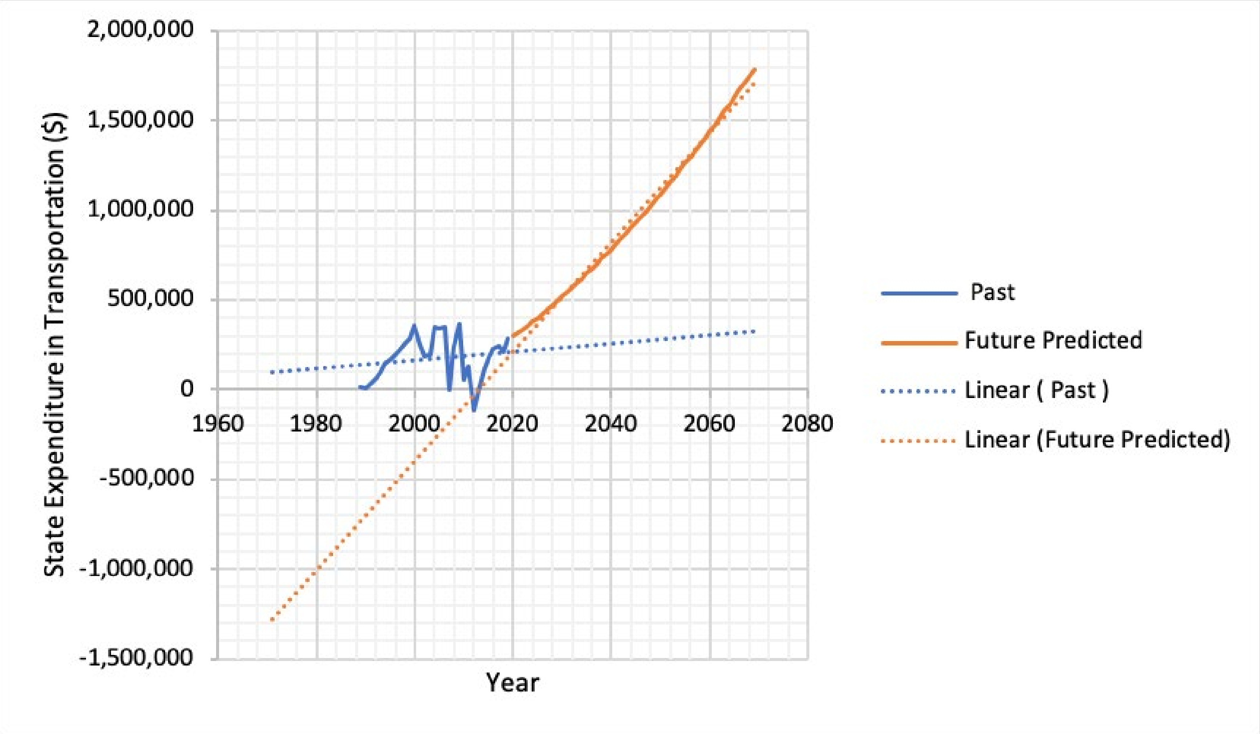

Figure 8. The Past and the Future Predicted Values of State Expenditure in Transportation

MULTIPLE REGRESSION MODELS FOR PREDICTING PAVEMENT MATERIAL UNIT PRICE

Project Size

In view of the information obtained from other states and the Caltrans database, pavement materials used in LCCA for future M&R activities were identified and their unit price data were grouped by the quantities of the material. The unit prices show a large variability depending on the size of the project and quantity of material used. Small projects which require low quantity of a material generally show higher unit prices than larger projects. The research team classified the projects into four categories by project size based upon the amount of material quantities used (small, medium, large, and extra-large). The maximum quantities of material in small, medium, and large projects were determined by the 25th, 50th, and 75th percentiles, respectively. The projects with material quantity greater than the 75th percentile value were classified as extra-large size projects. Table 17 shows the material type, unit, and the maximum quantity signifying the boundaries between small, medium, large, and extra-large projects (note that values exceeding the numbers in the large column correspond to extra-large projects).

Table 17. Maximum Quantities by Project Size for the Primary Pavement Materials Used in LCCA

Material Type	Unit	Small	Medium	Large
Roadway Excavation	CY	300	1,500	9,000
Class 2 Aggregate Subbase	CY	300	1,500	8,500
Class 2 Aggregate Base	CY	200	1,000	3,000
Class 3 Aggregate Base	CY	100	500	2,000
Hot Mix Asphalt (Type A)	Ton	300	1,500	4,500
Hot Mix Asphalt (Open Graded Friction Course)	Ton	100	500	2,000
Rubberized Hot Mix Asphalt (Gap Graded)	Ton	2,500	7,500	16,000
Rubberized Hot Mix Asphalt (Open Graded Friction Course)	Ton	2,000	6,000	16,000
Jointed Plain Concrete Pavement	CY	200	1,500	12,000
Jointed Plain Concrete Pavement (Rapid Setting)	CY	200	500	1,500
Lean Concrete Base	CY	200	1,000	7,000
Lean Concrete Base (Rapid Setting)	CY	100	300	1,000

To further investigate the impact of project size on materials' unit price, the average unit prices of the primary pavement materials used in the M&R activities in 2018 were calculated by project size, as shown in Table 18. For example, the average unit price ($637) of JPCP for the small project with an upper limit of 200 cubic yards was 4.4 times higher than the average unit price ($146) for the extra-large projects in 2018 for the same material. Figure 9 shows the average unit prices of Joint Plain Concrete Pavement by project size from 2008 to 2018. The average unit price for pavement materials varied widely (from $300 to $750) for small projects over the years, but the unit price remained relatively stable for all other project sizes with a slight increase over the years.

Table 18. Average Unit Prices of the Primary Pavement Materials by Project Size in 2018

Material	Unit	Small (no. of projects)	Medium (no. of projects)	Large (no. of projects)	Extra-Large (no. of projects)
Roadway Excavation	CY	$267 (1,048)	$106 (979)	$60 (1,076)	$30 (1,048)
Class 2 Aggregate Subbase	CY	$163 (55)	$110 (51)	$51 (52)	$32 (52)
Class 2 Aggregate Base	CY	$358 (224)	$127 (226)	$95 (153)	$55 (204)
Class 3 Aggregate Base	CY	$248 (44)	$185 (46)	$88 (32)	$66 (37)
Hot Mix Asphalt (Type A)	Ton	$591 (662)	$232 (653)	$147 (513)	$104 (586)
Hot Mix Asphalt (Open Graded Friction Course)	Ton	$255 (10)	$179 (19)	$162 (14)	$109 (14)
Rubberized Hot Mix Asphalt (Gap Graded)	Ton	$210 (170)	$132 (183)	$118 (160)	$108 (167)
Rubberized Hot Mix Asphalt (Open Graded Friction Course)	Ton	$160 (18)	$147 (15)	$115 (15)	$120 (17)
Jointed Plain Concrete Pavement	CY	$637 (47)	$433 (51)	$283 (53)	$146 (51)
Jointed Plain Concrete Pavement (Rapid Setting)	CY	$1,091 (28)	$792 (16)	$658 (25)	$385 (20)
Lean Concrete Base	CY	$379 (134)	$292 (124)	$199 (118)	$145 (125)
Lean Concrete Base (Rapid Setting)	CY	$821 (28)	$520 (27)	$375 (28)	$341 (22)

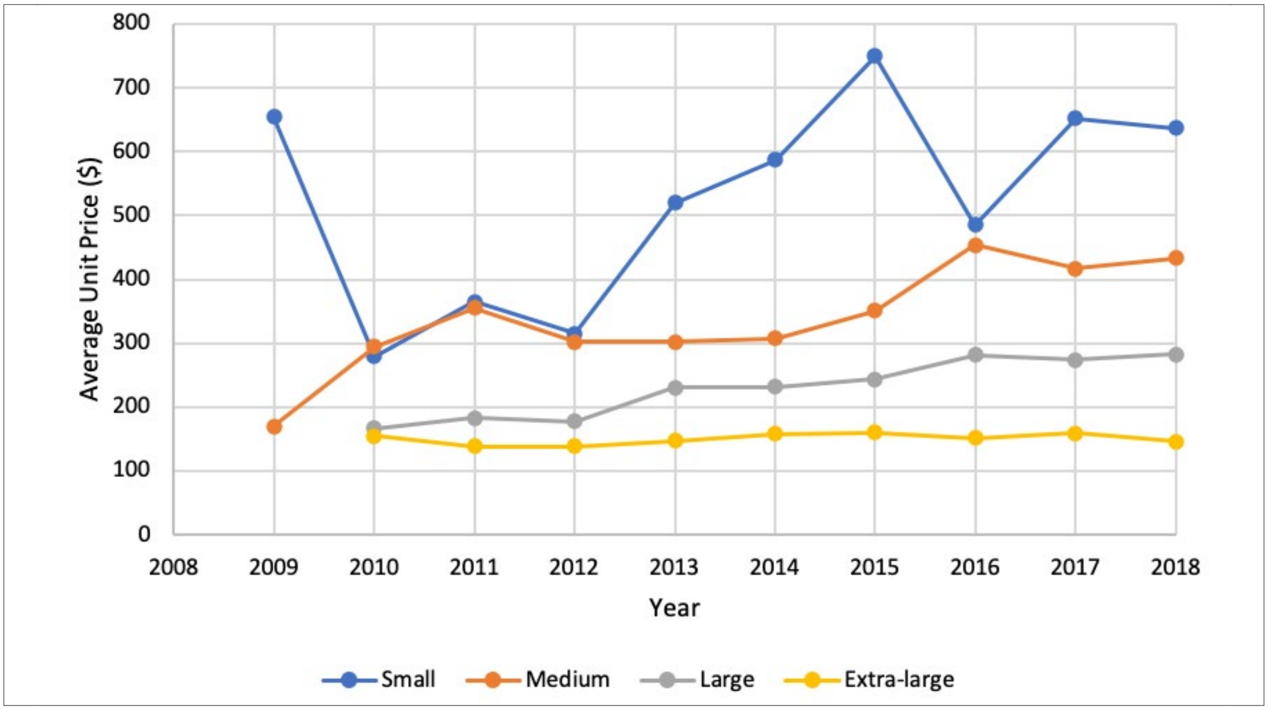

Figure 9. Average Unit Prices of Joint Plain Concrete Pavement by Project Size (2008–2018)

Multiple Regression Models

The previous sections presented the trends in pavement material unit price by geographic location and climate region, time-series trends for socio-economic variables, and variation in unit price of pavement materials by project size. In view of the observed trends and critical variables, the research team employed multiple regression models to predict the unit price of pavement materials for use in LCCA for future M&R projects in California. The four socio-economic parameters were included as continuous independent variables, and the project size (small, medium, large, and extra-large) was included as a discrete independent variable in the multiple regression models. The project size variable was considered as a binomial variable, that is, with any one project size being true and assigned a value of one, all other project sizes were assigned a value of zero. The unit price of a pavement material was set as the dependent variable.

Table 19 shows the R-squared values and the coefficients of the variables in the multiple regression models. The R-squared values are in the range between 0.40005 (Lean Concrete Base) and 0.8735 (Road Excavation). The models for some materials resulted in low R-squared values due to lack of unit price information or the small number of the projects in each project size category.

In the model development process, several models showed a decreasing or unrealistically increasing trend in the future years because of large variaions of insufficient data points from the past years. For example, the model for Class 2 Aggregate Subbase predicts a decreasing pattern for the future unit prices due to the decreasing trend in the past ten years. Due to the unique pattern of the average unit price of this variable, the multiple regression model predicts a decreasing pattern in the future. Therefore, for the Class 2 Aggregate Subbase, the research team recommends using the average unit price in the latest year to calculate the future M&R project cost instead of using the multiple regression model result. Similarly, the models for three materials—HMA Open Graded, RHMA Open Graded, and JPCP (RSC)—are not recommended for use in predicting the unit price for the future M&R activities because these models predict unrealistically high values in the future, compared to the other materials' unit costs, possible due to insufficient data points. The average unit price data for these materials were only available for the past 4–5 years, possibly contributing to the unrealistic results of the regression models. For an example, the predicted unit prices of the HMA Open Graded at the year 2069 were 15 to 20 times higher than the unit prices at the year 2019 because the HMA Open Grded had only two to four data points per project size group. For these three materials, the research team suggests using the average unit prices in the latest year for calculating the future M&R activity costs instead of using its multiple regression model until additional years of unit price data are available. The authors expect the unit price data will become large enough to update the models for these three materials in next five years as they are used more often recently. Although these three pavement materials were not shown in a small number of projects in the past 4–5 years, the authors still grouped them into the four categories by project size because the unit prices for the small size projects were higher than the unit prices for the large and extra-large projects.

Except for the four materials identified (Class 2 Aggregate Subbase, HMA Open Graded, RHMA Open Graded, JPCP (RSC)), the multiple regression models predict realistic unit prices of pavement materials for LCCA for future M&R activities when the trend of the future predicted unit price values were compared to the trend of the past unit price values. The predicted unit prices at the 50th year within a range between 150 and 400 percent of the unit prices at the 1st year (base year) were resulted in the pavement items with a large number of projects. For example, the multiple regression models for HMA-A and JPCP predict a realistic unit price by project size for the future 50 years from the independent variable values predicted by the ARIMA model (Figure 10 and 11). The use of such results highlights the usefulness of the approach in this research to obtain more realistic values of pavement material unit prices for accurate LCCA.

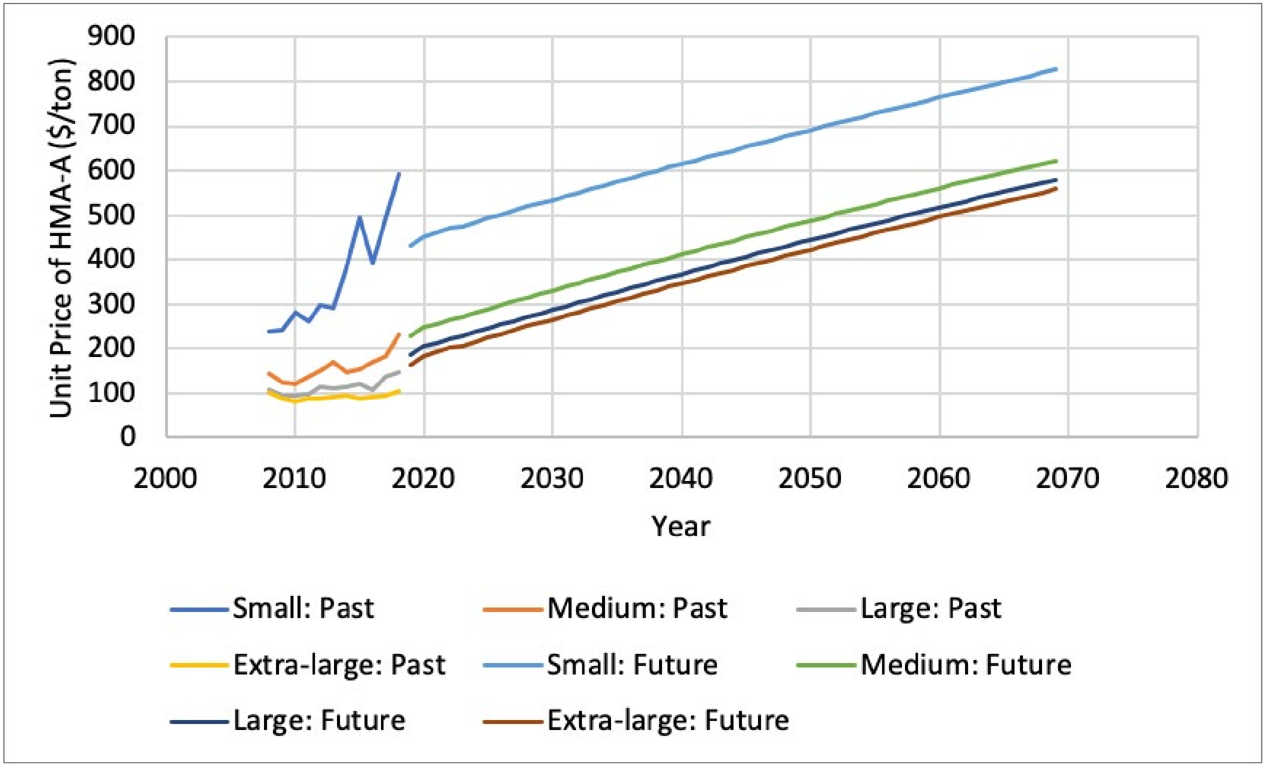

Figure 10. The Unit Price of HMA-A for the Past (Collected) and the Future (Predicted by Project Size)

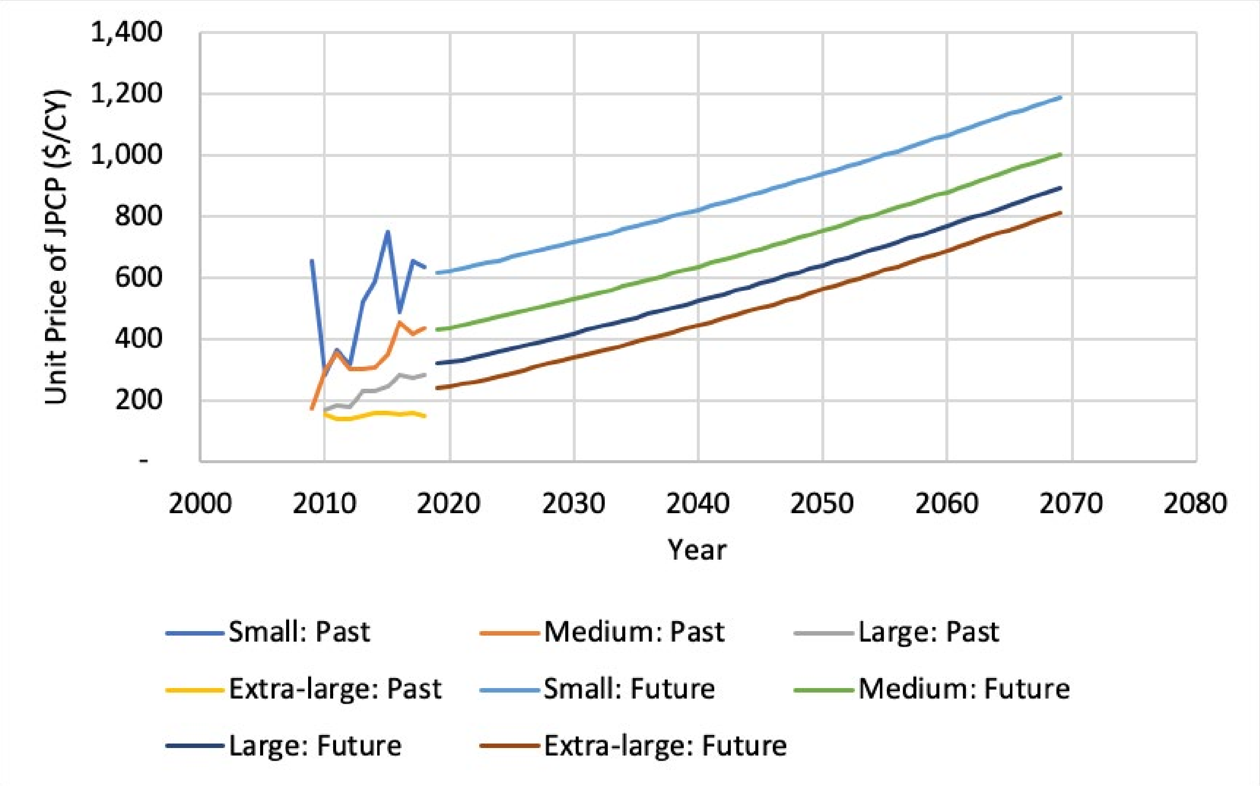

Figure 11. The Unit Price of JPCP for the Past (Collected) and the Future (Predicted by Project Size)

Table 19. The R-Squared Values and the Coefficients of the Variables in the Multiple Regression Models

Material	R-squared Value	Intercept	Crude Oil	Population	Vehicle Registration	Transportation Expenditure	Medium Project	Large Project	Extra-Large Project
Roadway Excavation	0.8735	-1.407e+3	4.682e-02	2.860e-05	1.721e-05	-1.753e-04	-1.209e+02	-1.506e+02	-1.718e+02
Class 2 Aggregate Subbase	0.5089	9.401e+00	1.555e-01	3.873e-06	1.087e-06	-7.012e-05	-1.169e+02	-1.404e+02	-1.562e+02
Class 2 Aggregate Base	0.8163	-1.657e+03	-3.703e-02	2.392e-05	3.297e-05	-2.541e-04	-1.121e+02	-1.410e+02	-1.707e+02
Class 3 Aggregate Base	0.7094	-3.464e+03	6.149e-01	1.052e-04	-1.666e-05	-1.618e-04	-4.682e+01	-1.066e+02	-1.282e+02
Hot Mix Asphalt (Type A)	0.8283	-2.073e+03	4.123e-01	5.257e-05	1.315e-05	-9.127e-05	-2.033e+02	-2.471e+02	-2.685e+02
Hot Mix Asphalt, Open Graded	0.7868	-2.243e+05	-7.413e+01	8.125e-03	-3.031e-03	NA	-2.360e+02	-2.802e+02	-3.170e+02
Rubberized Hot Mix Asphalt, Gap Graded	0.6767	-9.921e+02	6.691e-01	2.256e-05	8.544e-06	-7.062e-05	-6.238e+01	-7.182e+01	-7.619e+01
Rubberized Hot Mix Asphalt, Open Graded	0.5788	-2.033e+05	-6.540e+01	7.380e-03	-2.778e-03	NA	-4.310e+01	-5.080e+01	-6.036e+01
Jointed Plain Concrete Pavement	0.769	-8.828e+02	-1.094e-01	4.208e-05	-8.043e-06	2.580e-04	-1.858e+02	-2.984e+02	-3.781e+02
Jointed Plain Concrete Pavement (Rapid Setting Concrete)	0.802	-1.659e+04	5.697e+00	6.807e-04	-3.448e-04	4.023e-03	-3.214e+02	-4.063e+02	-5.453e+02
Lean Concrete Base	0.4005	1.094e+02	2.682e-01	-3.969e-06	1.437e-05	-1.310e-04	-1.520e+02	-1.993e+02	-2.541e+02
Lean Concrete Base Rapid Setting	0.6675	-1.027e+04	-4.374e+00	3.721e-04	-1.116e-04	-7.896e-04	-6.503e+01	-2.035e+02	-2.715e+02

V. LCCA CASE STUDY

To evaluate the results of the data analysis and statistical models developed in this research, a life cycle cost analysis case study was completed using the predicted unit price values of pavement materials. The LCCA results computed with predicted unit price values were compared with LCCA results that used uniform unit prices. In this case study, agency costs of the future M&R were included in the life cycle cost for eachthe alternative: HMA-A with 20-year design life and JPCP with 40-year design life, but road user costs were excluded in the comparison because road user costs are not associated with unit prices.

DESCRIPTION OF THE CASE STUDY

A pavement rehabilitation project on Interstate 80 in the Sacramento region was selected as a case study in this research with some modifications to represent the typical pavement rehabilitation project. Some relevant information about the case study is described as follows:

- The project length was 9.6 lane-miles on an eight-lane section;
- Two alternatives were compared in LCCA:
    1. Mill and overlay with hot mix asphalt (HMA) with 20-year design life, and
    2. Lane replacement Jointed Plain Concrete Pavement (JPCP) with 40-year design life;
- The rehabilitation start year was assumed to be 2020 and the LCCA period was 55 years ending in 2075;
- A four-percent annual discount rate (reflecting interest and inflation rates) was assumed in net present value calculation for the entire LCCA period (55 years).

Caltrans' LCCA procedure manual contains the future M&R schedule for pavement material types, project types, climate region, and maintenance service levels.[3, 7] In this case study, the future M&R schedules for both alternatives were determined using the automatic M&R sequence selection function in *RealCost CA2.5.4*. Tables 20 and 21 show the sequence of future M&R activities, years of action, annualized maintenance cost, and activity service years for Alternative 1 (HMA) and Alternative 2 (JPCP), respectively, determined by the M&R sequence selection in *RealCost CA2.5.4.*

Table 20. Future M&R Schedule of HMA Rehabilitation

Activity Number	Activity Name	Year of Action	Annualized Maintenance Cost ($/lane-mile)	Activity Service Life (year)
1	Rehab HMA	0	2,700	18
2	CAPM HMA	18	1,100	5
3	Rehab HMA	23	2,700	18
4	CAPM HMA	41	1,100	5
5	Rehab HMA	46	2,700	18

Table 21. Future M&R Schedule of JPCP Rehabilitation

Activity Number	Activity Name	Year of Action	Annualized Maintenance Cost ($/lane-mile)	Activity Service Life (year)
1	Rehab JPCP	0	800	45
2	CAPM CPR C	45	3,000	5
3	CAPM CPR B	50	1,500	10

UNIT PRICE OF PAVEMENT MATERIALS

Based on the M&R schedules determined in the previous section, the activity years of the future rehabilitation (REHAB) and capital maintenance (CAPM) projects for each alternative were decided. Caltrans calls major maintenance projects for restoring or repairing pavement as CAPM projects. Two separate LCCA were executed by using (1) the uniform unit prices without consideration of the project size and activity years; (2) the predicted unit prices by project size in the corresponding activity years.

For Alternative 1, $183/ton was used as both the uniform and the predicted unit price for HMA rehabilitation (extra-large project) in 2020. The predicted unit price of HMA increased over time; $404/ton was used for calculating the maintenance (medium size project) cost in 2028. When a four-percent annual discount rate was applied, the Net Present Value (NPV) of the uniform unit price of HMA for maintenance was $90/ton, but the NPV of the predicted unit price of HMA for maintenance (medium project) was $199/ton (Table 22).

For Alternative 2, $243/CY was used as the uniform unit price for all future JPCP M&R activities regardless of project size. The predicted unit price used was $243/CY for JPCP rehabilitation in 2020 and $836/CY for JPCP maintenance (CPR C) in 2065. The NPVs of the uniform and the predicted unit prices for JPCP maintenance in 2065 were $42/CY and $143/CY, respectively (Table 23). The NPV of the predicted unit price ($143/CY) was 240 percent higher than the NPV of the uniform unit price ($42/CY) for JPCP maintenance in 2065.

Table 22. The Uniform and the Predicted Unit Price and Net Present Values on the Activity Years for Alternative 1: HMA Rehab

Year	Uniform Unit Price of HMA ($/ton)	Predicted Unit Price of HMA ($/ton)	Uniform Unit Price of HMA, NPV ($/ton)	Predicted Unit Price of HMA, NPV ($/ton)
2020	183	183	183	183
2038	183	404	90	199
2043	183	370	74	150
2061	183	568	37	114
2066	183	537	30	88

Table 23. The Uniform and the Predicted Unit Price and Net Present Values on the Activity Years for Alternative 2: JPCP Rehab

Year	Uniform Unit Price of JPCP ($/CY)	Predicted Unit Price of JPCP ($/CY)	Uniform Unit Price of JPCP, NPV ($/ton)	Predicted Unit Price of JPCP, NPV ($/ton)
2020	243	243	243	243
2065	460	836	42	143

LIFE CYCLE AGENCY COSTS

The life cycle agency costs of Alternative 1 and 2 were calculated with two sets of the unit prices (uniform and predicted) for a 50-year life cycle analysis period in *RealCost CA2.5.4*. The life cycle agency cost of Alternative 1 (HMA rehab) was $24.6 million NPV with uniform unit prices and $31.2 million NPV with predicted unit prices. Applying the predicted unit price increased the life cycle agency cost by 27 percent in NPV (Table 24).

The life cycle agency cost of Alternative 2 (JPCP rehab) was $11.83 million NPV with uniform unit prices and $11.85 million NPV with predicted unit prices (Table 24). The difference between the two costs was less than one percent in this case because the M&R schedule of Alternative 2 did not include any rehabilitation activity in the future; instead, it included one small maintenance activity (CPR C in 2065).

In the LCCA results, the more cost-effective alternative was Alternative 2 (JPCP rehabilitation) when comparing the life cycle agency cost results obtained using the uniform and the predicted unit prices. The case study demonstrates the significant difference in the life cycle cost calculated by using the predicted unit prices of pavement materials by project size over time, which presents a more realistic expectation from an agency's perspective.

Table 24. Life Cycle Agency Costs for Alternative 1: HMA Rehab

Year	Agency Cost with Uniform Unit Price of HMA ($1,000)	Agency Cost with Predicted Unit Price of HMA ($1,000)	Agency Cost with Uniform Unit Price of HMA, NPV ($1,000)	Agency Cost with Predicted Unit Price of HMA, NPV ($1,000)
2020	11,341	11,341	11,341	11,341
2038	741	1,551	366	766
2043	11,341	21,481	7,147	13,445
2061	741	2,106	148	422
2066	11,341	22,470	2,900	7,724
Total Agency Cost in Life Cycle	35,505	58,949	24,598	31,218

Table 25. Life Cycle Agency Costs for Alternative 2: JPCP Rehab

Year	Agency Cost with Uniform Unit Price of JPCP ($)	Agency Cost with Predicted Unit Price of JPCP ($)	Agency Cost with Uniform Unit Price of JPCP, NPV ($)	Agency Cost with Predicted Unit Price of JPCP, NPV ($)
2020	11,794	11,794	11,794	11,794
2065	241	338	41	58
Total Agency Cost in Life Cycle	12,035	12,131	11,835	11,852

VI. SUMMARY AND CONCLUSION

The main objective of this research was to develop statistical models and guidelines for using a predictive unit pricing method for pavement materials instead of deferring to uniform unit prices in LCCA for future M&R activities. The research investigated trends in the primary pavement materials' unit price and various California socio-economic parameters over time. The primary pavement materials' unit prices in the past 20 years (1999–2018) were collected from the Caltrans Construction Contract Cost database, and trends were explored by geographical region (California districts), climate regions, and project size to identify any differences related to such factors. The results showed no significant price differences by geographical or climate region, but differences were observed according to project size. The authors categorized the unit prices of each pavement materials into four project sizes (small, medium, large, and extra-large projects), and calculated average units prices in each category. The project size was used as a binomial independent variable, and the unit prices were used as the dependent variable in multiple regression models.

The research also investigated socio-economic parameters related to highway construction to identify factors that affect and can help predict future prices of pavement materials. Various California socio-economic data were collected and after correlation analysis, four representative socio-economic parameters (national crude oil price, California population, number of vehicles registered in California, and State budget expenditure in transportation) were selected. Data on these socio-economic variables were collected for the past 20 years (1997–2018), and their future values were predicted for a 50-year LCCA period using ARIMA time-series models. The ARIMA model captured and smoothed the unique decline phenomenon of all four socio-economic parameters, except for population, during the U.S. economic recession (approximately 2008–2012), and it predicted the future values. The values of socio-economic variables (both current and predicted) were used as independent variables in multiple regression models to estimate pavement material items' unit price for the future M&R activities in the life cycle analysis period.

Using the pavement materials' unit prices from the Caltrans database and socio-economic data collected, multiple regression models were developed to estimate the annual unit prices of each pavement material for the next 50 years (2020–2069). The R-squared values for different variables were in the range of 0.5 to 0.9 indicating that the models were able to explain at least half or more of the variation in the response variables representing a good set of results. Although some of the predictions were realistic and reasonable, others were not considered realistic or satisfactory, possibly due to smaller numbers of years in past data or small numbers of projects in size categories. For example, HMA-O's unit price was recorded for only four years from 2015 to 2018. Due to the lack of the unit price information, the average unit price was not available in some project categories during the data collection period. The authors recommend using the latest unit prices of the materials having a lack of information instead of using the predicted unit prices in the model that might be biased. Conversely, the statistical models predicted the future annual unit prices by project size for the pavement material items used in a large number of projects in the past years, such as Roadway Excavation, Class 2 Aggregate Base, HMA-A, RHMA, JPCP, and LCB. These models were verified using the unit prices in the recent projects.

The predicted future values of pavement materials’ unit prices were used in a case study to compare the differences in the results from using uniform unit prices in the current LCCA procedure. The NPVs of the life cycle agency costs calculated by the model-predicted unit prices were higher than those calculated by the uniform unit prices for two alternatives; HMA-A with 20-year design life and JPCP with 40-year design life. The results represent a more realistic and dynamic life cycle cost calculation instead of assuming fixed unit price material cost values, and signify the importance of the statistical models and methods employed in this research.

In LCCA, long-term prediction includes uncertainties due to unexpected economic trends and industry demand-supply conditions. Economic recessions and a global pandemic are examples of unexpected events which can have a significant influence on variations in material unit prices and project costs in the future. Nevertheless, the data-driven scientific approach as described in this research reduces risk caused by such uncertainties and enables practically reasonable predictions for the future. The key contribution of this research was the development of statistical models to predict the future unit prices as an alternative to the standard practice of using unifirom unit prices for the future M&R activities. The models developed in this research can be implemented into enhancing the current LCCA procedure to predict more realistic unit prices and project costs for the future M&R activities and thus selecting the most cost-effective alternative in LCCA.

APPENDIX A: SOCIO-ECONOMIC PARAMETERS (PAST)

Year	Crude Oil Price ($/barrel)	California Population (person)	California Vehicle Registration (veh.)	State Expenditure in Transportation ($)
1986	15.04	27,052,000	NA	NA
1987	19.17	27,717,000	NA	NA
1988	15.98	28,393,000	NA	NA
1989	19.64	29,142,000	NA	12,460
1990	24.53	29,828,496	NA	5,978
1991	21.50	30,458,613	NA	36,270
1992	20.56	30,987,384	NA	67,751
1993	18.45	31,314,189	NA	93,850
1994	17.19	31,523,690	NA	149,903
1995	18.44	31,711,849	NA	173,078
1996	22.11	31,962,949	NA	199,170
1997	20.61	32,452,789	24,944,976	222,035
1998	14.45	32,862,965	25,600,250	259,744
1999	19.26	33,418,578	26,362,468	288,993
2000	30.30	34,095,209	27,697,923	360,420
2001	25.95	34,512,742	28,780,056	255,717
2002	26.12	34,938,290	29,618,605	189,737
2003	31.12	35,388,928	30,248,069	193,084
2004	41.44	35,752,765	31,399,596	347,468
2005	56.49	35,985,582	32,487,477	340,382
2006	66.02	36,246,822	33,182,058	349,855
2007	72.32	36,552,529	33,935,386	1,039
2008	99.57	36,856,222	33,483,061	232,433
2009	61.65	37,077,204	34,433,206	365,332
2010	79.40	37,318,481	31,014,128	59,045
2011	94.87	37,678,534	29,176,697	131,470
2012	94.11	38,045,271	27,702,150	-114,165
2013	97.91	38,425,695	28,074,977	-6,107
2014	93.26	38,756,940	28,686,646	115,255
2015	48.69	39,076,128	29,424,012	178,929
2016	43.14	39,328,337	30,221,033	224,626
2017	50.88	39,610,556	30,795,141	241,488
2018	64.94	39,825,181	31,022,328	213,914

APPENDIX B: SOCIO-ECONOMIC PARAMETERS (FUTURE PREDICTED)

Year	Crude Oil Price ($/barrel)	California Population (person)	California Vehicle Registration (veh.)	State Expenditure in Transportation ($)
2020	62.72	40,130,775	31,659,670	298,913
2021	61.24	40,268,622	31,874,178	315,509
2022	65.06	40,402,833	32,088,686	333,332
2023	64.04	40,519,690	32,303,195	358,368
2024	67.60	40,649,873	32,517,703	380,323
2025	66.98	40,784,319	32,732,211	402,190
2026	70.03	40,927,204	32,946,719	424,649
2027	69.95	41,065,007	33,161,227	448,036
2028	72.49	41,199,780	33,375,736	471,642
2029	72.85	41,330,263	33,590,244	495,569
2030	75.02	41,462,557	33,804,752	519,915
2031	75.68	41,596,678	34,019,260	544,710
2032	77.60	41,733,046	34,233,769	569,902
2033	78.48	41,868,859	34,448,277	595,492
2034	80.22	42,003,663	34,662,785	621,489
2035	81.24	42,137,270	34,877,293	647,896
2036	82.86	42,270,982	35,091,801	674,709
2037	83.98	42,405,219	35,306,310	701,927
2038	85.52	42,540,096	35,520,818	729,552
2039	86.71	42,675,008	35,735,326	757,584
2040	88.19	42,809,661	35,949,834	786,022
2041	89.43	42,943,971	36,164,343	814,867
2042	90.87	43,078,220	36,378,851	844,118
2043	92.15	43,212,590	36,593,359	873,776
2044	93.56	43,347,142	36,807,867	903,840
2045	94.85	43,481,748	37,022,375	934,311
2046	96.25	43,616,300	37,236,884	965,188
2047	97.56	43,750,756	37,451,392	996,472
2048	98.94	43,885,174	37,665,900	1,028,162
2049	100.26	44,019,614	37,880,408	1,060,259
2050	101.63	44,154,104	38,094,917	1,092,762
2051	102.96	44,288,618	38,309,425	1,125,672
2052	104.33	44,423,125	38,523,933	1,158,988
2053	105.66	44,557,606	38,738,441	1,192,711
2054	107.02	44,692,072	38,952,949	1,226,841
2055	108.36	44,826,540	39,167,458	1,261,376
2056	109.72	44,961,021	39,381,966	1,296,319
2057	111.06	45,095,511	39,596,474	1,331,667
2058	112.42	45,230,000	39,810,982	1,367,423
2059	113.76	45,364,484	40,025,490	1,403,585
2060	115.11	45,498,963	40,239,999	1,440,153

Year	Crude Oil Price ($/barrel)	California Population (person)	California Vehicle Registration (veh.)	State Expenditure in Transportation ($)
2061	116.46	45,633,440	40,454,507	1,477,128
2062	117.81	45,767,921	40,669,015	1,514,509
2063	119.16	45,902,405	40,883,523	1,552,297
2064	120.51	46,036,889	41,098,032	1,590,491
2065	121.86	46,171,372	41,312,540	1,629,092
2066	123.21	46,305,853	41,527,048	1,668,099
2067	124.56	46,440,334	41,741,556	1,707,513
2068	125.91	46,574,816	41,956,064	1,747,334
2069	127.25	46,709,298	42,170,573	1,787,560

APPENDIX C: AVERAGE UNIT PRICES OF THE PRIMARY PAVEMENT MATERIALS USED IN FOR FUTURE M&R ACTIVITIES IN LCCA

ROADWAY EXCAVATION (UNIT: $/CY)

Year	Small Project	Medium Project	LargeProject	Extra-Large Project
1999	174	76	35	17
2000	154	55	32	18
2001	181	63	33	19
2002	189	58	36	17
2003	207	58	39	21
2004	157	100	50	27
2005	262	98	62	31
2006	348	122	75	36
2007	325	98	67	35
2008	221	63	38	26
2009	131	47	29	20
2010	124	48	24	16
2011	141	52	28	15
2012	143	60	37	15
2013	152	52	34	17
2014	173	54	46	21
2015	172	94	48	19
2016	265	82	48	21
2017	207	115	55	24
2018	267	106	60	30

CLASS 1 AGGREGATE SUBBASE (UNIT: $/CY)

Year	Small Project	Medium Project	LargeProject	Extra-Large Project
1999	NA	NA	11	NA
2000	NA	33	NA	NA
2001	NA	NA	NA	NA
2002	217	NA	NA	NA
2003	76	NA	NA	NA
2004	NA	NA	NA	NA
2005	NA	NA	NA	NA
2006	NA	NA	NA	NA
2007	190	NA	NA	NA
2008	NA	NA	NA	NA
2009	63	NA	20	16
2010	156	NA	20	19
2011	84	NA	1	NA
2012	37	30	NA	11
2013	NA	90	NA	NA
2014	NA	NA	NA	NA
2015	NA	30	19	NA
2016	NA	29	26	24
2017	NA	NA	NA	NA
2018	NA	45	20	27

CLASS 2 AGGREGATE SUBBASE (UNIT: $/CY)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
1999	NA	52	29	23
2000	66	65	56	23
2001	109	62	34	27
2002	73	71	47	28
2003	108	89	23	20
2004	104	NA	NA	NA
2005	182	92	72	NA
2006	275	88	66	62
2007	196	81	75	42
2008	142	46	33	47
2009	155	41	NA	14
2010	144	32	22	15
2011	76	47	28	18
2012	520	70	27	10
2013	322	45	31	25
2014	245	NA	53	18
2015	116	64	NA	40
2016	162	91	28	19
2017	313	25	52	38
2018	163	110	51	32

CLASS 2 AGGREGATE BASE (UNIT: $/CY)

Year	Small Project	Medium Project	LargeProject	Extra-Large Project
2012	198	83	47	30
2013	123	73	56	35
2014	138	89	57	42
2015	179	101	67	39
2016	244	95	78	42
2017	246	134	102	49
2018	358	127	95	55

CLASS 3 AGGREGATE SUBBASE (UNIT: $/CY)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2012	227	56	50	38
2013	111	114	52	29
2014	195	156	64	46
2015	150	119	81	41
2016	92	112	44	50
2017	186	138	83	40
2018	248	185	88	66

HOT MIX ASPHALT, TYPE A (HMA-A) (UNIT: $/TON)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2008	237	142	108	101
2009	241	124	95	88
2010	282	121	96	80
2011	262	137	98	88
2012	297	150	113	89
2013	290	171	111	92
2014	383	147	113	93
2015	495	153	120	88
2016	393	168	108	92
2017	492	182	137	95
2018	591	232	147	104

HOT MIX ASPHALT, OPEN GRADED (HMA-O) (UNIT: $/TON)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2015	309	172	147	100
2016	517	186	116	90
2017		188	123	101
2018		179	162	109

RUBBERIZED HOT MIX ASPHALT, TYPE A (RHMA-A) (UNIT: $/TON)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2008	173	117	106	112
2009	137	90	90	74
2010	184	85	95	97
2011	120	104	93	91
2012	130	105	96	105
2013	281	103	104	91
2014	182	114	107	102
2015	133	123	95	92
2016	164	112	102	95
2017	185	127	104	94
2018	210	132	118	108

RUBBERIZED HOT MIX ASPHALT, OPEN GRADED (RHMA-O) (UNIT: $/TON)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2015	160	108	91	83
2016	191	90	115	86
2017	113	105	98	93
2018	160	147	115	120

JOINTED PLAIN CONCRETE PAVEMENT (JPCP) (UNIT: $/CY)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2009	654	170	NA	NA
2010	280	295	167	155
2011	365	356	183	139
2012	315	302	178	138
2013	520	302	231	148
2014	587	307	232	158
2015	750	350	244	160
2016	485	454	281	152
2017	653	417	274	159
2018	637	433	283	146

JOINTED PLAIN CONCRETE PAVEMENT, RAPID SETTING CONCRETE (JPCP-RSC) (UNIT: $/CY)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2014	765	583	529	420
2015	827	435	468	428
2016	856	557	536	405
2017	1,180	745	498	355
2018	1,091	792	658	385

LEAN CONCRETE BASE (LCB) (UNIT: $/CY)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
1999	306	161	175	106
2000	199	205	142	74
2001	282	142	141	98
2002	366	183	140	118
2003	NA	227	137	140
2004	443	249	246	122
2005	627	295	240	214
2006	593	428	403	213
2007	369	360	318	283
2008	282	267	226	203
2009	177	188	187	147
2010	230	163	150	112
2011	290	240	154	102
2012	1,111	197	127	97
2013	360	188	127	92
2014	388	226	124	102
2015	321	208	175	88
2016	310	288	247	127
2017	370	241	146	123
2018	379	292	199	145

LEAN CONCRETE BASE, RAPID SETTING CONCRETE (LCB-RSC) (UNIT: $/CY)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2013	400	368	380	209
2014	402	402	328	163
2015	733	509	338	389
2016	530	689	469	397
2017	575	583	349	334
2018	821	520	375	341

APPENDIX D: PREDICTED UNIT PRICES FOR FUTURE M&R ACTIVITIES

ROAD EXCAVATION, UNIT PRICES ($/CY)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2020	236	115	86	64
2021	241	120	90	69
2022	245	124	95	74
2023	248	127	97	76
2024	252	131	101	80
2025	255	134	105	84
2026	259	138	109	88
2027	263	142	112	91
2028	266	146	116	95
2029	270	149	119	98
2030	273	152	122	101
2031	276	155	126	104
2032	279	159	129	108
2033	283	162	132	111
2034	286	165	135	114
2035	289	168	138	117
2036	291	171	141	120
2037	294	173	144	122
2038	297	176	146	125
2039	300	179	149	128
2040	302	181	152	131
2041	305	184	154	133
2042	307	186	157	136
2043	310	189	159	138
2044	312	191	162	140
2045	314	193	164	143
2046	317	196	166	145
2047	319	198	168	147
2048	321	200	170	149
2049	323	202	172	151
2050	325	204	174	153
2051	326	206	176	155
2052	328	207	178	156
2053	330	209	179	158
2054	332	211	181	160
2055	333	212	182	161
2056	335	214	184	163
2057	336	215	185	164
2058	337	216	187	165
2059	339	218	188	167

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2060	340	219	189	168
2061	341	220	190	169
2062	342	221	191	170
2063	343	222	192	171
2064	344	223	193	172
2065	345	224	194	173
2066	345	224	195	174
2067	346	225	195	174
2068	347	226	196	175
2069	347	226	197	175

CLASS 2 AGGREGATE BASE, UNIT PRICES ($/CY)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2020	268	156	127	98
2021	275	163	134	104
2022	280	168	139	110
2023	284	172	143	113
2024	288	176	147	118
2025	293	181	152	122
2026	298	186	157	127
2027	302	190	161	131
2028	306	194	165	136
2029	310	198	169	140
2030	314	202	173	144
2031	318	206	177	148
2032	322	210	181	152
2033	326	214	185	155
2034	330	218	189	159
2035	333	221	192	162
2036	337	224	196	166
2037	340	228	199	169
2038	343	231	202	172
2039	346	234	205	176
2040	349	237	208	179
2041	352	240	211	181
2042	355	243	214	184
2043	358	246	217	187
2044	360	248	219	190
2045	363	251	222	192
2046	365	253	224	194
2047	367	255	226	197
2048	370	258	229	199
2049	372	260	231	201
2050	374	262	233	203
2051	376	263	235	205
2052	377	265	236	207
2053	379	267	238	208
2054	381	269	240	210
2055	382	270	241	211
2056	383	271	242	213
2057	385	273	244	214
2058	386	274	245	215
2059	387	275	246	216
2060	388	276	247	217
2061	389	277	248	218
2062	389	277	248	219
2063	390	278	249	219

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2064	391	278	250	220
2065	391	279	250	220
2066	391	279	250	221
2067	392	279	251	221
2068	392	280	251	221
2069	392	280	251	221

CLASS 3 AGGREGATE BASE, UNIT PRICES ($/CY)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2020	221	174	114	92
2021	228	181	121	100
2022	238	191	131	110
2023	242	195	135	114
2024	251	204	144	122
2025	257	210	151	129
2026	267	220	160	139
2027	274	227	167	146
2028	282	236	176	154
2029	289	242	182	161
2030	297	250	190	168
2031	304	257	197	175
2032	311	265	205	183
2033	319	272	212	190
2034	326	279	219	198
2035	333	286	226	205
2036	340	293	233	212
2037	347	300	240	219
2038	354	307	247	226
2039	361	314	254	233
2040	368	321	261	240
2041	374	328	268	246
2042	381	334	274	253
2043	388	341	281	259
2044	394	347	288	266
2045	401	354	294	272
2046	407	360	300	279
2047	413	367	307	285
2048	420	373	313	291
2049	426	379	319	298
2050	432	385	325	304
2051	438	391	332	310
2052	444	397	338	316
2053	450	403	343	322
2054	456	409	349	328
2055	462	415	355	334
2056	468	421	361	339
2057	473	426	367	345
2058	479	432	372	351
2059	484	438	378	356
2060	490	443	383	362
2061	495	448	389	367
2062	501	454	394	372
2063	506	459	399	378

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2064	511	464	405	383
2065	516	469	410	388
2066	521	475	415	393
2067	526	480	420	398
2068	531	485	425	403
2069	536	489	430	408

HOT MIX ASPHALT, TYPE A (HMA-A), UNIT PRICES ($/TON)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2020	452	248	204	183
2021	460	256	212	191
2022	469	266	222	201
2023	476	272	229	207
2024	485	281	238	216
2025	492	289	245	224
2026	502	299	255	233
2027	510	307	263	241
2028	519	315	272	250
2029	526	323	279	258
2030	535	331	288	266
2031	543	339	295	274
2032	551	348	304	283
2033	559	356	312	291
2034	567	364	320	299
2035	575	372	328	307
2036	583	380	336	315
2037	591	388	344	323
2038	599	396	352	331
2039	607	404	360	338
2040	615	412	368	346
2041	623	419	376	354
2042	630	427	383	362
2043	638	435	391	370
2044	646	443	399	377
2045	654	450	406	385
2046	661	458	414	393
2047	669	465	422	400
2048	676	473	429	408
2049	684	481	437	415
2050	691	488	444	423
2051	699	495	452	430
2052	706	503	459	438
2053	714	510	466	445
2054	721	518	474	452
2055	728	525	481	460
2056	735	532	488	467
2057	743	539	496	474
2058	750	547	503	481
2059	757	554	510	488
2060	764	561	517	496
2061	771	568	524	503
2062	778	575	531	510
2063	785	582	538	517

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2064	792	589	545	524
2065	799	596	552	531
2066	806	603	559	537
2067	813	609	566	544
2068	820	616	572	551
2069	826	623	579	558

RUBBERIZED HOT MIX ASPHALT, GAP GRADED (RHMA), UNIT PRICES ($/TON)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2020	205	142	133	128
2021	207	145	136	131
2022	214	151	142	137
2023	216	153	144	139
2024	221	159	149	145
2025	224	162	152	148
2026	230	167	158	153
2027	233	170	161	157
2028	238	175	166	162
2029	241	179	169	165
2030	246	183	174	169
2031	249	187	177	173
2032	254	191	182	177
2033	257	195	185	181
2034	261	199	190	185
2035	265	203	193	189
2036	269	207	197	193
2037	273	210	201	197
2038	277	214	205	201
2039	280	218	209	204
2040	284	222	213	208
2041	288	226	216	212
2042	292	229	220	216
2043	295	233	224	219
2044	299	237	227	223
2045	303	240	231	226
2046	306	244	234	230
2047	310	247	238	234
2048	313	251	242	237
2049	317	254	245	241
2050	320	258	249	244
2051	324	261	252	248
2052	327	265	255	251
2053	331	268	259	254
2054	334	272	262	258
2055	337	275	265	261
2056	341	278	269	264
2057	344	281	272	268
2058	347	285	275	271
2059	350	288	278	274
2060	353	291	282	277
2061	357	294	285	280
2062	360	297	288	284
2063	363	300	291	287

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2064	366	304	294	290
2065	369	307	297	293
2066	372	310	300	296
2067	375	313	303	299
2068	378	316	306	302
2069	381	318	309	305

JOINTED PLAIN CONCRETE PAVEMENT (JPCP), UNIT PRICES ($/CY)

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2020	622	436	323	243
2021	630	444	332	252
2022	638	452	340	260
2023	648	462	350	270
2024	657	471	359	279
2025	667	481	368	288
2026	676	491	378	298
2027	686	501	388	308
2028	696	510	398	318
2029	706	520	408	328
2030	716	530	418	338
2031	726	540	428	348
2032	737	551	438	358
2033	747	561	449	369
2034	757	572	459	379
2035	768	582	470	390
2036	779	593	480	401
2037	790	604	491	411
2038	800	615	502	422
2039	812	626	513	433
2040	823	637	524	445
2041	834	648	535	456
2042	845	659	547	467
2043	857	671	558	479
2044	868	682	570	490
2045	880	694	581	502
2046	892	706	593	513
2047	903	718	605	525
2048	915	730	617	537
2049	927	742	629	549
2050	940	754	641	562
2051	952	766	654	574
2052	964	778	666	586
2053	977	791	678	599
2054	989	804	691	611
2055	1,002	816	704	624
2056	1,015	829	716	637
2057	1,028	842	729	650
2058	1,041	855	742	663
2059	1,054	868	755	676
2060	1,067	881	769	689
2061	1,080	895	782	702
2062	1,094	908	795	716
2063	1,107	922	809	729

Year	Small Project	Medium Project	Large Project	Extra-Large Project
2064	1,121	935	823	743
2065	1,135	949	836	757
2066	1,149	963	850	771
2067	1,163	977	864	784
2068	1,177	991	878	799
2069	1,191	1,005	892	813

ABBREVIATIONS AND ACRONYMS

CAPM	Capital Maintenance
CPI	Consumer Price Index
CRCP	Continuously Reinforced Concrete Pavement
HMA	Hot Mix Asphalt
HMA-O	Hot Mix Asphalt, Open Graded
JPCP	Jointed Plain Concrete Pavement
LCB	Lean Concrete Base
LCCA	Life Cycle Cost Analysis
M&R	Maintenance and Rehabilitation
RHMA	Rubberized Hot Mix Asphalt
RSC	Rapid Setting Concrete

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