Street Maintenance Audit

November 2015

City Internal Auditor's Office

City of College Station

File#: 15-02

Audit Executive Summary:
Street Maintenance Program

What We Found

Process Effectiveness. The Street Maintenance Program experiences difficulties in certain areas of operations. Turnover rates in the Streets Division are higher than other comparable city departments and the private construction industry. Employees are not as skilled as required for efficient job task completion, which is influenced by high turnover. High levels of equipment maintenance impact the ability to complete work in a timely manner.

Policy Considerations. Citizen complaints have resulted in a shift away from the preventative maintenance techniques of chip and crack sealing. This shift has led to increased costs for the Streets Division, both in time and money. These complaints are primarily driven by the aesthetic look of streets when chip sealing or crack sealing methods are utilized.

Streets maintenance is irrevocably linked to street construction standards. The City utilizes the Bryan-College Station Unified Guidelines and Specifications in its capital improvement projects and requires the same specifications be used by developers. However, there are opportunities in the City's system to construct streets below current standards. The City should consider taking on the construction of streets classified as minor collector or higher in order to ensure better quality roads. In addition, while many city streets are constructed in asphalt, concrete roads may be more effective and less costly in the long-term.

Flexibility is key in operating street maintenance programs effectively. Given the uncertainty that comes with weather and high turnover, the funding source should reflect this flexibility. Some cities institute transportation fees allocated to a street maintenance fund for this purpose.

Why We Did This Audit

The City's largest capital asset is its streets infrastructure. In fiscal year 2015, $2,330,000 was allotted for street maintenance projects and $20,435,000 was appropriated for street related capital improvement projects. Actions taken regarding street maintenance and construction will have long-term impact on streets' useful life and quality. Street maintenance programs were also the most audited area across local government audit shops in the nations during fiscal year2014 due to the deterioration of roads nationwide.

What We Recommended

- The Streets Division should reinstitute skill based pay for heavy equipment operators (recommendation 1).
- Consider only having an engineering firm conduct a Pavement Condition Analysis every three years and in-house in years in between. Investigate alternative data collection methods (recommendation 3).
- Consider allowing contractors to take over the majority of millings and overlays so that the City can reallocate more resources toward preventative maintenance; if not, consider a dedicated mechanic for streets heavy equipment (recommendations 2, 4, and 5).
- Consider raising construction standards for local roads and moving toward more concrete construction for city streets (recommendations 6 and 7).
- Institute a transportation fee and allocate the revenue into a dedicated street maintenance fund.

Street Maintenance Audit

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Introduction

The Office of the City Internal Auditor conducted this performance audit of the street maintenance program pursuant to Article III Section 30 of the College Station City Charter, which outlines the City Internal Auditor's primary duties.

A performance audit is an objective, systematic examination of evidence to assess independently the performance of an organization, program, activity, or function. The purpose of a performance audit is to provide information to improve public accountability and facilitate decision-making. Performance audits encompass a wide variety of objectives, including those related to assessing program effectiveness and results; economy and efficiency; internal control; compliance with legal or other requirements; and objectives related to providing prospective analyses, guidance, or summary information. A performance audit of street maintenance was included in the fiscal year 2015 audit plan based on direction given by the Audit Committee.

Audit Objectives

This audit addresses the effectiveness of the City to maintain its most valuable municipal asset—city roadways. This report answers the following questions:

- Is Public Works utilizing appropriate techniques, staffing levels, and equipment to best maintain the City's street inventory?
- Are proper policies being implemented and standards being upheld?
- Are the methods used to construct and maintain city streets successful at ensuring the highest level of street infrastructure at the lowest possible cost?

Scope and Methodology

This audit was conducted in accordance with government auditing standards (except for the completion of an external peer review),[1] which are promulgated by the Comptroller General of the United States. Audit fieldwork was conducted from June 2015 through September 2015. The scope of review varied depending on the analysis being performed. The methodology used to complete the audit objectives included:

[1] Government auditing standards require audit organizations to undergo an external peer review every three years.

- Reviewing the work of auditors in other jurisdictions and researching professional literature to identify (1) street maintenance best practices, (2) current challenges facing street infrastructure, and (3) industry trends.

- Reviewing applicable policies and procedures and relevant state and federal laws and regulations.

- Examining applicable financial and performance reports and data.

- Observing street maintenance operations to examine how maintenance actions are carried out in the field and how the work environment affects productivity.

- Interviewing various Public Works and Planning and Development employees to identify (1) potential improvements to overall street performance and (2) possible problems that can impact street performance.

- Examining the effectiveness of the street maintenance program and its alignment to the Streets Division's goals through (1) observing employees in the field, (2) interviewing management, (3) reviewing records of applications and work orders, and (4) comparing Streets Division employment statistics with similar positions in other city departments.

- Analyzing the maintenance performed by the Streets Division and identifying patterns between (1) amount of maintenance and road type, (2) types of maintenance and their frequency, (3) costs per maintenance type, and (4) maintenance costs per street type.

- Analyzing reports regarding Streets Division equipment maintenance and equipment use in the field.

- Identifying the Pavement Condition Analysis report (the street condition data collected and analyzed by an engineering firm) functionality and appropriateness by (1) reviewing report variations, (2) interviewing the report reviewer (City of College Station employee), (3) interviewing Streets management, and (4) observing whether the recommendations issued were appropriate through observations of randomly selected streets.

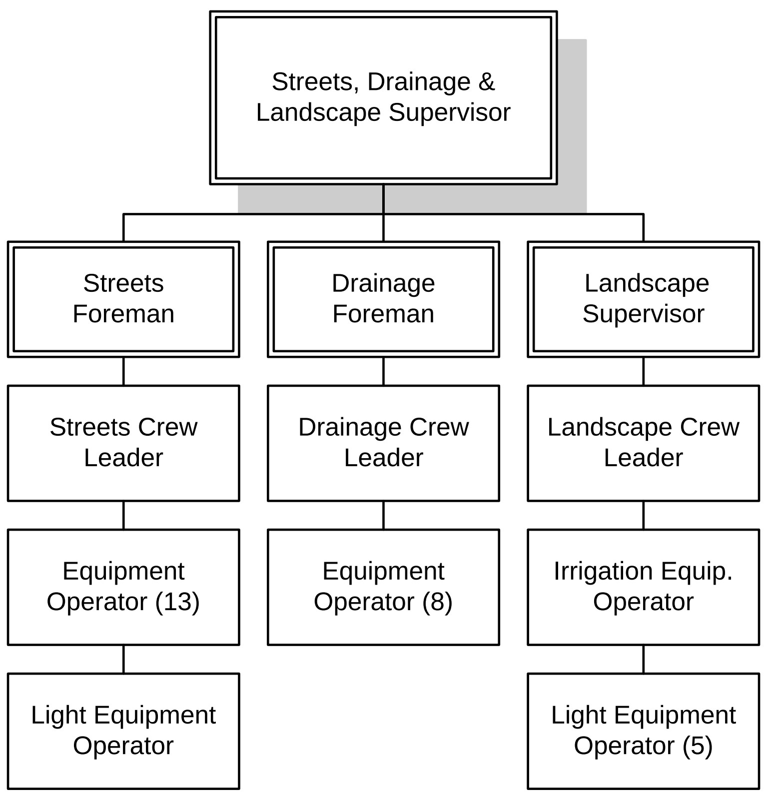
- Identifying CityWorks' (the work order catalog information system) functionality and reporting capabilities by (1) reviewing the CityWorks software, (2) interviewing the system administrator (City of College Station employee), and (3) observing whether work orders reported in the system were accurate through observations of randomly selected streets.

Streets Maintenance Background

Streets, Drainage, & Landscape is a division within the Department of Public Works. The division consists of 36 full-time employees maintaining approximately 310 miles of paved streets, 90 miles of storm water lines, 21 miles of concrete valley gutters, and 150 miles of natural creek line. They also provide heavy equipment support for other departments and traffic management support for major community events. In addition, the division provides 24 hour, seven day a week response to street maintenance problems, drainage issues, and incident management support for public safety agencies.

Although there are three unique business units within the division, employees are crossed trained. Therefore, occasions arise when crews from one unit will aid others in another unit, especially when weather prohibits Street Maintenance Work. Figure 1, below provides the flowchart of the division.

Figure 1: Streets, Drainage & Landscape Organization Chart

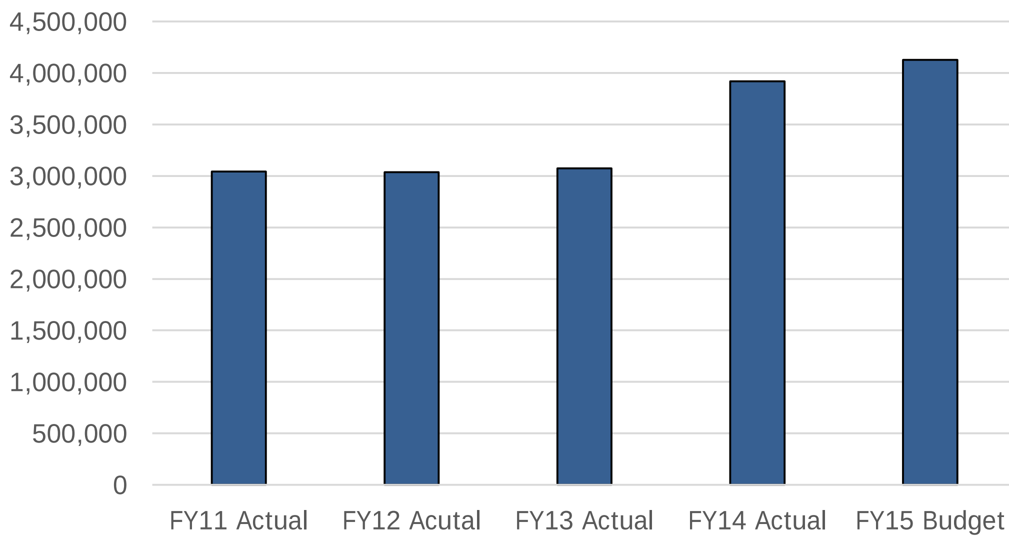


For the purpose of this report, the streets business unit of the Streets, Drainage, & Landscape Division will be referred to as the "Streets Maintenance Division" or "Streets Division." In fiscal year 2015, the total number of authorized Streets Division employees was seventeen. This includes thirteen Equipment Operators, a Light Equipment Operator, a Crew Leader, and a Foreman.

The Streets Maintenance Division of the Public Works Department strives to ensure that the street system within the City of College Station is properly maintained. This is done through a number of programs, including a street maintenance program that addresses street repair before more expensive reconstruction measures are needed.

The effectiveness of this service is currently measured by the average pavement rating of the City's streets conducted by an outside consultant. The citywide average pavement rating for 2014 was 88 out of 100, which indicates that city streets are in good condition overall, a slight improvement over 2013 which had a score of 86. A decision matrix is used to determine the maintenance strategy for a particular roadway and is based upon the type of distresses present, the density of the distresses, and the roadway classification. The Street Maintenance Division is funded out of the General Fund (see Figure 2 below).

Figure 2: Street Maintenance Division Funding



Several Factors Impact the Useful Life of Streets

Although many factors can play a significant role in impacting the useful life of a street, the following are likely the greatest contributors to reducing the longevity of city streets:

Soil Conditions: College Station is inundated with clay soils that have a high plasticity and shrink-swell capability. This can be especially dangerous for concrete roads as the high level of soil expansion and contraction can interfere with the uniformity of the soil under the pavement. Having uniformity of soil under concrete pavement is perhaps the most important aspect of construction. Concrete distributes the weight of loads traveling over its surface more evenly across the entirety of the slab. Asphalt on the other hand channels the weight deeper into the subgrade under the localized area the weight is traveling. Careful attention to the design and construction of subgrades and subbases is essential to ensure the structural capacity and ride quality of all types of bases. Therefore, having a thorough soil testing process, high quality subgrade materials, and proper subgrade depth are important for ensuring a full life for the street.

Traffic Load: The traffic load can have a great impact on the useful life of a street. Streets are built to certain standards based on the expected volume of traffic they will carry during their lifetime, resulting in the residential, collector, and arterial classifications. Streets of a certain classification are built assuming that the street will only carry the traffic load determined by its specifications. When a road carries more than its specifications were designed for, the road experiences more stress. This results in a larger number of distresses faster, shortening the useful life of the street. It is important to ensure that streets are being built for the proper amount of traffic to mitigate this problem. Research concerning traffic loads throughout the City are key for proper street specification designations.

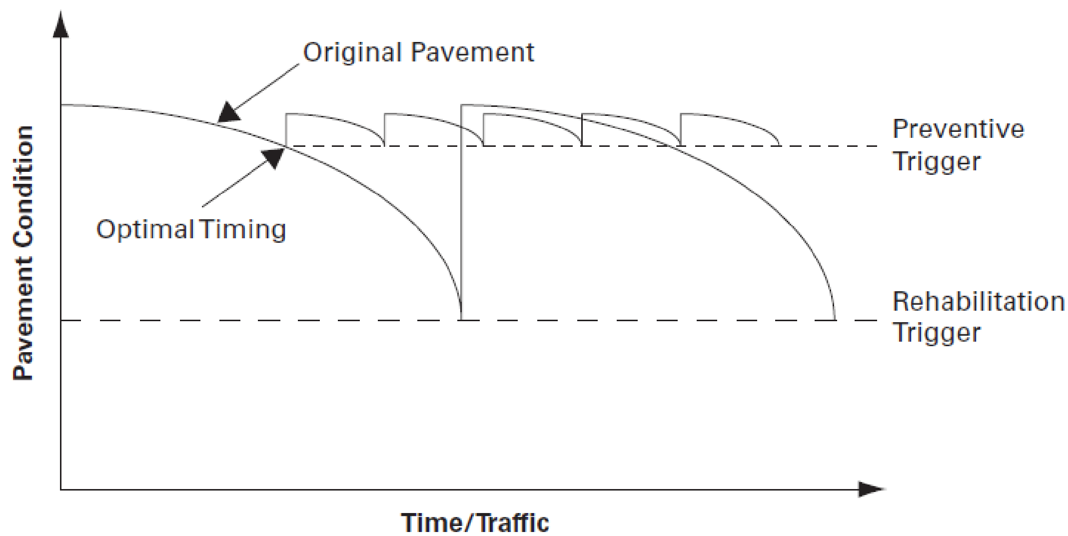
Material Quality: In addition to soil conditions and traffic, the quality and strength of the paving materials used are important for determining the useful life of a street. Asphalt is composed of bitumen cement and aggregates of different sizes that are then heated to create a viscous material. Having the correct amount of aggregate, emulsion, and other additives is necessary for ensuring the pavement is able to function properly over the course of its life. Materials' strength and quality is also affected by the process used to create it, which requires specific temperatures and storage strategies before application of the materials begin. It is necessary to ensure that materials are up to standards through an inspection process, as well as to determine whether material standards are high enough to reach the full useful life of a road.

Weather: Lastly, weather can have an adverse impact on road conditions. Rain and freezing temperatures exacerbate cracks and potholes when water seeps into the pavement. Water erodes the subgrade and pavement while cold temperatures cause the trapped water to expand and shrink, resulting in more distresses in the pavement. This is true for both concrete and asphalt. Long periods of rain also mean that asphalt and concrete cannot be laid, as the water would then be trapped under the pavement. Water works its way into cracks in the roads and causes further damage as seasons change. Wet winters and springs are likely to lead to more distresses in the roads, which may not have occurred as quickly if the weather was dry. Extreme fluctuations in temperature over the course of the year can also result in distresses developing more quickly. Weather is an uncontrollable factor for street maintenance and therefore the best strategy for handling unexpected weather events is to maintain flexibility in scheduling and operating capabilities in case disruption occurs.

The City Utilizes Different Types of Maintenance Techniques

The City of College Station utilizes multiple techniques to maintain and repair city streets. They can be broken into three categories: (1) preventative, (2) corrective, and (3) reconstruction. Each type of maintenance techniques plays a role during the life cycle of a street.

Figure 3: Pavement Life-Cycle



When pavement is young, it deteriorates at a slower rate. At a certain point in the young road's life, the timing becomes optimal for preventative maintenance techniques to be used, keeping the road in good condition. As time goes on, preventative techniques lose effectiveness due to the aging process of the street. As potholes and other more severe distresses begin to appear, corrective maintenance techniques are used to patch and repair those areas of a street that require more help than preventative maintenance can give. Eventually a street will reach such an advanced age that reconstruction of the road becomes necessary.

As Figure 3 illustrates, preventative maintenance extends the life of the road and helps ensure that pavement can undergo the full life cycle of a street rather than waiting until reconstruction becomes necessary. Roads that generally are in good condition do not register a major change in condition rating after a preventative treatment is applied—the rating continues as good. What is important, however, is the condition rating several years later—roads that receive preventative maintenance are in better condition than those left without. For the purposes of this audit, we define the techniques used by the City in the following ways and in the following categories.

Preventative: These maintenance techniques are used to prevent more serious road deterioration and generally are conducted in the early life of the street. The following are common examples of preventative maintenance techniques that are used nationwide.

Crack sealing: Sealing and filling asphalt or concrete pavement cracks is a common road maintenance activity. Specialized materials are placed into or above cracks to prevent the intrusion of water and incompressible material into the cracks and to reinforce the adjacent pavement.

Seal coating/Chip sealing: Seal coats have been used for decades to preserve riding surfaces. The most common type of seal coat the City has used in the past is chip sealing. A chip seal is a surface treatment in which the pavement is sprayed with emulsion and then immediately covered with aggregate and rolled. Chip seals are used primarily to seal a pavement with non-load-associated cracks, and to improve surface friction. A chip seal's main purpose is to seal the fine cracks in a pavement's surface and prevent water intrusion into the base and subgrade. To achieve the pavement preservation benefits of a chip seal, an agency must apply it on roadway surfaces when the level of pavement distress is low. This technique is used primarily for asphalt roads though it can be used for concrete as well.

Joint sealing: Resealing concrete pavement joints is a common pavement maintenance activity. Joint sealants reduce the amount of water entering the pavement structure and prevent incompressible materials from filling the joints. Joint sealing is used for concrete roads and areas where concrete curbs and aprons connect to asphalt pavement.

Corrective: These maintenance techniques are used when a road is experiencing more severe distresses or failures and generally are conducted in the later life of the street. Corrective maintenance occurs when preventative maintenance is no longer effective or cannot be used given the severity of the distresses. Examples of common corrective techniques used by the City of College Station are listed below.

Level Ups: This maintenance technique is utilized when a road begins to recede below the curb along the side of the street. Level ups require milling out the asphalt along the curb and then laying new asphalt, making the street flush with the curb again. This usually becomes necessary as a road ages. It is an asphalt maintenance technique.

Patching: A patch can be done in a few ways based on which type of distress is being repaired. Potholes consist of small bowl-shaped depressions in the pavement surface typically having sharp edges and vertical sides near the top of the hole. They are localized failures and are repaired by filling the pothole with asphalt and compressing it down into the pavement. Failures usually require milling out a larger portion of asphalt to ensure the subbase is still functioning and then laying new asphalt over the milled area and compressing the material. Patching is mostly used for asphalt roads but may also be used as a measure for concrete surface distresses.

Overlays: For severely distressed surfaces, overlays will provide a new surface, prolong pavement structure life, and make a pavement stronger. Overlays generally require milling up old asphalt and laying between 0.5 and 2 inches of new asphalt.

Reconstruction: Reconstruction refers to removing all or a significant portion of the pavement material and replacing it with new or recycled materials. This may include full-depth reclamation, where the pavement surface is demolished in place and new pavement surface is applied. It also may be partial reconstruction if the road does not have enough severe distresses to necessitate the replacement of the entire road.

Asphalt: Partial reconstruction consists of localized base repairs along with a milling of the existing hot mix asphalt concrete pavement and replacing it with a new asphalt surface. Full reconstruction occurs when severe levels of distress in most or all areas necessitate a full replacement of the roadway. The old asphalt will be removed, the subbase repaired, and then new asphalt will be laid.

Concrete: Once a concrete slab has been injured beyond the point of joint and crack sealing, the entirety of the slab must be removed to replace. If the problem has to do with joint failure, there is a strong possibility that a neighboring slab, if within six feet of the problem, must be removed as well. For some types of concrete pavement, any cracking, breaking, or spalling of slab edges on either side of a transverse joint need to be repaired. This can be full depth repair or partial depth repair.

Municipal Maintenance Strategies Vary

Comparing the City of College Station to peer cities found that there is a wide variety of staffing and maintenance strategies used amongst surveyed Texas cities. Although there is no city that exactly matches College Station, we attempted to identify cities that best resembled College Station's soil, weather and traffic. As a result, we surveyed the Public Work's departments of Bryan, Mansfield, Sugar Land, San Marcos, and Waco.

College Station is well within the normal range for staffing of the Streets Division, especially given comparable number of lane miles[2] and work done in-house[3]. Figure 4 on the next page provides a comparison of College Station Streets Division staffing with those of comparable Texas cities.

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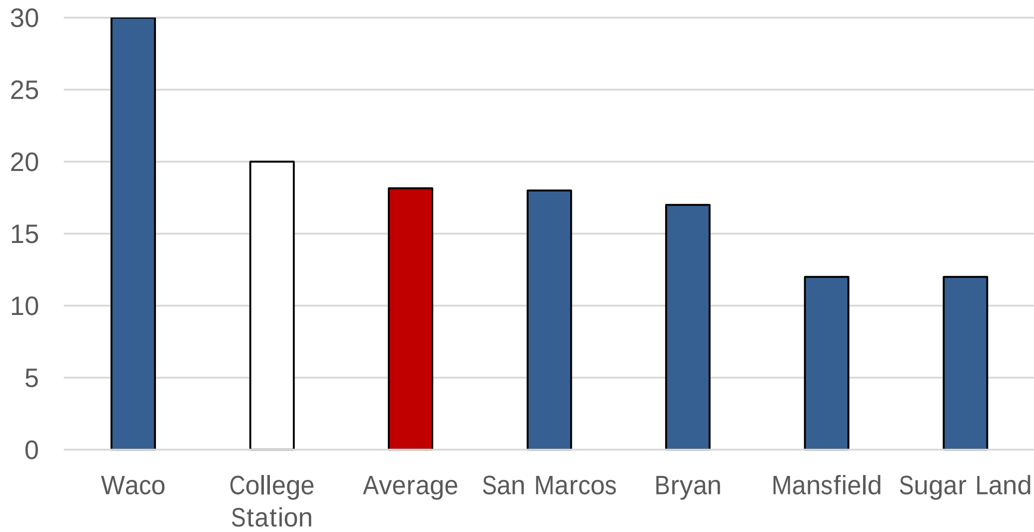
[2] College Station maintains the second most lane miles of streets compared to cities we surveyed (see Figure 6, p. 13).
[3] Like Mansfield and Waco, College Station conducts most street maintenance in-house (see Figure 5, p. 11).

Figure 4: Streets Division Staffing Comparison amongst Texas Cities



While there are different opinions about how much and for which projects contractors should be used, there is a consensus among peer cities that contractors are a necessary aspect of street maintenance. Generally speaking, city staff conducts most maintenance in peer cities with the exceptions of Sugar Land and Bryan which both use contractors at higher rates.[4]

Figure 5: Percentage City Staff vs. Contractor

Peer cities also differ in allocation of their employees versus contractors. See Table 1 below.

[4] Bryan is not included in the Figure 3 due to a lack of numerical data, however, per our conversation with staff, Bryan contracts out most its maintenance work.

Table 1: Current Division of Labor between Contractors and City Staff

City	Overlays	Potholes	Base Failures	Crack Sealing	Concrete Reconstruction
College Station	City Staff/ Contractors	City Staff	City Staff	Contractors	Contractors
Mansfield	City Staff/ Contractors	City Staff	City Staff	City Staff	Contractors
Bryan	Contractors	City Staff	City Staff	Contractors	Contractors
Sugar Land	Contractors	City Staff/ Contractors	Contractors	Contractors	Contractors
San Marcos	City Staff/ Contractors	City Staff	City Staff	City Staff	Contractors
Waco	Contractors	City Staff	City Staff	City Staff	City Staff

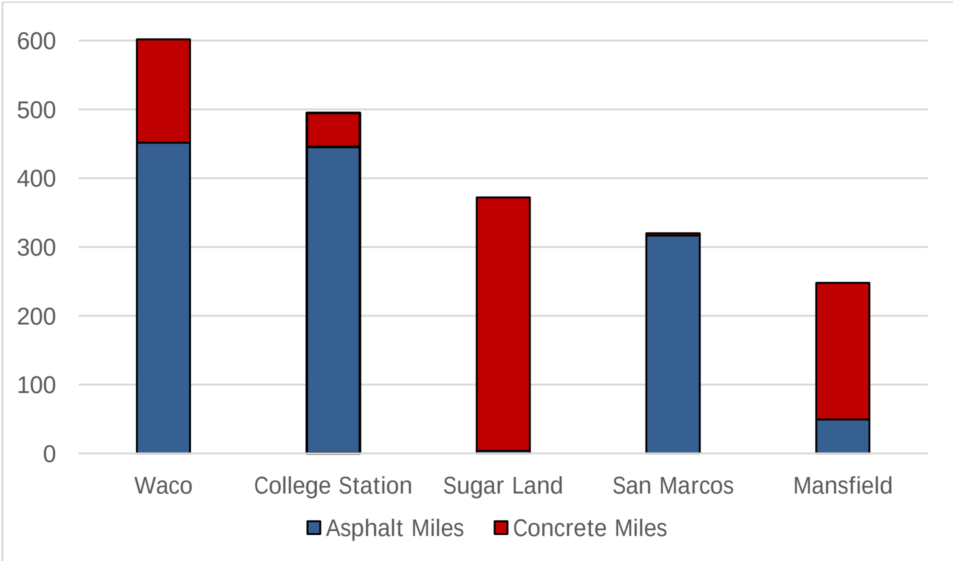
City staff repair potholes and base failures in every peer city except Sugar Land, likely due to the high amount of concrete in that particular city. Contractors are used for major street rehabilitation projects, as well as concrete reconstruction in every city excluding Waco. There is a division of labor between city staff and contractors for crack sealing and overlays, but it is important to note that the two other cities that contract out crack sealing (Bryan and Sugar Land) contract out most of their maintenance as shown in Table 1.

With regards to asphalt and concrete, there are two schools of thought: (1) concrete has a longer useful life and is more aesthetically pleasing and (2) asphalt is cheaper and easier to repair. This is reflected in the percentage of asphalt and concrete streets that peer cities have, some of which are chiefly concrete and some that are predominantly asphalt.[5] See Figure 6 on the next page.

Hiring requirements were largely the same throughout each of the peer cities. Each city also relied on city employees doing visual inspections of the roads to determine how maintenance scheduling should be done regardless if they had a plan put together by an outside engineering firm. In fact, with the exception of Bryan (who does in-house data collection and analysis), College Station has the most frequent Pavement Condition Analysis. Each division supervisor we interviewed also stated that street maintenance depends on multiple factors and therefore requires a high level of flexibility.

[5] While the City of Bryan does not appear in the Figure 6 due to a lack of numerical data, it has significantly more asphalt than concrete per our conversation with staff.

Figure 6: Miles of Asphalt and Concrete Comparison[6]



[6] These numbers include all of the miles of street in each City, ownership notwithstanding.

Findings and Analysis

Obstacles to Optimal Maintenance of City Streets Exist

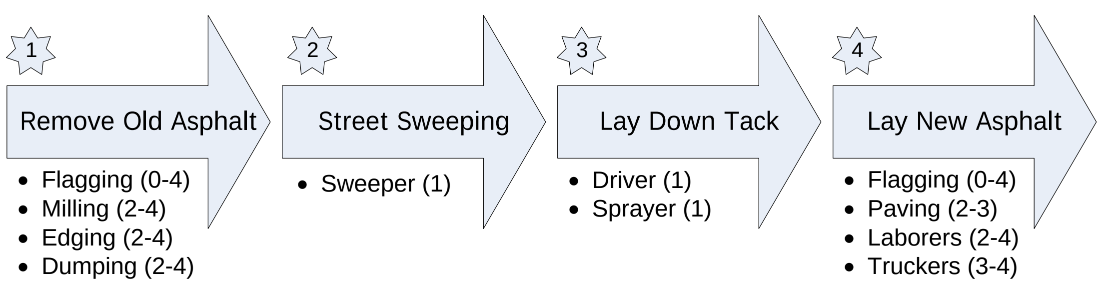
The stated mission of College Station with regards to transportation is to ensure that the City has a "safe, efficient and well-connected multimodal transportation system that contributes to a high quality of life and is sensitive to surrounding uses." This suggests that city streets, sidewalks, bike lanes, and multi-modal paths should be well-maintained and free of hazards. To accomplish this, the City provides streets that accommodate vehicles, bicyclists and pedestrians, plans for infrastructure that meets projected growth and development, and maintains and rehabilitates the system to avoid costly replacement.

Several Factors Impact Street Maintenance Crews' Productivity

Maintaining and rehabilitating city streets requires that street maintenance be accomplished efficiently and effectively. Therefore, we examined multiple aspects of the College Station street maintenance program to determine if street maintenance services are meeting the stated goals of the City of College Station Strategic Plan.

During the course of the audit, we observed the process of a street overlay, which encompasses removing old asphalt and laying new asphalt on a stretch of road. Overlays are the most labor intensive function the Streets Division performs, and can take multiple days to complete depending on the size and length of the road. The overlay process is illustrated in Figure 7. We also observed the pothole repair process.

Figure 7: Steps Used to Overlay a Street



There are bottlenecks in the process of overlaying a street. This results in the number of crew members allocated for a certain job exceeding the number of members necessary to accomplish the task. For example, when laying down asphalt for an overlay, the crew must wait for the asphalt to be delivered to the site. This means that if there is a situation at the asphalt plant which delays the delivery of asphalt, then the crew may be unable to conduct meaningful work on the project until the delivery is completed. Trucks drive to the asphalt plant to get more asphalt continually throughout the day. Tonnage of asphalt required for a stretch of road is estimated by the crew leader, who is generally conservative in his estimates to ensure that funds are not wasted on excess materials.

Turnover has contributed to Operator Inexperience

In our observations, we noted that many of the crew members were not skilled in their work, which negatively affects the efficiency and effectiveness of the street maintenance crews. This can be partially attributed to the large turnover rate that exists in the Streets Division. New workers are going to be less skilled than those who have been on the job for a number of years, but crew members generally do not stay for very long in comparison to similar jobs in other city departments (illustrated in Table 2 below). This means that employees do not gain those skills that would make them more effective in doing street maintenance, especially in the operation of maintenance equipment.

Table 2: Comparison of 'Blue Collar' Employee Turnover Rates

	FY10 Actual	FY11 Actual	FY12 Actual	FY13 Actual	FY14 Actual	FY15 Estimate[7]
Streets	22.6	31.5	48.6	33.4	24.5	16.6
Public Works Turnover	13.6	12.0	21.7	16.7	32.0	11.1
Parks & Rec	5.1	14.7	8.8	13.2	15.9	9.8
Water Services	0	0	0	0	0	5.3
Waste Water	2.9	0	0	2.9	0	0
Electric Utility	3.1	6.3	6.3	3.1	15.6	0
Construction Industry	6.3	6.3	5.7	5.3	4.7	5.0

Turnover is more prevalent amongst street maintenance employees than comparable 'blue collar' employees in other city departments.[8] This is true for every year except fiscal year 2014, in which the Public Works Facilities, Drainage, and Traffic Signs and Markings divisions had a 32 percent turnover rate amongst their 'blue collar' staff and Streets had 24.5 percent turnover rate. While a number of these terminations occur during the probationary period, the division still averages over 26 percent turnover across the five years analyzed. Regardless, Streets is losing nearly a third of its workforce on an annual basis. Not only is this significantly higher than other comparable positions throughout the City, it is also much higher than published[9] national construction industry turnover rates.

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[7] October 1, 2014 to June 30, 2015.

[8] We only included positions that most resembled heavy or light equipment operators and their supervisors in our analysis.

[9] Data taken from the US Bureau of Labor Statistics

Additionally, the heavy equipment operator position seems to take more time to fill and has a higher turnover rate than other positions within the Streets Division. This high turnover can reduce efficiency as new members must be hired and trained for their new job. It also can hinder work if employees resign during a busy period.

Several Factors Contribute to High Turnover Rates

The causes of turnover can be varied, but widely accepted reasons are as follows: inadequate compensation, lack of opportunities for advancement, perception of unfair treatment, feeling undervalued, and job stress. The strength of these causes for turnover in the Streets Division are addressed below.

Compensation: There is a perception in the Streets Division that pay is not adequate for the work conducted. Recently, the City hired a consultant to conduct a salary survey, which found that the current average salary of light equipment operators in the City of College Station is 98 percent the average of comparable cities.[10] The current average salary of heavy equipment operators in the City of College Station is 96 percent of comparable cities. Though no survey could be completely accurate, the salary survey results are an indicator that pay is unlikely to be the *primary* cause of turnover. Other factors are likely to have an equal or greater effect on why employees leave the Streets Division.

The primary goal of an effective compensation strategy should be to attract and retain top performers not to eliminate turnover. Assuming that streets employees are compensated at or close to market, the average employee is less likely to leave *solely* based on pay, though it is an important factor. High performers, however, are more likely to seek work elsewhere because of the combination of pay and few opportunities for financial acknowledgement of their performance level.

Lack of Advancement: There are few opportunities for advancement in the Streets Division which is likely due to multiple factors. There are only nineteen allotted positions in the Streets Division for fiscal year 2015. The only opportunities to advance are for light equipment operators to become heavy equipment operators, heavy equipment operators to become crew leaders, and crew leaders to become foremen. However, this is only possible when those positions have a vacancy. During the time period between fiscal year 2010 and fiscal year 2015, there were three crew leader position postings for the Streets Division. All of those positions were filled by a current city employee at the time. The foreman position was also filled by a current Streets employee when a vacancy opened. So while there are not many opportunities for advancement due to the small size of the division and the limited vacancies that open for higher level positions, those vacancies that have opened in the past were filled by internal hires.

[10] No public survey data sources were available.

Personality Conflicts: Another cause of turnover can be conflicting personalities among employees and supervisors. Conflicting personalities may lead to a tense and inefficient workplace and disrupt trust between the different levels of employees in the division, which can lead to higher rates of turnover. Personality conflicts also lead to communication failures and the perception that an employee is undervalued or is treated unfairly in comparison to other coworkers. Much of this problem can be traced to a difference in values. A possible solution to this problem is to hire employees based more on whether their values fit with the values of the Streets Division rather than solely whether the applicant is qualified to run certain equipment or has a certain amount of experience in similar work. It also means that current employees should be informed of the division's foundational values and a culture of dedication to those values should be developed within the division. This requires identifying the overarching values that drive the Streets Division and formulating a hiring strategy to determine whether an applicant shares those fundamental values.

Feeling Undervalued: In addition, feeling undervalued by the employer can be another reason for higher turnover rates. Feelings of this nature were noted during our field observations. Employees noted that people performing more difficult tasks than others receive the same pay without regard to skill differentials. Some employees expressed that they felt that those who had more skill were undervalued considering the differences in work are not reflected in salaries.

This perceived lack of appreciation for the skill needed to do the work could be a contributing factor to the turnover rate in the Streets Division. While some turnover is good for an organization, the goal is to retain high performers which is difficult with the current incentive and reward system. Acknowledgement of individual and group success in multiple ways could be helpful in creating a feeling of appreciation among employees.

Job Stress: One of the other causes for turnover is the nature of the work and stress that comes with the job. During our observations, many crew members commented on how difficult it was to work in the heat during the summer, especially when laying asphalt. Some employees stated that they believed one of the reasons for the high turnover in the Streets Division compared to other 'blue collar' divisions in the City was due to the heat that comes from working with asphalt in the summer. We found that 46 percent of all service separations occur between June and September, indicating that heat is a factor in turnover. Regardless, there is not much that can be done to lower the physical demands of the job beyond making sure that basic needs like water are easily accessible. Other causes resulting in turnover are more easily mitigated.

Applicant Qualification: While turnover is significant, we found that there seem to be enough qualified applicants for open positions based solely on stated qualifications. However, Streets Division management noted that while there are qualified applicants in terms of physical ability, the interview process is where they judge whether the applicant is motivated to do the work and willing to rotate between different equipment as needed. The interview process is where it becomes clearer that some applicants are not appropriate. In this case, we believe that Streets is receiving enough applications to fill the positions for the light equipment operator, foreman, and crew leader positions. Though there are less qualified applicants for the heavy equipment operator position there are still enough to adequately fill the position based solely on capabilities stated in applications.

Table 3: Qualified Applicants

Position Title	Percent of Qualified Applicants	Number of Applicants	
		Qualified	Total
Heavy Equipment Operator	14.5%	43	296
Light Equipment Operator	23.1%	57	247
Crew Leader	35.3%	6	17
Foreman	18.8%	3	16

Skill-based Pay Should Be Implemented for Heavy Equipment Operators

While turnover is a problem that can affect the skill level of the overall crew and should be addressed, there should also be a system put in place to give crew members incentives to gain skills and implement those skills effectively. The current low skill level affects how efficient street crews are when conducting maintenance work. During our observations, we noted that there was little pro-active behavior on the part of the crew. This may be a result of a new crew leader and crew members—as most Streets Division employees were hired less than a year ago. The lack of senior leadership that can train new employees how to perform the job may be an issue. For instance, we noted that the crew leader often had to halt different essential tasks in order to ensure that other tasks were performed up to standards. This lack of confidence may be due to the skill deficiency demonstrated by some crew members, which led to forced inactivity as the crew leader switched between tasks.

There is currently no incentive to become skilled on the machinery required for the job which limits the effectiveness of crews. Skill-based pay could provide incentive for workers to gain the skills necessary to perform the job as quickly as possible, which in turn would increase overall crew effectiveness. It would also address some of the causes of turnover, particularly employees feeling undervalued and the lack of advancement. Skill-based pay objectively acknowledges the value of the employee and results in greater competency in work. Therefore more responsibility can be given to employees in the field because of their greater skill level.

While we believe that skill-based pay should be reinstituted, we find that skill-based pay should only be instituted for the position of heavy equipment operator. The reasons for this are twofold. First, rather than making skill-based pay a part of the development track that naturally occurs from light equipment operator to heavy equipment operator, limiting it to heavy equipment operator requires that a light equipment operator already have demonstrated their ability to perform at the higher level required for the position. Therefore, the promotion to heavy equipment operator would open the door to further skill-based raises that the individual would be further motivated to obtain beyond their already high performance. Secondly, the possibility for abuse is present within a skill-based pay system. Limiting skill-based pay to a position requiring those higher skills makes it less likely that system abuse will occur, unwittingly or otherwise.

Recommendation: Reinstitute skill-based pay for heavy equipment operators.

Street Maintenance Equipment Is Prone to Problems

The City currently owns over 50 separate pieces of equipment that are used in conducting street maintenance work. We were able to observe some of the equipment being used in the field and gain access to maintenance reports for 20 of the different pieces (summarized in Table 4).

In the field, there were clear instances in which the equipment was not functioning as it should. At one point, it was observed that there was difficulty with the Milling Machine. Because the milling machine is an essential piece of equipment to perform a street overlay, when this occurs work on an overlay project would need to be halted.

Table 4: Unscheduled Maintenance of Streets Equipment

Equipment Name	First Maint. Date	Last Maint. Date	Avg. Hrs in Shop	Days in Shop	Avg. time between visits
Milling Machine	8/05/13	7/24/15	6.61	33	15.50
2011 Multi-Terrain Loader	9/03/13	5/28/15	3.35	10	48.20
Truck Tractor w/Winch	12/04/13	7/01/15	3.75	5	131.67
Autocar w/Schwarze Patcher	6/20/14	5/08/15	1.67	6	44.20
Ford F250 Crewcab	9/26/13	5/23/15	0.93	6	83.00
Entyre Lowboy	8/12/13	5/12/15	5.61	8	62.57
F750 Diesel Dump Truck	7/28/14	-	0.25	1	-
9 Wheel Pneumatic Roller	8/09/13	6/23/15	2.33	23	20.82
Freightliner Dump Truck	8/27/13	7/21/15	2.10	38	12.86
Tool Trailer	5/27/14	6/05/15	7.46	6	51.60
Tandem Drum Roller	8/14/13	6/08/15	3.30	24	19.74
2009 Peterbilt CC w/Patcher	10/07/13	7/22/15	2.99	55	8.44
Highway Sweeper	4/28/15	-	1.00	1	-
2014 Carlson Paver CP100	5/16/14	3/23/15	3.80	4	70.33
Peterbilt Dump Truck	9/10/13	7/21/15	1.55	15	31.07
Tilt Trailer	1/28/14	9/26/14	1.50	3	84.50
250G Tack Oil Trailer	1/07/14	7/11/14	0.83	3	64.50
4x2 Super Cab SRW	10/15/13	2/03/15	1.13	4	132.33
Flatbed Haul Trailer	8/27/13	6/26/15	1.16	10	51.00
2014 Cat Excavator	11/18/14	-	0.50	1	-

Multiple pieces of equipment experience significant amounts of time in the shop undergoing maintenance. In particular, the Milling Machine, Peterbilt Pothole Patcher Truck, and Freightliner Dump Truck are in the shop at least every 20 days on average. They have also been in the shop the most within the two year time frame for which we had maintenance records. Of these pieces of equipment, the milling machine spends the most time in the shop for each visit, averaging 6.67 hours per visit. In cross referencing the maintenance reports with work orders, we identified an instance in which work on a street (a level up) was halted for a week while the milling machine underwent maintenance.[11] In this case, maintenance resulted in an inability to finish an assigned task within the expected time frame. According to Public Works management, when this occurs, street crews will be reassigned to other maintenance activities.

It seems the most significant delays in work occur when multiple pieces of equipment are undergoing maintenance at the same time. For instance, between April 23, 2014 and May 13, 2014, the following heavy equipment vehicles were all in and out of the shop for unscheduled repair: (1) Milling Machine, (2) Entyre Lowboy, (3) Peterbilt Pothole Patcher Truck, (5) Freightliner Dump Truck, and (6) Peterbilt Dump Truck. That time also did not see significant rainfall or other weather problems that could have caused the lack of street maintenance work. Again, between June 23, 2014 and July 14, 2014, seven different pieces of equipment underwent unscheduled repair and there was not significant weather that could explain the long period with no work orders written up, especially since the average time between work orders is three days.

The key concern regarding equipment is how necessary it is to effectively and efficiently complete maintenance tasks. Currently, more resources have been allocated toward corrective maintenance techniques. This means that heavy equipment is needed more frequently to accomplish overlays, level ups, and other large distresses. For instance, though the milling machine is prone to needing repair, it is used for overlays, level ups, and base failures. Without a milling machine, many of the distresses would be much more difficult to fix. While rentals have been used in emergency situations if a piece of equipment cannot function, it would ultimately be less efficient with the flexibility needed for street maintenance. Sometimes equipment is not needed for a particular maintenance activity, but when needed it should be available. Given the frequent necessity of heavy equipment with the current maintenance strategy, a more effective option would be to have a dedicated mechanic for heavy equipment or greater compensation for mechanics with more skill and expertise to ensure that equipment is being repaired quickly and thoroughly.

Recommendation: If the City chooses to retain its current maintenance strategy, it should consider increasing funding and instituting skill-based pay for mechanics.

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[11] The two different work orders (12672 and 12757) were identified as covering the same stretch of road and having the same maintenance work being done.

City Streets Could Be Impacted by Policy Considerations

During our audit we identified several street infrastructure policy related issues that could have a significant impact on the long-term effectiveness of the street maintenance program. These issues include (1) the reliability of the pavement condition analysis report for scheduling purposes, (2) a shift in maintenance techniques, (3) street construction standards, and (4) constraints in current funding for street maintenance.

Effectiveness of Pavement Condition Analysis Reports is Uncertain

Each year, the City contracts an engineering firm to conduct data collection and analysis on the conditions of city streets – the Pavement Condition Analysis report. The firm assigns each segment of road a score based on the number of distresses present which in turn is input into an algorithm to determine what type of maintenance should be carried out and when. The firm then recommends a three-year plan for maintenance and rehabilitation, based on estimated deterioration rates from current distresses.

In an effort to ensure an unbiased report, the City hired an outside engineering firm to conduct the pavement condition analysis. Prior to 2012, the City used in-house personnel to annually evaluate street conditions and recommend appropriate maintenance for the year. The shift to using an independent engineering firm for analysis was motivated by a desire for impartiality regarding street maintenance performance and funding estimates. The first engineering firm to conduct the pavement condition analysis only did so in 2012 before the City decided to utilize a different firm for the 2013 and 2014 reports due to questions regarding the quality of the report.

The Pavement Condition Analysis report is used only as an aide, not as a comprehensive pavement management plan that can contribute to operational scheduling. This aligns with the Pavement Condition Analysis report data, which only gives the year in which it believes the maintenance should be conducted, not an actual timetable within those years. Management stated that it usually sends a Streets employee to look over the streets to check if the Pavement Condition Analysis report gave an accurate recommendation for the road before the division begins maintenance work. When we assessed street conditions on site, we determined that sometimes recommendations were not appropriate for given street segments, supporting the necessity of street condition review by the division. The actual scheduling of street maintenance is done by management and is decided based on which job seems most pressing. The report does not seem to offer a logical long term pavement management plan that could be appropriately scheduled given the shifting yearly estimates that are stated in the report or the amount of revision necessary to meet the City's desired level of quality. This year, data collection and report finalization occurred between October 2014 and May 2015, indicating that an annual report may be unnecessary. It was noted that the report did not offer consistency in strategy and consistency in year for adjacent street segments on a year by year basis.

However, the Pavement Condition Analysis report is useful for giving a general idea about expected deterioration and current street conditions during the three-year estimation period, which can contribute to scheduling and development of the annual work plan. Hiring an outside engineering firm to develop a roadway condition analysis is helpful in three major ways: (1) as a method of independently evaluating street crew's performance in maintaining city streets, (2) as a means to assess overall street conditions, and (3) estimating funding needed to maintain the City's roadways. For these reasons, we recommend that an engineering firm still be hired to provide a roadway condition analysis to mainly be used as a strategic document to assess street maintenance performance and funding needs for upper level management and policy makers. Contracting with an outside firm to conduct this work on an annual basis, however, may not be warranted.

Research into an alternative possibility for creating an unbiased record of pavement conditions is currently being done. There is the possibility of using a DTS mobile asset collection vehicle for in-house data collection and analysis. This may address concerns for both the scheduling component of the report and the necessity for an impartial assessment of street conditions.

Recommendation: Consider only having an engineering firm conduct a Pavement Condition Analysis every three years and in-house in years in between. As an option to maintain the highest level of objectivity, the City should continue to investigate using a DTS mobile asset vehicle for in-house data collection and analysis.

The City Should Consider Modifying its Use of Contractors

Contractors are used by the City to complete major projects, assist on overlays, and conduct preventative maintenance like crack sealing. However, one of the large benefits of contractors is related to the effect of weather on street maintenance work and increased schedule flexibility.

Street maintenance is unique because the weather has a large impact on how much work can be completed depending on seasonal changes and unexpected weather events. For instance, the large amounts of rain in June of 2015 meant that maintenance involving asphalt could not be conducted until the roads had dried sufficiently. Rain stronger than a slight drizzle means that the asphalt plant closes and therefore repairs requiring asphalt cannot be performed. In addition, when water is present in the road while asphalt is being laid, asphalt will not properly adhere to the surface and the road is more likely to experience major flaws and distresses more quickly. Asphalt also should not be lain when the temperature are less than 40-50 degrees so temperature fluctuations must be taken into account.

The use of contractors gives the Streets Division more flexibility, allows for more variability in workload, and assists when there are unforeseen circumstances that can affect scheduled maintenance. Weather, vacant positions, broken-down equipment, and injured personnel can all disrupt maintenance. Generally, street crews repair any failures or distresses in preparation for overlays and then contractors conduct the actual overlay. Crew members perform overlays but generally only for shorter street segments. The Streets Division does not have enough resources to complete all desired street maintenance in-house. Therefore, contractors are essential for completing scheduled maintenance tasks. The City should consider letting contractors take over millings and overlays completely due to the technical and expense costs that come with using and maintaining the necessary equipment, plus the amount of time and cost that overlays require. This system has been implemented by peer cities like Bryan and Sugar Land, though it should be noted that Sugar Land's roadways are primarily concrete.

However, we acknowledge that flexibility is an important and necessary part of street maintenance and that contractors, while important contributors, are limited by the amount of work required of them by multiple customers. While there are certain years when contractors may be able to carry the workload associated with the amount of overlays the City requires, there may be times when they cannot, limiting their usefulness as an asset to schedule flexibility. Therefore, there may be circumstances where city staff performing overlays is justified. This requires the use of equipment that is necessary for those tasks, such as the milling machine and paver. The Streets Division should retain the capability to do overlays in these circumstances, but overlays should not be the primary maintenance technique. Instead, preventative techniques should be the heart of a long-term street maintenance program.

Recommendation: The City may want to consider allowing contractors to take over a larger percentage of milling and overlay projects. Doing so would allow the Streets Division to reallocate in-house activities to do more preventative maintenance.

Being Responsive to Citizen Complaints Comes at a Cost

Preventive maintenance is usually the first priority when implementing a planned pavement maintenance program and provides the highest return on investment for pavements. In a 2008 report the City contracted to analyze whether changing pavement thickness in College Station would be a feasible choice, emphasis was put on the importance of a preventative maintenance plan for the City. Preventive maintenance consists of both localized maintenance (e.g. crack and joint sealing and patching) and global maintenance (e.g. surface sealing). The 2013 Pavement Condition Analysis Report also focused on preventative maintenance, stating that preventative maintenance was treated as the highest priority in decision tree calculations, with all crack seal, patching, and chip seal assigned first in order to prevent further degradation of pavement as much as possible.

Chip sealing and crack sealing are two cost-effective techniques that the City has historically used to extend the useful life of its roadways. Prior to 2010, chip seal was a useful method used to seal cracked roadways. However, chip sealing in non-rural roads was discontinued over five years ago due to citizens' complaints concerning texture and appearance. This led to a focus on crack sealing as the next best cost-effective preventative maintenance measure. But recently, the amount of crack sealing has decreased significantly in reaction to further citizen complaints over the aesthetic look of crack sealed streets. This has led to an increase in overlays and level ups. Meanwhile, Public Works has been exploring alternative preventative maintenance methods in order to find the most cost-effective approach that will satisfy citizens' desires for an aesthetically pleasing street.

Between March 2013 and July 2015 some crack sealing was performed by outside contractors, but at levels below previous crack sealing or chip sealing efforts We examined work order data from the 29 months after this shift and compared it to the previous 38 months (Jan 2010 – Feb 2013) when crack sealing was performed in-house. We found that average maintenance costs and labor hours were greater while the number of work orders completed decreased during the months when crack sealing wasn't performed in-house (see Table 5 below).

Table 5: Comparison of Before and After Crack Sealing in-house Suspension

Crack sealing Suspension	**Avg. Cost per Month**	**Avg. Hrs. per Month**	**Avg. Number of WO Complete per Month**
Before	$83,407.42	1,407.4	37
After	$87,355.59	1,471.6	31
Crack sealing Suspension	**Avg. Cost per Year**	**Avg. Hrs. per Year**	**Avg. Number of WO Complete per Year**
Before	$1,000,889.14	16,888.5	447
After	$1,048,267.09	17,659.7	372

Overlays and other corrective techniques are more costly and labor intensive. After analyzing work order data from the past five years, we found crack sealing to be the least expensive maintenance method and overlays to be the most expensive. A breakdown of the cost of each maintenance type is described in Table 6 on the next page.

Table 6: Costs per Maintenance Type (2010 – 2015)

Work Type	Avg. Hrs. per WO	Avg. Cost per Hr.	Avg. Materials Cost per Hr.
Crackseal	23.08	$12.47	$1.96
Sealcoat	24.00	$15.83	$3.53
Potholes	19.20	$20.98	$8.76
Failures	59.01	$55.55	$45.13
Level Up	54.59	$81.30	$68.70
Overlay	83.77	$96.24	$83.09

Crack sealing and seal coating are preventative maintenance techniques while failure repair, pothole repair, overlays and level ups are all considered restructuring or repaving techniques, or corrective maintenance. Given the above costs, it was determined that the overall costs based on average cost per hour and average materials cost per hour for preventative techniques versus corrective techniques are as follows:

Table 7: Costs per Maintenance Technique

Maintenance Technique	Weighted Avg. Cost per Hr.	Weighted Avg. Materials Cost per Hr.
Preventative (Crackseal and Seal Coat)	$12.50	$1.98
Corrective (Failures, Level Up, Potholes, and Overlays)	$161.06	$49.65

Overall, the corrective techniques that the City uses are over thirteen times more expensive in total cost and almost twenty-five times more expensive in materials cost than preventative techniques.

In addition to the considerations of cost, preventative maintenance seems to ensure that streets remain in better condition for a longer amount of time, lengthening the useful life of the road before more expensive corrective measures need to be taken. Street segments that have experienced crack sealing in the last five years had on average 91.5 pavement score out of 100, while assets that had not been crack sealed had an 87.9 pavement score. The average for all assets was about 88.3.

In summary, the Streets Division implemented a fiscally prudent strategy of chip sealing or crack sealing roads as pavements begin to exhibit signs of distress[12] in order to extend street useful life prior to the need of more expensive corrective measures. In a desire to be more responsive to citizen complaints, street maintenance resources were shifted from the preventative maintenance methods of chip sealing and crack sealing to

[12] See Figure 3 on page 8 of this report.

corrective maintenance techniques such as mills and overlays. Consequently, being responsive to citizen complaints over the aesthetic or texture of streets has resulted in a less cost-effective approach to street maintenance.

The decisions to halt chip (for non-rural roads) and reduce crack sealing due to citizen complaints, especially when those complaints are driven by aesthetic reasons, should be reevaluated moving forward. If there is investigation into new techniques for possible future use, it should occur parallel to ongoing preventative maintenance strategies. The possibility of a concrete alternative for streets will be addressed in the next sections.

Recommendation: Reallocate more resources for preventative maintenance techniques, such as crack sealing, chip sealing (or other comparable techniques) for asphalt roads.

Strengthening Development Standards Would Lead to Longer Useful Lives

In addition to city-built streets are those that are constructed by developers, primarily in residential areas. The City has a growing number of development projects due to the continuous influx of new residents.

Due to the nature of the development business, developers do not have strong incentives to build streets beyond the lowest possible standards. Developers are driven by profit first and foremost. Therefore, the development community is likely to contest increased costs of production or added building requirements set forth by the City. Given that developers currently build most local streets and minor collectors, the standards they must reach are important for ensuring that streets can meet the full range of their useful life.

There are two enforcement mechanisms in place to try and ensure that developers adhere to the standards set forth by the Bryan-College Station Unified Guidelines. The first of these mechanisms is the warranty, which lasts for one year from the completion and approval of the road. After that period of time, the Streets Division takes over maintenance of the road. However, a year-long warranty is a short amount of time to recognize flaws in a street and any underlying faults that can cause major problems shortly after that warranty period will then be handled by the City. An example of a developer-built residential road that was not built to standards is Baker Meadow Loop in the

Figure 8: Baker Meadow Alligator Cracking

Creek Meadows subdivision, which is a year old and has already developed severe alligator cracking and other obvious distresses.

Possible reasons why this may have occurred are poor quality construction (subgrade not being installed properly), poor quality material (asphalt with shingles and wrap rather than pure emulsion and aggregates), and poor workmanship. This road in particular demonstrates that the warranty system may not be an effective deterrent for subpar street construction, especially as in this case the developer will be repairing the road after construction is completed.

The second enforcement mechanism is the city inspection process. This process, while thorough, is not without the possibility of fraud or deceit. There are only four inspectors for a large number of projects occurring within the City. Inspectors do not take samples or test materials themselves. Instead this process is contracted out to labs, who, then send the results to the inspectors with the data showing whether the developers have passed or failed the required tests. Therefore, inspectors are not required to go out to sites, although we were told and observed that most inspectors choose to do so in order to verify the numbers and processes that the lab technicians are conducting on site. There have also been instances in which inspectors said that a street did not meet requirements but were instructed to pass the street anyway, despite it not meeting standards. This constitutes a flaw in the effectiveness and objectiveness of the inspection process. These weaknesses in the inspection mechanism can exacerbate the possibility of poor construction and existing flaws in development standards.

In addition, when developers build roads that are residential, the City provides them with specifications for those types of roads without considering traffic load. During the first few years of the road's life it experiences a traffic load that is much greater than a normal residential street because of continuing development in the subdivision. Concrete trucks, dump trucks, and other heavy equipment put increased pressure on the road and cause shifting underneath the pavement, leading to abnormal rates of distress. Baker Meadow Loop's condition could be exacerbated by this problem, as we watched a heavy construction truck coming onto the street during our fieldwork. Recently a consultant evaluated how asphalt and concrete support different traffic loads in College Station and what the ideal thickness of road building materials would be to ensure that streets perform as long as they should and as well as they should. This Flexible and Rigid Pavements report, located in Appendix C, noted that traffic loads are key in understanding how long a street may last and how well it is likely to perform, mentioning in particular the construction trucks that travel down residential roads during development. The current specifications then do not seem appropriate for the type of loads that the streets are bearing, especially in development areas.

Increasing pavement thickness and requiring more virgin materials in construction could increase the useful life of the road in residential and collector areas.[13] Given the recent report submitted to the City, there are clear changes that have been suggested and could function as a starting point for creating new standards. However, updating the Bryan-College Station Unified Guidelines is done with collaboration from community developers and the City of Bryan, which may make raising standards difficult for the City of College Station.

Recommendation: Consider raising standards of street construction for residential streets.

Concrete Roads Can Reduce Maintenance Costs and Increase Useful Life

The City of College Station currently maintains 310 miles of roads, of which 87 percent are paved in asphalt and 12.5 percent are concrete. The different classifications of streets from lightest traffic load to heaviest are local/residential streets, minor collectors, major collectors, minor arterials, and major arterials. The different types of pavement and street classifications require different maintenance and development standards. Therefore, the way in which the City decides to build and maintain its streets has a direct impact on whether a certain street type is more or less effective. The City almost exclusively uses concrete in capital improvement projects unless there are extenuating circumstances that require the use of asphalt. Conversely, developers generally use asphalt for road construction in residential areas and for collectors as part of development projects.

While initial costs of concrete street construction are higher than comparable asphalt street construction, in the long-run total concrete maintenance costs may be less than asphalt. An analysis conducted by the Public Works Department found that, in capital improvement project bids, average asphalt costs were $36.00 per square yard and average concrete costs were $42.00 per square yard—approximately 15 to 25 percent higher than asphalt. However, the maintenance required for concrete streets is much less extensive. The Flexible and Rigid Pavements report found that concrete streets can support more heavy traffic loads for a longer amount of time and that the building material requirements for streets to meet their potential is less for concrete than for asphalt. This supports analysis conducted by the City that has found that vehicles with heavier loads like buses and dump trucks have a larger impact on street conditions and cause more distress. Where concrete becomes more expensive than asphalt is when reconstruction must be done. Once a concrete slab has been injured beyond the point of joint and crack sealing, the entirety of the slab must be removed to replace. However, the useful life of a concrete street (40 years) is much longer than an asphalt street (20 –

[13] Current standards can be found the Bryan-College Station Unified Guidelines.

25 years) so it may be more cost effective in the long run to build concrete streets rather than asphalt.

Collectors and arterials see the most traffic loads and therefore constructing them in concrete would be the most cost effective option so as to require less maintenance than asphalt would need. However, developers currently build many of the minor collectors in College Station. Given that concrete reconstruction costs are very extensive and expensive, and given that developers do not have incentive to construct streets to the highest standard, the City should consider building streets that are classified as minor collector or higher. The City has greater incentive to ensure that concrete streets are built up to standards, which means that the street should be less likely to fail and have a greater useful life. There are three funding options for implementing this strategy: (1) the City pays for all of the project, (2) a portion of the project is paid for by developers and a portion paid by the City, or (3) the developers pay for the whole project through a fee.

In addition, concrete offers a more uniform appearance and is more pleasing to the eye. This reason was cited in the majority of cities that we interviewed for peer comparisons. Citizen complaints about aesthetics also appear to be a driving force in policy decisions concerning street maintenance. However, such a decision to convert to concrete would be a long-term venture rather than one exclusively dealing with street maintenance. Such a decision will also have implications for the overall purpose of the Streets Division and street maintenance program.

Recommendation: Consider having the City build arterials and collectors in concrete. Conduct further research into a long-term shift to concrete streets.

A Dedicated Maintenance Fund Would Grant Greater Flexibility

Given the seasonal and unpredictable nature of street maintenance work, a separate fund with rollover capability should be created for the Streets Division. Currently the Streets Division is under the General Fund and therefore must use all their money by October 1st because it does not roll over into the next fiscal year. However, weather patterns during the year can derail the street maintenance schedule and therefore impact the ability of the Streets Division to use the allotted funds despite the need to still complete scheduled maintenance. Because zero-based budget system creates incentives for money to be spent in its entirety prior to year-end regardless if it makes sense to do so, a better option could be to create a fund that is dedicated to street maintenance. Doing so would allow the money for maintenance and repair to roll over each fiscal year as needed for Streets projects.

One possible option for funding is to institute a transportation fee in College Station similar to a drainage/utility fee. The fee for transportation could be used for maintenance every year and put into a Streets Maintenance Fund rather than relying only on the General Fund. The City of Bryan has instituted a fee for street maintenance called a Transportation fee. The fund is used to help prolong the life of city infrastructure and assets. By managing and maintaining public right of way infrastructure, the City of College Station would be able to save taxpayer money by intervening before full reconstruction is needed. Full street reconstruction can be costly and time-consuming, therefore maintenance financed by the fee could help reduce these costs.

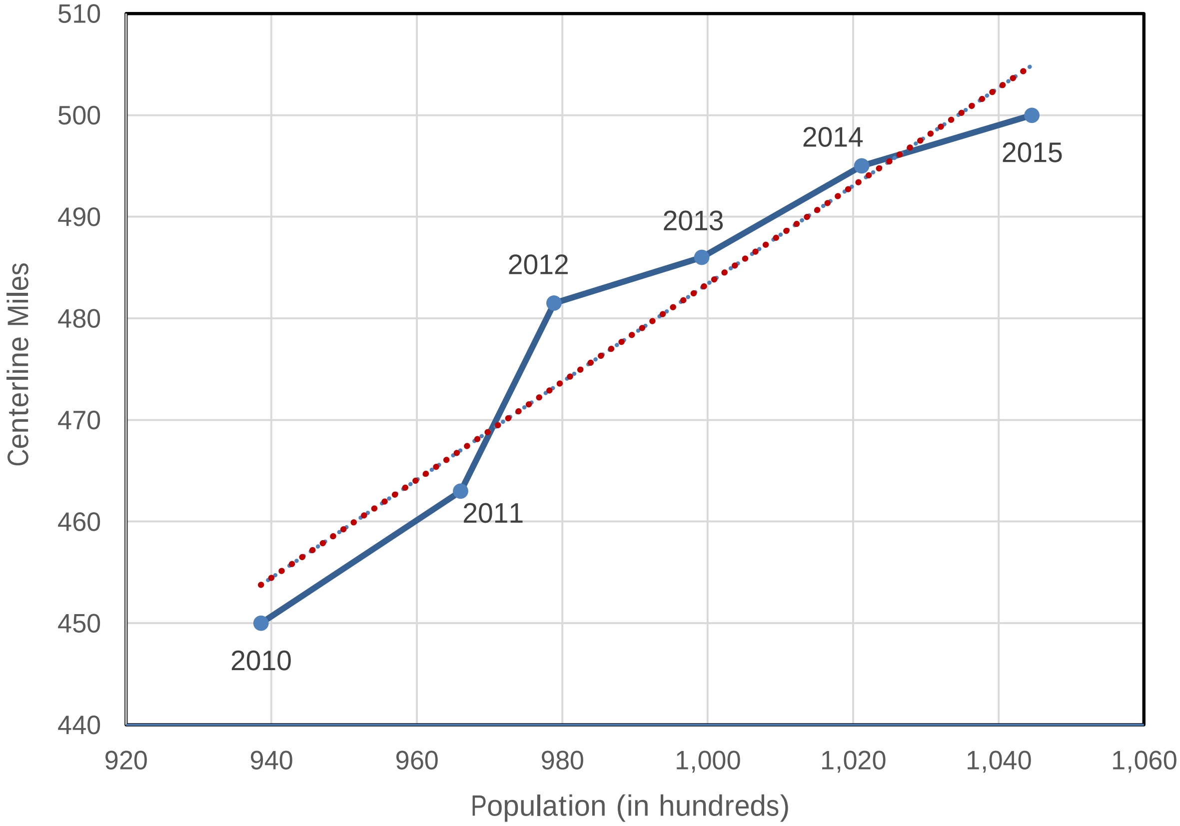
Recommendation: Create a dedicated street maintenance fund

Summary of Audit Recommendations

The City of College Station is growing. The population has dramatically increased over the past two and a half decades, growing by almost three percent each year, and growth will likely continue.

In the future there will be more streets that will need substantial maintenance. The past five years has seen a consistent increase in centerline miles in the City, more of which are then being turned over to the City for maintenance and upkeep. Fifty centerline miles in five years is substantial.

Figure 9: Relationship between Centerline Miles and Population (2010-2015)



Maintaining the current street infrastructure and ensuring it does not deteriorate is important for the City, especially given the expanding population. The City is at a critical juncture regarding the creation of a long-term strategy for handling the inevitable wear and tear of city roads. The following recommendations are to help the City's street maintenance program function more effectively and efficiently and to address policy issues that affect city streets' useful life going forward.

(1) **Reinstitute skill-based pay for heavy equipment operators.** Skill-based pay at the heavy equipment operator level will motivate workers who begin in the light equipment operator level to learn the skills necessary to advance as quickly as possible. This would increase efficiency as more workers would have more skills, and low performers could be more easily distinguished from high performers. Skill-based pay would also address some of the issues causing higher turnover, such as feeling undervalued and lack of advancement.

    Though we recommend skill-based pay, we also limit this recommendation to the heavy equipment operator position, not the light equipment operator position. This is because (1) it creates extra motivation for light equipment operators to gain the skills necessary to become heavy equipment operators, and (2) limiting skill-based pay to heavy equipment operators reduces the likelihood of system abuse.

(2) **If the City chooses to maintain its current maintenance program strategy, it should consider increasing funding and reinstituting skill-based pay for mechanics**. Equipment is a key factor in maintaining City streets. If equipment is in the shop for significant amounts of time it can have a negative impact on street maintenance productivity. Therefore, having mechanics that are skilled at repairing the heavy equipment the Streets Division requires will be a necessity. Skill-based pay may be a way to do this. In the long-term, if the City maintains its current strategy, it may want to consider hiring on a full-time mechanic to handle heavy equipment for the Streets Division.

(3) **Consider only having an engineering firm conduct a Pavement Condition Analysis every three years and in-house in years in between.** As an option to maintain the highest level of objectivity, the City should continue to investigate using a DTS mobile asset vehicle for in-house data collection and analysis. A pavement condition analysis conducted by a contractor allows for outside expertise and has a certain amount of value. However, we believe that this analysis need not be conducted by a contractor every year, as it is more useful as a strategic document (assessing the above conditions) than a planning document (directing the Streets Division maintenance schedule day-to-day). In-house data collection and analysis in the intervening years should be sufficient for understanding street conditions.

(4) **The City may want to consider allowing contractors to take over a larger percentage of milling and overlay projects. Doing so would allow the Streets Division to reallocate in-house activities to do more preventative maintenance.** A redirection towards preventative maintenance will help the Streets Maintenance Division save money in the long-run through prolonging streets' useful life and materials cost. The money that is saved could be reallocated to help pay for the increase in contractor work. However, this redirection does not warrant a

downsize in staffing levels or equipment as the streets crews may still need to do occasional overlays and much of the equipment needed for overlaying is also needed for other maintenance techniques.

(5) **Reallocate more resources for preventative maintenance techniques, such as crack sealing, chip sealing (or other comparable techniques) for asphalt roads.** While there have been citizen complaints that led to the current lack of preventative techniques, the City should not let public pressure result in poor street maintenance strategies. Preventative techniques also extend the useful life of streets and keep them in a better condition for a longer amount of time. If there is investigation into new techniques for possible future use, it should occur parallel to ongoing preventative maintenance strategies.

(6) **Consider raising standards of street construction for residential streets.** Because of continuing development, many developer-built streets in residential areas experience unusually high strain for a number of years after being constructed. There are also opportunities for developers to cut corners in building streets with few consequences. Raising the standards for these streets to adjust to actual traffic usage could help to solve this problem and save money in the long run because these streets would need less maintenance. However, a raise in standards might upset the development community whose focus is on keeping costs low.

(7) **Conduct further research into a long-term switch to concrete streets.** Though this would cost more initially, the reduction in necessary maintenance would likely make up the cost over the useful life of the street. However, it is important that concrete streets are constructed correctly, otherwise maintenance costs could be much larger than if the street had been asphalt. Formulating a long-term plan could include the City taking on the majority of minor collectors rather than having developers build them and constructing more streets in concrete on a citywide level.

(8) **Create a dedicated fund for street maintenance.** A dedicated fund for street maintenance would help to save money from year to year as it could roll over and would allow the streets management greater flexibility on an annual basis. The inherent fluctuations that come with weather, contractor supply, and unforeseen events requires a more flexible method of funding. Creation of this fund would also be helped by instituting a transportation fee that is assessed to residents like the drainage/utility fee. This fee would help pay for street maintenance, which could also help balance the City's budget.

Appendix A: Skill-based Pay Methodology

Skill based pay is one of the most widely-implemented, poorly understood, and under-researched organizational practices. In implementing skill-based pay for specific types of positions in the City of College Station, a system must be put in place to ensure that positions with skill-based pay meet certain criteria. Ultimately, skill-based pay must assist in furthering productivity and efficiency of the department in pursuit of the department's goals. For this reason, some basic requirements must be met.

Positions Eligible for Skill-based Pay:

1. Entry-level positions
2. Job requires a wide depth/breadth of skills to be performed effectively (flexibility in tasks done for positions)
3. Skills increase self-management capability
4. Non-clerical/non-exempt positions
5. Hourly positions

The goals of a skill-based pay system are to reward an appropriate balance between employee flexibility through skill breadth (the ability to do different jobs in the organization); skill depth; and self-management skills, all of which are critical in system with supervisors. The jobs that fall into this category typically require higher skills, flexibility to do different jobs, the ability to work without close supervision, and a high level of training. Employees must understand the overall production or service delivery process and respond quickly when problems arise. None of this is possible if employees know only one job and therefore one small part of the overall process. To implement skill-based pay (SBP), the following steps must be taken:

1. **Identify Positions:** Identify potential SBP jobs; that is, a job in which development of skill depth and/or breadth is possible and desirable.
2. **Define Skills:** For each job level, identify the specific skills (both depth and breadth) sought. It is encouraged that employees be included in the skill identification process as well as which skills are more difficult to master. Each skill on the plan must be directly applicable to job performance.
3. **Determine Benefits:** Evaluate the potential costs and benefits of the SBP plan (these are discussed below); proceed with further consideration of the SPB plan only if the likely benefits outweigh the costs for the organization.
4. **Develop Assessment:** Develop the appropriate techniques that will be used to assess the new skills, knowledge and competencies gained and/or developed.
5. **Establish Standards:** Establish certification standards and processes for employees to demonstrate their successful skill acquisition. This can be manifested as different skill bands.
6. **Specify Payment System:** Determine the dollar amount or pay percentage of SBP for the acquired skills, such as indicating the payout for each skill block.

One city department previously utilized skill-based pay for a specific set of its employees. Its policy is given below. **Per the opinion of the audit department, the above guidelines,**

indicated in bold, are met through the procedures below. While this exact policy may not be appropriate for every department, it is an adequate example of a skill-based pay system.

Example – Water Utilities Department

1. Purpose of Skill Band Pay (SBP) system (**Determine Benefits, Identify Positions**[14])
    a. Incentivize training in job skills to maximize the value of our Employees
    b. Determines skills and experience for employees rate of pay
    c. Communicates professional development and advancement roadmap
    d. Pay raises up to Midpoint based on achieving an established set of skills/competencies
    e. Possible for employee to reach Midpoint in 3 years
        i. Can be less, only if they start above Entry level pay
    f. Applies to certain specifically designated Non-Exempt, Non-Clerical positions
    g. Applies to new hires or employees promoted/transferred into a Skill Band position
2. Structure of Skill Band system (**Define Skills, Establish Standards**)
    a. List of Skill Band positions, and any future changes, will be approved by DCM
    b. Skill sets required to achieve each Skill Band level will be approved by Department Director
        i. Each Skill on the plan must be directly applicable to job performance
        ii. Any substitutions or changes must have written approval of Dept Director
        iii. Achievement of each Skill must be signed off by Crew Leader or Supervisor
        iv. Completion of a Skill Band requires Supervisor through Director approval
    c. Two acceptable breakdowns of Skill Levels:
        i. 6 Skill Levels total; can earn max of 2 per year
        ii. 3 Skill Levels total; can earn max of 1 per year
        iii. Year is defined to start at hire date (or promotion date)
3. Administration of Skill Band pay (**Specify Payment System**)
    a. Newly hired (or promoted/transferred) employee starts at Entry level pay
        i. Existing skills or experience may justify starting at a certain Skill Band Level
    b. Eligibility starts when Probationary period is complete
    c. Upon completing all Skill Bands, at Midpoint, employee shifts to Merit Pay system
    d. Department Directors will manage their budget for pay increases to be certain that Skill Band pay increases are funded.
    e. If Budget dictates no funding for any pay increases, the Skill Band raises earned will be deferred until funds are available, but not paid retroactively.
    f. Employees shall be eligible for additional City-wide pay increases regardless the date of any SBP increase
    g. Employees who complete all their Skill Bands and transition to Merit Pay shall be eligible for Merit Pay increases regardless of the date of SBP increases.

[14] Guidelines the Audit Department feel are met by this section.

To be consistent throughout the Water Services Department the following process is being implemented to establish a standard for an employee to ensure timely review and/or approval of their skill bands. (**Develop Assessment, Establish Standards**)

1. The employee will email their supervisor requesting the supervisor review the required skills documentation that was given to them and schedule a date and time within 5 working days from the date the email was sent to review and demonstrate the skill if needed.
2. If the supervisor does not schedule a review, and demonstration if required, the employee will resend the email to their supervisor and copy the supervisor's superintendent or manager.
3. The supervisor must schedule a review, and demonstration if required, within 3 working days from the date the email was resent.
4. If the supervisor does not schedule a review, and demonstration of the skill if required, within 3 days the employee will resend the email and copy the supervisor's superintendent or manager and the assistant director. The superintendent or manager shall schedule a review, and demonstration if required, within 2 days of the date the email was resent.

The above four steps ensure that an employee's request, that will potentially impact their rate of pay is handled in ten working days from the initial request.

If the superintendent or manager has to be copied because of inaction by the supervisor a copy of the emails shall be placed in the supervisor's file and be considered during their next evaluation.

If the assistant director has to be copied because of inaction by the supervisor and superintendent or manager a copy of the emails shall be placed in all of their files and be considered during their next evaluation and a verbal warning be given to each.

Appendix B: Management's Responses to the Audit Recommendations

The following is the Public Works Department's response to the recommendations made in the City Internal Auditor's Office Street Maintenance Audit. Each of the eight recommendations includes a response describing how the recommendation will be addressed by the Public Works Department.

1. Audit Recommendation

Reinstitute skill-based pay for heavy equipment operators.

Management Response

Management concurs with this recommendation and will work with the City Manager and the Human Resources Director to reinstitute skill-based pay for heavy equipment operators.

2. Audit Recommendation

If the City chooses to maintain its current maintenance program strategy, it should consider increasing funding and reinstituting skill-based pay for mechanics.

Management Response

Management concurs with this recommendation and will work with the City Manager and the Human Resources Director to reinstitute skill-based pay for mechanics.

3. Audit Recommendation

Consider only having an engineering firm conduct a Pavement Condition Analysis every three years and in-house in years in between.

Management Response

Management concurs with this recommendation. For clarification, in-house analysis would not preclude data collection and reporting from a contractor in lieu of utilizing Public Works personnel.

4. Audit Recommendation

The City may want to consider allowing contractors to take over a larger percentage of milling and overlay projects. Doing so would allow the Streets Division to reallocate in-house activities to do more preventative maintenance.

Management Response

Management concurs with this recommendation and will increase the percentage of contracted milling and overlay projects.

5. Audit Recommendation

Reallocate more resources for preventative maintenance techniques, such as crack sealing, chip sealing (or other comparable techniques) for asphalt roads.

Management Response

Management concurs with this recommendation and will work with the City Manager to increase preventative maintenance techniques that will extend the useful service life of the roadway and meet citizen expectations.

6. Audit Recommendation

Consider raising standards of street construction for residential streets.

Management Response

Management concurs with this recommendation and will work with the City Manager and the Planning and Development Services Director to study increasing the design standards for residential streets.

7. Audit Recommendation

Conduct further research into a long-term switch to concrete streets.

Management Response

Management concurs with this recommendation and will work with the City Manager and the Planning and Development Services Director to study requiring concrete streets.

8. Audit Recommendation

Create a dedicated fund for street maintenance.

Management Response

Management concurs with this recommendation and will work with the City Manager to create a dedicated street maintenance fund that would roll over unexpended funds from year to year.

Appendix C: Flexible and Rigid Pavements Report

September 24, 2015

City of College Station
P.O. Box 9960
College Station, Texas 77842

Attention: Mr. James Smith, P.E., City of College Station Public Works Department

Re: Report of Limited Analysis of Flexible and Rigid Pavements
City of College Station, Brazos County, Texas
CME Project Number: 55143
Texas Board of Professional Engineers Firm Registration Number: F-1068

Dear Mr. Smith:

CME Testing and Engineering, Inc. (CME) is pleased to submit to the City of College Station (City) this report of a limited analysis of flexible and rigid pavements.

This letter transmits one (1) electronic copy in pdf format of the report that is entitled "Report of Limited Analysis of Flexible and Rigid Pavements; City of College Station, Brazos County, Texas."

The limited analysis was performed in accordance with our proposal to the City that was dated August 12, 2015, and was transmitted to Mr. James Smith, P.E., of the City, on the same date. The proposal was accepted following the issuance of a purchase order that was dated September 2, 2015, and was received by CME via the United States Postal Service on September 11, 2015.

The accompanying report focuses on two (2) primary objectives which can be described as follows: (1) the evaluation of existing minimum flexible and rigid pavement sections outlined in the *2012 Bryan/College Station Unified Design Guidelines for Streets and Alleys* (BCSUDGSA) for residential roadways and minor collector based on variable subgrade stiffnesses or strengths and (2) performing a limited analysis of various flexible and rigid pavement sections based on the following factors: (a) variable traffic frequencies that are typical of the roadway classifications outlined in Table V – *Street Classification Definitions* of the BCSUDGSA, i.e. residential roadways, minor collectors, major collectors, minor arterials, and major arterials; (b) variable percentages of truck traffic that could be considered typical for each roadway classification, i.e. 2 percent, 4 percent, and 6 percent; (c) variable design periods or analysis periods, i.e. 10 years, 20 years, 30 years, and 40 years; and (d) a single subgrade soil stiffness or strength that is considered representative of the predominately cohesive subgrade soils, i.e. clays, typically encountered in the College Station area. The limited analysis was performed utilizing the design methods outlined in the 1993 American Association of State Highway and Transportation Officials (AASHTO) for flexible and rigid pavement sections.

The limited analysis presented in the accompanying report focuses predominately on the following types of pavement materials (with the assumption that the pavement sections are constructed on a subgrade that can be characterized as having an effective California Bearing Ratio value of 5): (1) flexible pavement sections consisting of a surface course of hot-mix asphalt concrete, a flexible base course of crushed limestone, and a subgrade that is chemically stabilized and (2) rigid pavement sections consisting of a surface course of Portland cement concrete (PCC) and a chemically stabilized subgrade. However, computations performed as part of the evaluation of existing minimum flexible pavement sections outlined in the BCSUDGSA for residential roadways and minor collectors also included flexible pavement sections with a cement stabilized base course. In addition, the evaluation of existing minimum flexible and rigid pavement sections also considered the pavement sections being founded on a very weak subgrade soil that exhibited an effective CBR of 3. The results of this limited analysis are presented in the accompanying report for your review and consideration.

CME sincerely appreciate the opportunity to have performed this work for the City of College Station and look forward to continuing our working relationship in the future. Please do not hesitate to contact us at (979) 690-3600 if you have any questions or need additional information concerning this matter.

Sincerely,
CME TESTING AND ENGINEERING, INC.

M. Frederick Conlin, Jr.

M. Frederick Conlin, Jr. P.E.
Senior Engineer

GTS:MFC:ts

REPORT OF LIMITED ANALYSIS OF
FLEXIBLE AND RIGID PAVEMENTS
CITY OF COLLEGE STATION, BRAZOS COUNTY, TEXAS

Prepared for

The City of College Station
P.O. Box 9960
College Station, Texas 78842

Prepared by

CME Testing and Engineering, Inc.
320 Graham Road
College Station, Texas 77845
Texas Board of Professional Engineers Registration Number: F-1068
CME Project No. 55139

September 24, 2015

M. Frederick Conlin, Jr., P.E.
Senior Engineer

Taylor Stinson, E.I.T., M.S.
Project Engineer

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1.0 INTRODUCTION

This report was prepared by CME Testing and Engineering, Inc. (CME) for the City of College Station (City) to document the results of a limited analysis of flexible and rigid pavements.

The limited analysis was performed in accordance with our proposal to the City that was dated August 12, 2015, and was transmitted to Mr. James Smith, P.E., of the City, on the same date. The proposal was accepted following the issuance of a purchase order that was dated September 2, 2015, and was received by CME via the United States Postal Service on September 11, 2015.

The work effort associated with the limited analysis was initiated shortly after CME received the previously referenced purchase order and was completed on September 24, 2015.

A summary the pavement design methodologies utilized to perform the limited analysis, key assumptions made during the limited analysis, the results and conclusions of the limited analysis, and recommendations for future studies and practices that should be considered by the City are presented in this report for your review and consideration.

1.1 PROJECT DESCRIPTION

1.1.1 Sources of Project Information

Information concerning the limited analysis was provided during two (2) meetings that occurred at the City's Department of Public Works offices. The first meeting occurred on June 3, 2015, and was attended by Messrs. Donald Harmon, P.E. and Alan Gibbs, P.E., of the City, and Messrs. Rick Conlin, P.E. and Taylor Stinson, E.I.T., M.S., of CME. The second meeting was conducted on August 3, 2015, and was attended by Messrs. Harmon, Troy Rother, P.E., and James Smith, P.E. of the City, and Messrs. Conlin and Stinson of CME. Additional information pertaining to the limited analysis was obtained in an e-mail communication from Mr. Smith that was dated August 6, 2015.

1.1.2 Understanding of Limited Analysis

Based on the conversations of the previously referenced meeting conducted on June 3, 2015, CME understands that the City is experiencing issues and conflicts related to the existing minimum pavement design thicknesses for flexible and rigid pavement sections which are outlined in the *2012 Bryan/College Station Unified Design Guidelines for Streets and Alleys* (BCSUDGSA) for residential roadways and minor collectors. More specifically, some of the flexible pavement sections designed utilizing the minimum pavement sections outline in the BCSUDGSA are approaching terminal serviceability, i.e. the lowest acceptable serviceability level of a roadway before resurfacing or reconstruction becomes necessary, shortly after construction of the minimum flexible pavement section, and as a result are requiring excessive maintenance. In addition, the City feels there is a discrepancy between the minimum pavement sections outlined for flexible and rigid pavement sections in the BCSUDGSA, e.g. the structural integrity of the flexible pavement section is not comparable to the rigid pavement section. Following the initial conversations of the meeting, CME and the City developed an approach to evaluate design sections of flexible and rigid pavements based on the following factors: (1) traffic frequencies that are typical for various roadway classifications outlined in Table V of the BCSUDGSA, i.e. minor collectors, major collectors, minor arterials, and major arterials; (2) variable percentages of truck traffic that could be considered typical for each roadway classification, i.e. 2 percent, 4 percent, and 6 percent; and (3) variable design periods or analysis periods, i.e. 10 years, 20 years, 30 years, and 40 years.

The second meeting was conducted so that additional employees of the City, i.e. Messrs. Smith and Rother, could voice their options regarding the limited analysis proposed by CME. Based on the conversations of the second meeting and the previously referenced e-mail communication from Mr. Smith, the City requested that an additional traffic frequency be added to the limited analysis so that a typical residential roadway would also be reflected in the analysis. In addition, the City requested for CME to evaluate the existing minimum flexible and rigid pavement sections outlined in the BCSUDGSA for residential roadways and minor collectors.

1.2 OBJECTIVES AND SCOPE OF THE LIMITED ANALYSIS

The specific objectives of the limited analysis were to perform the following:

- Analyze the existing minimum flexible and rigid pavement sections outlined in Table VIII – *Minimum Pavement Thickness Criteria* of the BCSUDGSA for "equivalency". Two effective subgrade stiffnesses or strengths were considered during this evaluation.
- Perform a limited analysis of flexible and rigid pavement sections by evaluating three variable conditions which will include: (1) variations in average daily traffic (ADT); (2) variations in the percentage of trucks that contribute to the ADT; and (3) variations in the analysis period or design period. Stiffness or strength of the subgrade or foundation soils were not varied in this portion of the analysis.
- Evaluate the findings of the limited analysis to determine if any conclusions can be made.
- Based on the finding of the limited analysis and CME's experiences with pavement design in the College Station area, provide recommendations for future studies and/or practices that should be considered by the City.

It should be recognized that the results of the limited analysis are meant to provide examples of variations in design pavement sections based on numerous assumptions which are outlined in subsequent sections of this report. The results of the limited analysis are not meant to be utilized for the design of a specific roadway in the College Station area due to variable soil conditions. Prior to the selection of a final pavement section for a given roadway, numerous variables should be evaluated by a Professional Engineer to ensure that the pavement section is adequate for the roadway under consideration. Some of the influential variables that should be evaluated include the following, among others: (1) anticipated traffic volumes or frequency over the course of the pavements design life or design period; (2) anticipated magnitudes of loading that will occur over the pavements design life, e.g., volume of heavy trucks; (3) the pavement materials utilized to support the anticipated traffic frequency and magnitudes of loading and the reliability of the assumed properties of such materials; (4) drainage conditions along the roadway alignment; and (5) the underlying subgrade soils that will support the pavement section and the anticipated traffic frequency and magnitudes of loading.

1.3 OUTLINE OF REPORT

Section 2.0 of the report presents an overview of flexible and rigid pavement sections and the design methodologies utilized to perform the limited analysis. In addition, Section 2.0 discusses some of the variables that are considered to significantly impact the required thickness of a flexible or rigid pavement section based on the design guidelines selected for the limited analysis of flexible and rigid pavements.

Section 3.0 presents the results of the evaluation of the existing minimum pavement sections outlined in the BCSUDGSA for residential roadways and minor collectors. Assumptions made for the evaluation are outlined and the results are present in terms of the maximum allowable traffic “capacity” or maximum allowable equivalent single-axle loads (ESALs) of each type of pavement section. In addition, an extended evaluation is performed to estimate the theoretical design life of the minimum pavement sections based on CME’s various design assumptions. The minimum pavement sections are evaluated based on two effective subgrade stiffnesses or strength that could be considered typical of the cohesive soils, i.e. clays, prominent in the College Station area.

Section 4.0 presents the assumptions that were developed by CME, with assistance from the City, to perform the limited analysis of flexible and rigid pavements based on the following factors: (1) variable traffic frequencies; (2) variable percentages of truck traffic; (3) variable design periods or analysis periods; (4) a single subgrade soil stiffness or strength. In addition, the section presents the results of the limited analysis in tabular form based on the outlined assumptions.

Section 5.0 provides a discussion of the findings of the limited analysis and attempts to formulate conclusions from the generated data. In addition, the section also provides recommendations for future studies and practices that may be considered by the City.

2.0 PAVEMENT DESIGN OUTLINE

2.1 GENERAL SUMMARY OF PAVEMENT SYSTEMS

Pavements with asphalt and concrete surface layers have been used in the United States since the late 1880s (FHWA, 1996). In general, a pavement system with an asphalt surface course is referred to as flexible pavement system and a pavement system with a concrete surface course is referred to as a rigid pavement system; however, flexible and rigid pavement sections cannot be characterized purely by the surface course utilized to construct the pavement system. The following subsections provide a more detailed description of the components that contribute to a flexible and rigid pavement system. In addition, the subsections present a summary of the theory associated with each pavement system. Key differences between the two pavement systems are also addressed.

2.1.1 Flexible Pavement Systems

Flexible pavements in general consist of an asphalt-bound surface course or layer on top of unbound base and subbase granular layers over the subgrade soil. In some cases, the subbase and/or base layers may be absent, e.g. full-depth asphalt pavements, while in others the base and/or subbase layers may be stabilized or bound using cementitious or bituminous admixtures. A flexible pavement section may also incorporate a chemical stabilization agent such as lime or cement to increase the strength of the surficial subgrade soils.

The design of a flexible pavement system is based on load distributing characteristics of the component layers used to develop the pavement. More specifically, the flexible pavement layers transmit the vertical or compressive stresses imposed by vehicles through grain transfer across the contact points of the materials comprising the pavement layers. As one might expect, the vertical compressive stresses are largest on the pavement surface directly under the wheel loads and is equal to the contact pressure under the wheels. Due to the flexible nature of the pavement system, the stresses are distributed in the shape of a truncated cone and the stresses decrease as the stresses travel through the layers comprising the pavement system. Due to the nature of stress distribution in a flexible pavement system, materials with larger strengths are typically used at or near the surface of the pavement section; whereas materials with lower strength are typically utilized in the lower layers of the pavement section.

2.1.2 Rigid Pavement Systems

Rigid pavement in general consist of Portland cement concrete (PCC) slabs constructed on a granular base layer over the subgrade soil. The base layer serves to increase the effective stiffness of the slab foundation; however, the base course may not always be utilized to construct a rigid pavement system. The base course is typically omitted when a rigid pavement surface course is constructed over a coarse-grained, i.e. granular or sand, subgrade or when a roadway will be subjected to low traffic volumes, e.g. typically less than 1 million equivalent single axle loads (ESALs). A rigid pavement system is typically designed as one of the following types of pavement systems: (1) continuously reinforced concrete pavement (CRCP); (2) jointed reinforced concrete pavement (JRCP); or (3) jointed plain concrete pavement (JPCP). Another method of rigid pavement design is known as post-tensioned concrete pavement design; however, this method of rigid pavement design is typically only incorporated for airport pavements and not for roadways.

The design of a rigid pavement system is based on providing a structural PCC slab of sufficient strength to resist the loads of traffic. The rigid characteristics of the pavement system are associated with the rigidity or flexural strength and high modulus of elasticity of the PCC slab which distributes traffic loads over a relatively wide area.

2.1.3 Key Differences between Flexible and Rigid Pavement Systems

The primary difference between a flexible and rigid pavement system is associated with the manner in which each type of pavement distributes traffic loads over the subgrade. As previously discussed, a rigid pavement system is designed with a very high stiffness that allows for the distribution of loads over a relatively wide area of subgrade. Due to the high stiffness of a rigid pavement system, a major portion of the pavements structural capacity is derived from the PCC slab itself. Alternatively, the load carrying capacity of a true flexible pavement system is derived from the load distribution characteristics of a layered system. Due to the manner in which a flexible pavement system distributes loads, minor variations in subgrade strength have a significant influence on the structural capacity of the flexible pavement system. On the other hand, minor variations in subgrade strength have less influence on the structural capacity of a rigid pavement system due to the distribution of loads over a wide area. Additional key differences between flexible and rigid pavement systems can be summarized as follows:

- Flexible pavement systems will reflect the deformations of pavement layers and subgrade layers on the surface; whereas rigid pavement systems are typically able to bridge over localized failures and isolated areas of inadequate support.
- Temperature variations in flexible pavement systems do not produce stresses in flexible pavement; whereas temperature changes in rigid pavements can induce heavy stresses in rigid pavements.
- Flexible pavements are capable of recovering from larger stresses to some extent; whereas excessive deformations in rigid pavement systems are not recoverable, i.e. settlements are permanent.

- Flexible pavement systems will often times require significant maintenance costs during the design life of the pavement system; whereas properly designed and constructed rigid pavement systems will require much less maintenance.

2.2 SUMMARY OF METHODOLOGIES TYPICALLY USED FOR PAVEMENT DESIGN

There are generally three approaches that can be employed to design flexible and rigid pavements: (1) an empirical approach; (2) a mechanistic approach; or (3) a mechanistic-empirical approach. An empirical approach is one that is based solely on the results of experiments or experience. Observations made during an experiment or over a given period of time are used to establish correlations between inputs and the outcomes of a process, e.g. pavement design and pavement performance. Empirical pavement design procedures generally do not have a scientific basis; however, the procedures and design inputs implemented in the design process are typically considered reasonable and have been confirmed based on previous experiments or experience. On the other hand, a mechanistic approach is based on the theories of mechanics and relates a pavements behavior and performance to traffic loadings and environmental influences. As the name suggest, a mechanistic-empirical approach to pavement design combines features from both the mechanistic and empirical approaches.

In the United States, there are various flexible and rigid pavement design procedures currently available for the design of a specific paved roadway. One of the most well-known design guides was developed by the *American Association of State Highway and Transportation Officials (AASHTO)*. The AASHTO design guide utilizes empirical methods that are based on field performance data measured during a series of experiments which were conducted between 1958 and 1960 in Ottawa, Illinois. Several design methodologies based on mechanistic-empirical concepts include the Asphalt Institute design procedure for flexible pavements (Shook et al., 1982), the Portland Cement Association (PCA) design procedure for rigid pavements (PCA, 1984), and the National Cooperative Highway Research Program (NCHRP) 1-37A design procedure (NCHRP, 2002) for both flexible and rigid pavements. Although several attempts have been made to develop purely mechanistic design procedures for pavement, a fully mechanistic design approach does not exist at this point in time due to the overall complexity of flexible and rigid pavement systems, e.g. modeling environmental impacts, forecasting future traffic, modeling bound and unbound materials as a system, etc.

2.3 PAVEMENT DESIGN METHODOLOGY SELECTED FOR LIMITED ANALYSIS

As previously discussed in Section 2.2, the AASHTO design guide is one of the most well-known design guideline for both flexible and rigid pavements. The design procedures outlined in the most recent 1993 AASHTO design guide, while complex in theory, are much simpler than those outlined by the NCHRP

1-37A design procedure which is currently considered one of the more sophisticated design approaches for flexible and rigid pavements. Due to the relative simplicity of the 1993 AASHTO design procedures compared to other design procedures, the 1993 AASTO design guide was selected to perform the computations required for the current limited analysis. It is worth noting that the AASHTO design guide is the primary document used to design new and rehabilitated highway pavements. Approximately 80 percent of all states use the AASHTO pavement design procedures, with a majority using the 1993 version (NCAT, 2014).

2.3.1 DESIGN INPUTS OF SIGNIFICANT IMPORTANCE IN THE 1993 AASHTO DESIGN GUIDE

As previously discussed, the 1993 AASHTO design guide incorporates an empirical approach that can be utilized to design flexible and rigid pavements. The empirical approach outlined in the design guide focuses predominately on relating traffic, pavement structure, and pavement performance. The overall approach of the 1993 AASHTO design guide for flexible and rigid pavements is to design for a specified serviceability loss at the end of the design life of the pavement. The serviceability loss that occurs over the design life of a pavement system is considered to be affected by traffic and environmental effects, such as may be associated with frost heave and/or swelling of subgrade soils. The following subsections of this report discuss the design inputs that are considered of significant importance when utilizing the 1993 AASHTO design procedures to design both flexible and rigid pavements. In addition, inputs used exclusively for a given type of pavement design procedure are discussed.

2.3.1.1 Design Inputs of Significant Importance for Flexible and Rigid Pavement Design

The empirical expressions outlined in the 1993 AASHTO design guide for both flexible and rigid pavements rely heavily on five (5) input variables that are outlined below, along with a reference to the subsequent subsections of this report in which the design inputs are discussed:

- Analysis period (see Section 2.4.1.1);
- Traffic (see Section 2.4.1.2);
- Reliability and Overall standard deviation (see Section 2.4.1.3);
- Serviceability (see Section 2.4.1.4); and
- Subgrade soil stiffness or strength (see Section 2.4.1.5).

2.3.1.2 Analysis Period

The analysis period or design period refers to the time that a pavement is intended to last before it needs to be rehabilitated or reconstructed. The term analysis period is synonymous to the overall duration that the design strategy must last. The analysis period may be identical to the performance period; however, performance limitations may require planned rehabilitation within the desired analysis period, e.g. the analysis period may encompass multiple performance periods. The 1993 AASHTO design guide provides recommended ranges for flexible and rigid pavement analysis periods based on the following roadway classifications and anticipated traffic volumes: (1) high-volume urban roadways – 30 to 50 year analysis period; (2) high-volume rural roadways – 20 to 50 year analysis period; (3) low-volume paved roadway – 15 to 25 year analysis period; and (4) low-volume aggregate surface roadway – 10 to 20 year analysis period. As one might expect, multiple performance periods are typically assumed during the analysis period for high-volume roadways; whereas the analysis period may be identical to the performance period for low-volume roadways.

It's worth noting that low-volume roadways constructed with a rigid pavement section are typically evaluated with longer analysis periods due to the costs associated with constructing or rehabilitating a rigid pavement system. The analysis period for any rigid pavement system will typically range from 30 to 50 years regardless of the roadway classification and anticipated traffic volume.

2.3.1.3 Traffic

Traffic is one of the most important design inputs in pavement design. In order to accurately model traffic for a given roadway, the initial traffic volume, traffic growth, directional distribution, lane distribution, and traffic type (vehicle characterization) must be established. The 1993 AASHTO design guide is based on cumulative 18 kip equivalent single-axle loads (ESALs) that are anticipated to travel across the design lane of a roadway during a certain analysis period or design period. ESALs provide a means of expressing traffic loading from numerous types of vehicles with various axle configurations and loadings in terms of unit 18 kips single-axle loads. Thus, every vehicle, no matter what the axle loading, can be expressed as a number of 18 kips equivalent single-axle load units. For example, passenger cars with single-axle loads of 1 kip can have an ESAL of 0.00018, whereas a large truck with a single-axle loading of 20 kips can have an ESAL of 1.51. Therefore, the type of truck traffic and percentage of truck traffic expected to travel on a given roadway will have a significant impact on the ESALs calculated, whereas the volume of passenger cars expected to travel on a given roadway will have a significantly smaller impact on the ESALs calculated.

It is worth noting that the ESALs calculated for a rigid pavement will differ slightly from those calculated for flexible pavement subjected to the same frequency of traffic and magnitudes of loading over a given period of time. ESALs are dependent upon the pavement type (flexible or rigid) and the pavement structure (structural number for flexible pavements and slab depth for rigid pavements). This is primarily due to the way loads are distributed by the two pavement systems (see Sections 2.1.1 and 2.1.2 for a summary of load distributions in flexible and rigid pavement systems). As a rule-of-thumb, the 1993 AASHTO design guide, recommends the use of a multiplier of 1.5 to convert flexible ESALs to rigid ESALs (or a multiplier of 0.67 to convert rigid ESALs to flexible ESALs), although the conversion multiplier is not constant and can vary with different factors.

2.3.1.4 Reliability and Overall Standard Deviation

Design reliability, *R (%)*, is defined in the 1993 AASHTO design guide as "the probability that the design will perform satisfactorily over the analysis period." The reliability must account for uncertainties in traffic loading, environmental conditions, and construction materials. The 1993 AASHTO design procedure accounts for the uncertainties by incorporating a reliability level to provide a factor of safety into the pavement design and thereby increases the probability that the pavement will perform as intended over its design life. The 1993 AASHTO design guide recommends ranges in reliability based on a roadways functional classification as follows: (1) local roadways – 50 to 80 percent; (2) collectors – 75 to 95 percent; (3) principal arterials – 75 to 99 percent; and (4) interstates and other freeways – 80 to 99.9 percent. The selection in reliability will also depend on whether the roadway is located in an urban or rural area. As one might expect, higher reliabilities are typically utilized for roadways subject to higher frequencies of traffic and larger magnitudes of loading in an urban setting, whereas lower reliabilities are selected for roadways with lower anticipated traffic frequencies in a rural environment.

In addition to reliability of pavement performance, the 1993 AASHTO design guide also incorporates an overall standard deviation, S_o, which is used to describe how well the design inputs for a given roadway fit the 1993 AASHTO design equations. For flexible pavements, values of overall standard deviation typically range between 0.40 and 0.50. For rigid pavements, values of overall standard deviation typically range between 0.30 and 0.40. The lower the overall standard deviation, the better the equation models the data for a given roadway.

2.3.1.5 Serviceability

The serviceability of a pavement system can be simplistically compared to smoothness of the pavement riding surface and is quantified by the "Present Serviceability Index" (PSI). PSI values theoretically range from 5 to 0 with the value of 5 corresponding to a roadway with the best “rideability” characteristics and the value of 0 corresponding to a roadway with the worst “rideability” characteristics. However, the actual range of PSI values for pavements is between about 4.5 and 1.5. The initial serviceability, P_i, of a roadway corresponds to road conditions immediately after construction and the terminal serviceability, P_t, of a roadway corresponds to the lowest acceptable PSI before resurfacing or reconstruction become necessary. The initial serviceability of a rigid pavement is typically considered higher than the initial serviceability of a flexible pavement. Typical values of initial serviceability range from 4.5 (for rigid pavements) to 4.2 (for flexible pavements). The terminal serviceability of a pavement is typically selected based on a roadway functionality classification and can be summarized as follows: (1) 2.0 for secondary roads and local residential streets; (2) 2.25 for minor collectors and commercial streets; and (3) 2.50 for major collectors and arterials. Therefore, a typical allowable serviceability loss due to traffic for a local residential street that is constructed with a flexible pavement section is 2.2 (4.2 – 2.0 = 2.2). It worth noting that the serviceability loss of a pavement system can also arise from environmental conditions such as frost heave and/or soil expansion. The 1993 AASHTO design guide provides methods to determine serviceability loss due to these environmental impacts; however, these methods are considered crude by many agencies and design firms, and as a result, are often ignored during pavement design calculations.

2.3.1.6 Subgrade Stiffness or Strength

The stiffness or strength of the subgrade soils supporting a given pavement section are considered important in the design of any pavement. Subgrade soils are typically characterized in pavement design by their response to deformation under load, which can be either a measure of the stiffness or strength. Two common stiffness properties used to characterize the stiffness of subgrade soils are: (1) the resilient modulus, M_R, which is the measurement of the elastic property of a soil (recognizing certain nonlinear characteristics); and (2) the modulus of subgrade reaction, *k*, which depends upon the soil’s stiffness and a slab’s size and stiffness. The 1993 AASHTO design procedure for flexible pavements utilizes the direct input of the effective modulus of rupture of a subgrade. The effective modulus of rupture is determined based on the variations in the modulus of rupture of a subgrade as a result of environmental changes, e.g. increase/decrease in moisture content, changes in temperature, etc. On the other hand, 1993 AASHTO design procedure for rigid pavements utilizes the direct input of a subgrade’s effective modulus of subgrade reaction, *k*, which is determined by considering similar environmental changes.

The resilient modulus is a basic material property that can be measured directly in the laboratory, evaluated in-situ for nondestructive tests, or estimated using various empirical relations such as soil classification. The resilient modulus of a subgrade soil is typically estimated based on correlations between the resilient modulus and the California Bear Ratio (CBR) values for a subgrade soil. On the other hand, the modulus of subgrade reaction of the foundation soils (natural soil and embankment) can be measured by plate bearing tests but is usually estimated from correlations with soil type, soil strength measures such as the CBR, or by back calculation from deflection testing on existing pavements. The stiffness or strength of cohesive soils, i.e. clays, is typically much lower than the stiffness or strength of granular soils, i.e. sands.

As previously discussed, the stiffness or strength of a subgrade soil is typically estimated based results of CBR tests. Typical CBR values for cohesive soils range from 3 to 20; whereas CBR values for granular soils typically range from 15 to 40 (USACE, 1953). Therefore, the resilient modulus and modulus of subgrade reaction for a subgrade soil will be much lower for a cohesive soil than for a granular soil.

2.3.2 Other Design Inputs Pertinent to Flexible Pavement Design

There are two other design inputs that are considered for the 1993 AASHTO design procedures outlined for flexible pavement design. The following paragraphs summarize these inputs and discuss the importance of each input.

As one might expect, the design of a flexible pavement system will rely heavily on the types of materials incorporated in the layered pavement system. The 1993 AASHTO design procedure for flexible pavements requires material properties for each layer which are typically referred to as structure layer coefficients or layer coefficients. The structural layer coefficient for a material will depend on the stiffness or strength of the material under consideration and the location of the material within the layered flexible pavement system. Based on the 1993 AASHTO design guide, the following ranges in structural layer coefficients were determined for various materials based upon design charts that utilize correlations between structural layer coefficients and various stiffness and strength parameters such as the CBR, the elastic modulus of a material, unconfined compressive strength, etc.: (1) hot mix asphalt concrete (HMAC) surface course with an elastic modulus greater than approximately 350,000 pounds per square inch (psi) – 0.40 to 0.45; (2) cement treated granular base with an unconfined compressive strength ranging from approximately 200 psi to 650 psi – 0.12 to 0.20; (3) flexible base with a CBR ranging from 40 to 100 – 0.12 to 0.14; and (4) chemically stabilized and compacted subgrade with a CBR ranging from 6 to 100 – 0.06 to 0.14.

Another design input for flexible pavements is the drainage coefficient for unbound materials such as a flexible base. Drainage coefficients of unbound layers are meant to be selected based on the percentage of time a material approached a saturated condition and also `based on the quality of drainage in the pavement layer. It is worth noting that a drainage coefficient basically makes a specific layer thicker if a fundamental drainage problem is suspected. A thicker layer may only be of marginal benefit if a drainage problem is suspected. A better solution to address a potential drainage concern is to utilize very dense layers in the pavement system or to design a drainage system.

2.3.3 Other Design Inputs Pertinent to Rigid Pavement Design

There are four other design inputs that are considered for the 1993 AASHTO design procedures outlined for rigid pavement design. The following paragraphs summarize these inputs and also discuss the importance of each input.

Similar to flexible pavement design, the material properties of a rigid PCC slab are of significant importance when selecting a design slab thickness. There are two material properties that are considered of significant importance in the design of a rigid pavement section and these properties include: (1) the 28-day modulus of rupture, M_R, i.e. flexural strength, of the PCC slab and (2) the modulus of elasticity, E_c, of the PCC slab. The 2011 TxDOT – *Pavement Design Manual* recommends the following default values be utilized for rigid pavement design: (1) a 28-day modulus of rupture of 620 pounds per square inch (psi) and (2) a modulus of elasticity of 5,000,000 psi. It's worth noting that based on the current correlations that exist between the 28-day compressive strength of concrete, f'_c, and the two required inputs, the default values recommended by TxDOT appear to be significantly over-estimated. For example, an elastic modulus of 5,000,000 psi correlates to a 28-day concrete compressive strength of approximately 7,700 psi based on the correlation outlined in the American Concrete Institute publication 318 (ACI-318). In addition, the default value recommended by TxDOT for a 28-day modulus of rupture correspond to a 28-day compressive strength of approximately 4,750 psi. Based on the correlations outlined in ACI-318, a modulus of rupture of approximately 570 psi and an elastic modulus of approximately 3,600,000 psi appear to correlate to cast-in-place concrete with a 28-day compressive strength of 4,000 psi.

Additional required properties for rigid pavement design include a joint transfer coefficient, J, which depends on various design conditions such as the shoulders constructed with the pavement system and the type of rigid pavement system design, i.e. JPCP, JRCP, or CRCP, and a drainage coefficient, C_d, which is similar to the drainage coefficients previously discussed for flexible pavement design.

3.0 EVALUATION OF MINIMUM PAVEMENT SECTIONS OUTLINED IN THE BCSUDGSA

3.1 GENERAL

As previously discussed, the City requested CME to evaluate the existing minimum flexible and rigid pavement sections outlined in the BCSUDHSA for residential roadways and minor collectors. More specifically, the standard pavement sections that the City requested to be analyzed for "equivalency" are outline in Table VIII – *Minimum Pavement Thickness Criteria* found in the BCSUDGSA. In addition, the standard pavement sections are also outlined on BCS Detail Nos. ST4-04 and ST4-05. The minimum design sections outlined for flexible and rigid pavements in the BCSUDGSA are summarized below in Table 3.1.1 – *Minimum Pavement Thickness Criteria (Adapted from Table VIII of the BCSUDGSA)*.

Table 3.1.1 Minimum Pavement Thickness Criteria (Adapted from Table VIII of the BCSUDGSA)

FLEXIBLE PAVEMENTS			
STREET CLASSIFICATION	**SUBGRADE TREATMENT**	**BASE MATERIAL**	**SURFACE TREATMENT**
RESIDENTAL	6-in. Lime-Stab.	6-in. Limestone, 6-in. Cement Stabilized Base	2-in. HMAC
MINOR COLLECTOR	6-in. Lime-Stab.	8-in. Limestone, 8-in. Cement Stabilized Base	2-in. HMAC

RIGID PAVEMENTS		
STREET CLASSIFICATION	**SUBGRADE TREATMENT**	**CONCRETE PAVEMENT**
RESIDENTAL (includes alleys)	6-in. Lime-Stab.	6-in.
COLLECTORS AND PRIVATE LOCAL STREETS	6-in. Lime-Stab.	8-in.

3.2 EVALUATION OF FLEXIBLE PAVEMENT SECTIONS OUTLINED IN THE BCSUDGSA

3.2.1 Assumptions Incorporated in Minimum Flexible Pavement Section Evaluation

There were several assumptions that had to be made in order to evaluate the minimum flexible pavement sections previously outlined in Table 3.1.1 for residential roadways and minor collectors. The inputs of particular interest included the effective stiffness or strength of subgrade soils supporting the flexible pavement, the reliability and overall standard deviation that was selected to evaluate the minimum flexible pavement sections, and the structural layer coefficients that were utilized to develop the design thickness of each layer comprising the flexible pavement sections. Table 3.2.1 – *Design Inputs Selected for Limited Analysis of Minimum Flexible Pavement Systems Outline in the BCSUDGSA* summarizes the design inputs selected to evaluate the minimum flexible pavement sections. In addition to the inputs outlined in Table 3.2.1, the following structural layer coefficients were selected for the pavement materials being evaluated: (1) HMAC – 0.44; (2) Cement stabilized base – 0.16; (3) Flexible base or crushed limestone base (flex base) – 0.13; and (4) chemically stabilized subgrade – 0.08.

Table 3.2.1 Design Inputs Selected for Limited Analysis of Minimum Flexible Pavement Systems Outlined in the BCSUDGSA

Street Classification	R (%) (Reliability)	S_o (Overall Standard Deviation)	EFFECTIVE CBR VALUES OF SUBGRADE SOIL CONSIDERED Note 1	P_i (Initial Serviceability)	P_t (Terminal Serviceability)
RESIDENTIAL	80%	0.5	3 and 5	4.2	2.0
MINOR COLLECTOR	90%	0.5	3 and 5	4.2	2.25

Note:
1. The CBR values considered in the evaluation correspond to a lower bound and upper bound for clay of high plasticity or fat clays (3 to 5) (FHWA, 2006).

3.2.1 Results of Minimum Flexible Pavement Evaluation

Based on the assumptions previously outlined in Section 3.2.1 and Table 3.2.1, the minimum flexible pavement sections outline in the BCSUDGSA for residential roadways and minor collectors were evaluated and the maximum allowable design ESALs for each minimum flexible pavement section was computed. The results of this evaluation are presented in Table 3.2.2 – *Maximum Allowable Design ESALs* *for Minimum Flexible Pavement Sections Outlined in the BCSUDGSA (Based on Assumptions Outlined in Section 3.2.1 and Table 3.2.1).*

Based on the results presented in Table 3.2.2, one can infer that the maximum allowable traffic "capacity" or maximum allowable ESALs for each type of flexible pavement section will rely heavily on the effective subgrade stiffness or strength. In addition, it can be deduced that a flexible pavement system utilizing a cement stabilized base course will out-perform a flexible pavement system utilizing a crushed limestone base course of the same thickness. However, consideration of reflective cracking of the flexible surface course may have to be examined with the use of a relatively rigid cement stabilized base course.

Table 3.2.2 Maximum Allowable Design ESALs for Minimum Flexible Pavement Sections Outlined in the BCSUDGSA (Based on Assumptions Outlined in Section 3.2.1 and Table 3.2.1)

Street Classification	Pavement Layers	Maximum Allowable ESALs	
		CBR = 3	CBR = 5
RESIDENTIAL	2-in. HMAC, 6-in. limestone, and 6-in. lime-stab.	35,000	74,000
	2-in. HMAC, 6-in. cement stabilized base, and 6-in. lime-stab.	57,000	123,000
MINOR COLLECTOR	2-in. HMAC, 8-in. limestone, and 6-in. lime-stab.	41,000	87,000
	2-in. HMAC, 8-in. cement stabilized base, and 6-in. lime-stab.	73,000	157,000

Note:
1. Maximum allowable ESALs rounded to the nearest 1,000 ESALs.

Based on the results presented in Table 3.2.2, an extended analysis was performed to evaluate the design life of a given flexible pavement section based on variations in the subgrades effective stiffness or strength. The following assumptions were made to perform the extended analysis: (1) a residential and minor collector with a crushed limestone base course were the only pavement sections considered; (2) the ADT of the residential roadway was assumed to be 2,500 VPD and the ADT of the minor collector was assumed to be 5,000 VPD; (3) 2 percent of the ADT for each street classification was assumed to be associated with truck traffic; (4) the 2 percent truck traffic was assumed to be due to medium-weight trucks only, i.e. Federal Highway Administration (FHWA) vehicle classifications such as Classes 4, 5, 6, and 7;

and (5) effective CBR values of 3 and 5 were considered. Based on these assumptions, it was determined that the design life of the minimum flexible pavement sections outlined in the BCSUDGSA would vary with the two (2) considered strengths of the supporting soils by as much 10 years. More specifically, the minimum flexible pavement section outlined for residential roadways (with a crushed limestone base course) founded on a subgrade soil with an effective CBR of 3 would theoretically have a design life of 10 years; whereas a residential roadway and minor collector founded on a subgrade soil with an effective CBR of 5 would theoretically have a design life of 20 years. On the other hand, the minimum flexible pavement section outlined for minor collectors (with a crushed limestone base course) founded on a subgrade soil with an effective CBR of 3 would theoretically have a design life of 6 years; whereas a residential roadway and minor collector founded on a subgrade soil with an effective CBR of 5 would theoretically have a design life of 12 year. As one might expect, the design life computed for each minimum flexible pavement section considered in this extended evaluation would decrease even more if larger percentages and magnitude of truck traffic, i.e., heavier trucks with FHWA vehicle classifications of greater than Type 7, traveled a given residential roadway or minor collector. As a result, it should be recognized that the design life and performance of the minimum flexible pavement sections outlined in the BCSUDGSA for residential roadways and minor collectors will depend heavily on the stiffness or strength of the subgrade supporting the flexible pavement section and on the frequency and types of traffic utilizing a given roadway.

3.3 EVALUATION OF RIGID PAVEMENT SECTIONS OUTLINED IN THE BCSUDGSA

3.3.1 Assumptions Incorporated in Minimum Rigid Pavement Section Evaluation

There were several assumptions that had to be made in order to evaluate the minimum rigid pavement sections previously outlined in Table 3.3.1 for residential roadways and minor collectors. The inputs of particular interest included the effective stiffness or strength of subgrade soils supporting the rigid pavement, the reliability and overall standard deviation that was initially selected to develop the minimum rigid pavement sections, the 28-day modulus of rupture and elastic modulus of the concrete slab, and the load transfer coefficient selected for the minimum pavement section evaluation. Table 3.2.2 – *Design Inputs Selected for Limited Analysis of Minimum Rigid Pavement Systems Outline in the BCSUDGSA* summarizes the design inputs selected to evaluate the minimum pavement sections. In addition to these assumed design inputs, a load transfer coefficient of 3.6 was selected which corresponds to a JRCP section with curb and gutter edge treatment. Values utilized for the modulus of rupture and elastic modulus of the PCC slab were 570 psi and 3,600,000 psi, respectively, and correlate to a 28-day concrete compressive strength of 4,000 psi based on correlations outline in ACI-318.

Table 3.3.1 Design Inputs Selected for Limited Analysis of Minimum Rigid Pavement Systems Outlined in the BCSUDGSA

Street Classification	R (%) (Reliability)	S_o (Overall Standard Deviation)	EFFECTIVE CBR VALUES OF SUBGRADE SOIL CONSIDERED Note 1	P_i (Initial Serviceability)	P_t (Terminal Serviceability)
RESIDENTIAL	80%	0.4	3 and 5	4.5	2.0
MINOR COLLECTOR	90%	0.4	3 and 5	4.5	2.25

Note:
1. The CBR values considered in the evaluation correspond to a lower bound and upper bound for clays of high plasticity or fat clays (3 to 5) (FHWA, 2006).

3.3.2 Results of Minimum Rigid Pavement Section Evaluation

Based on the assumptions previously outlined in Section 3.3.1 and Table 3.3.1, the minimum rigid pavement sections outline in the BCSUDGSA for residential roadways and minor collectors were evaluated and the maximum allowable design ESALs for each minimum rigid pavement section was computed. The results of this evaluation are presented in Table 3.3.2 – *Maximum Allowable Design ESALs for Minimum Rigid Pavement Sections Outlined in the BCSUDGSA (Based on Assumptions Outlined in Section 3.3.1 and Table 3.3.1)*.

Based on the results presented in Table 3.3.2, one can infer that the maximum allowable traffic "capacity" or maximum allowable ESALs for each pavement section will vary depending on the effective subgrade stiffness or strength. In addition, it can be deduced that an 8-inch PCC slab will have a much larger traffic "capacity" than a 6-inch PCC slab as one would expect.

Similar to the extended analysis previously discussed for flexible pavement sections outlined in the BCSUDGSA (see Section 3.2.2), an extended analysis of the results presented in Table 3.3.2 was also performed to evaluate variations in the design period of rigid pavement sections based upon variable subgrade stiffness or strength. Similar to the extended evaluation performed in Section 3.2.2, the following assumptions were made: (1) the ADT of the residential roadway was assumed to be 2,500 VPD and the ADT of the minor collect was assumed to be 5,000 VPD; (3) 2 percent of the ADT for each street classification was assumed to be associated with truck traffic; (4) the 2 percent truck traffic was assumed to be due to medium-weight trucks only, i.e. FHWA vehicle classifications such as Classes 4, 5, 6, and 7; and (5) effective CBR values of 3 and 5 were considered. The theoretical design periods computed for each minimum rigid pavement (based on the variable effective subgrade stiffness or strength) were quite large and ranged from 35 to 75 years in length. This is primarily due to the low frequencies and magnitudes of traffic that were assumed for the extended evaluation.

Table 3.3.2 Variations in Computed Design ESALs based on Variable Subgrade Stiffness

Street Classification	Pavement Layers	Maximum Allowable ESALs	
		CBR = 3	CBR = 5
RESIDENTIAL	6-in. PCC slab and 6-in. lime-stab.	190,000	260,000
MINOR COLLECTOR	8-in. PCC slab and 6-in. lime-stab.	670,000	830,000

Note:
1. Maximum allowable ESALs rounded to the nearest 1,000 ESALs.

3.4 EVALUATION OF "EQUIVALENCY" OF MINIMUM PAVEMENT SECTIONS OUTLINED IN THE BCSUDGSA

As previously discussed, the purpose of this portion of the limited analysis was to evaluate the "equivalency" of the existing minimum flexible and rigid pavement sections outlined in the BCSUDGSA. Based on the results presented in Sections 3.2.2 and 3.3.2, it can be concluded that the minimum rigid pavement sections outlined for residential roadways and minor collectors are capable of supporting larger traffic "capacities" or ESALs than a flexible pavement section founded on the same type of subgrade. More specifically, a rigid pavement section for a residential roadway (founded on a subgrade with an effective CBR of 5) can support approximately 3.5 times as many ESALs (260,000/74,000 ≈ 3.5) as a flexible pavement section (constructed with a flexible base course) and approximately 2.1 times as many ESALs as a flexible pavement section (constructed with a cement stabilized base course) (260,000/123,000 ≈ 2.1). Alternatively, a rigid pavement section for a minor collector (founded on a subgrade with an effective CBR of 5) can support approximately 9.5 times as many ESALs as a flexible pavement section (constructed with a flexible base course) (830,000/87,000 ≈ 9.5) and approximately 5.3 times as many ESALs as a flexible pavement section (constructed with a cement stabilized base course) (830,000/157,000 ≈ 5.3) for a minor collector founded on the same type of subgrade. Due to these significant variations, the minimum rigid pavement sections outline in the BCSUDGSA will theoretically exhibit much longer design lives than the "equivalent" flexible pavement sections outline in the BCSUDGSA.

4.0 LIMITED ANALYSIS OF PAVEMENTS BASED ON VARIABLE TRAFFIC FREQUENCIES, MAGNITUDES OF LOADING, AND DESIGN PERIODS

4.1 GENERAL

As previously discussed, the second portion of this limited analysis consists of evaluating flexible and rigid pavements based on variable traffic frequencies, magnitudes of loading, and design periods. In order to simplify this portion of the limited analysis, a single subgrade stiffness or strength was assumed. The following paragraphs summarizes the scope of this portion of the limited analysis. The scope was developed by CME with the assistance of the City during the previously referenced meetings conducted at the City's Department of Public Works offices of June 3 and August 3, 2015

Variations in ADT utilize five (5) different ADT conditions which include: (1) 2,500 vehicles per day (VPD); (2) 5,000 VPD; (3) 10,000 VPD; (4) 20,000 VPD; (5) 40,000 VPD. The ADTs selected are meant to be representative of the various roadways common to the College Station area such as: residential roadways, minor collectors, major collectors, minor arterials, and major arterials. The two (2) lower volumes of traffic, i.e. 2,500 and 5,000 VPD, will assume one (1) design lane in each direction with 100 percent of the traffic loads being transmitted to the design lane; whereas the three (3) higher volumes of traffic, i.e. 10,000, 20,000, and 40,000 VPD, will assume two (2) design lanes in each direction with approximately 80 percent of the traffic loads being transmitted to the design lane. For each ADT condition, three (3) alternative truck traffic conditions are assumed and include: (1) 2 percent truck traffic; (2) 4 percent truck traffic; and (3) 6 percent truck traffic. The truck traffic was evaluated based on the percentage of medium-weight trucks, i.e. FHWA vehicle classifications such as Classes 4, 5, 6, and 7, and heavy-weight trucks, i.e. FHWA vehicle classifications such as Classes 8, 9, and 10, that travel a given roadway. For an ADT of 2,500 VPD, 90 percent of the truck traffic will be assumed to be medium-weight trucks and the remaining 10 percent will be assumed to be heavy-weight trucks. For an ADT of 5,000 VPD, 80 percent of the truck traffic will be assumed to be medium-weight trucks and the remaining 20 percent will be assumed to be heavy-weight trucks. For ADTs of 10,000, 20,000, and 40,000 VPD, 70 percent of the truck traffic will be assumed to be medium-weight trucks and the remaining 30 percent will be assumed to be heavy-weight trucks. Finally, the design periods considered during the analysis include: (1) 10 years; (2) 20 years; (3) 30 years; and (4) 40 years.

4.2 ASSUMPTIONS MADE PERFORMING LIMITED ANALYSIS OF FLEXIBLE AND RIGID PAVEMENT SECTIONS

As one might expect, there were several assumptions that had to be made in order to perform the limited analysis for flexible and rigid pavements in addition to the assumptions previously outlined in Section 4.1. These assumptions were generally focused towards design inputs previously discussed in Section 2.0; however, other assumptions were also required in order to simplify the limited analysis. Some of the assumptions were similar for both the flexible and rigid pavement section analysis and other assumptions were pertinent to just a flexible or rigid pavement system. The following subsections describe the various assumptions made to perform this portion of the limited analysis.

4.2.1 Similar Assumptions Pertinent to both Flexible and Rigid Pavement Analysis

Similar assumptions made during the limited analysis for both flexible and rigid pavement sections are summarized below as follow:

- The flexible and rigid pavement sections are founded on a subgrade that exhibits a single stiffness or strength that is considered representative of the predominately cohesive subgrade soils, i.e. clays, typically encountered in the College Station area. Based on previous project experience, a clay exhibiting an effective CBR value of 5 was selected to perform the computations required for the limited analysis.
- The following reliability levels were selected for the analysis based on roadway functionality classification: (1) 80 percent for residential roadways (ADT = 2,500 VPD); (2) 90 percent for minor collectors (ADT = 5,000 VPD) and major collectors (ADT = 10,000 VPD); (3) 95 percent for minor arterials (ADT = 20,000 VPD); and (4) 99 percent for major arterials (ADT = 40,000 VPD).
- Terminal serviceability of a pavement was varied based on roadway functionality class and can be summarized as follows: (1) 2.0 for residential roadways (ADT = 2,500 VPD); (2) 2.25 for minor collectors (ADT = 5,000 VPD); and (3) 2.5 for all other roadway functionality classes analyzed.
- All pavement section were assumed to have a 6-inch chemically stabilized and compacted subgrade layer.
- Drainage coefficients were neglected for the analysis.
- The computed design ESALs for flexible and rigid pavement sections were held constant even though ESALs calculated for a rigid pavement typically differ from those calculated for flexible pavement subjected to the same frequency of traffic and magnitudes of loading over a given period of time (see Section 2.4.1.2).

4.2.2 Assumptions Pertinent to Flexible Pavement Section Analysis

As previously discussed, there are variable inputs required by the 1993 AASHTO design procedures for flexible pavement design that deviate from those required for rigid pavement design. The assumed inputs pertinent for the analysis of a flexible pavement section are summarized below as follows:

- The pavement materials considered for the analysis of flexible pavement sections were a surface course of HMAC, a flexible base course of crushed limestone, and a subgrade that is chemically stabilized.
- The structural layer coefficients assumed for flexible pavement materials were the same as those assumed in Section 3.0 and were as follows: (1) HMAC – 0.44; (2) Flexible base or crushed limestone base – 0.13; and (3) chemically stabilized subgrade – 0.08.
- An overall standard deviation of 0.5 was selected for the analysis of flexible pavement sections.
- An initial serviceability of 4.2 was selected for the analysis of flexible pavement sections.
- The HMAC surface course thickness selected for each flexible pavement section was based on the ESALs anticipated to travel over a given roadway for a given design period. The minimum thicknesses were determined based on minimum asphalt thickness surface course thicknesses outline in the 1993 AASHTO design guide and in Figure 14 - *Suggested Minimum Thickness of Asphalt Concrete Pavement* in TEX-117-E, September 1995.

4.2.3 Assumptions Pertinent to Rigid Pavement Section Analysis

The assumed inputs pertinent for the rigid pavement analysis are summarized below as follows:

- The pavement materials considered for the analysis of rigid pavement sections were a surface course of Portland PCC and a chemically stabilized subgrade.
- The stiffness properties of a PCC slab remained the same as those utilized in Section 3.0 and consisted of a modulus of rupture of 570 psi and an elastic modulus of 3,600,000 psi.
- An overall standard deviation of 0.4 was selected for the analysis of rigid pavement sections.
- An initial serviceability of 4.5 was selected for the analysis of rigid pavement sections.
- A load transfer coefficient of 3.6 was assumed for rigid pavement computations.

4.3 RESULTS OF LIMITED FLEXIBLE PAVEMENT ANALYSIS

The results of the limited flexible pavement analysis are presented on the subsequent pages of this report in Tables 4.3.1 thorough 4.3.5. Each table is meant to represent one of the five roadway functionality classes previously discussed, i.e. residential roadways, minor collectors, major collectors, minor arterials, and major arterials.

The results presented for flexible pavement sections did not consider overlays or rehabilitation techniques being incorporated during the analysis period. It’s worth noting that the 1993 AASHTO design procedure for flexible pavements does not directly consider rutting or thermal cracking of a flexible pavement section, which will likely occur over the design life of any flexible pavement section. In addition, environmental impacts due to swelling soils were not considered in the computations. As a result, the theoretical pavement sections presented in Tables 4.3.1 through 4.3.5 would likely require rehabilitation or overlays during the design life of each section, especially for any flexible pavement sections with a design life exceeding 10 to 20 years in duration.

The results presented in Tables 4.3.1 through 4.3.5 for various flexible pavement sections are significant and are primarily attributable to the number of variables that were evaluated for this portion of the limited analysis. Nevertheless, a number of conclusions can be made based on the results obtained. Some of the most notable conclusion can be generalized as follows:

- The total design thickness of a flexible pavement section will increase with an increase in traffic frequency, magnitudes of loading, and design period.
- For a given design period, the total required thickness of a flexible pavement section (for a given roadway functionality class) will vary by as much as 4 inches (typically 2 to 3 inches) based on the variable percentages in truck traffic considered for each roadway functionality class.
- Based on the variable ESALs calculated for a residential roadway, a minimum HMAC surface course thickness of 2.5 inches appears most appropriate for any residential roadway subjected to significant truck traffic over the course of its design period.
- Based on the variable design ESALs calculated for minor and minor collectors, a minimum HMAC surface course thickness of 2.5 to 3.0 inches appears most appropriate for a 20 year design period. This minimum thickness may be greater if large percentages of truck traffic are expected to travel on the minor collector or if a smaller thickness of crushed limestone base is desired.
- For minor and major arterials, the required thickness of crushed limestone base course begins to become excessive. This could be avoided by either using a larger thickness of HMAC or by replacing the crushed limestone with a stiffer material such as cement stabilized base. As previously discussed, the replacement of the crushed limestone base with a cement stabilized base would require the consideration of reflective cracking of the flexible surface course.

Table 4.3.1 Limited Flexible Pavement Analysis Based on Variable Traffic Frequencies, Magnitudes of Loading, and Design Periods (ADT = 2,500 VPD)

ADT = 2,500 vehicles per day (Residential Roadways)

Pavement Layers	**Design Period**			
	10 years	**20 years**	**30 years**	**40 years**
Design ESALs for 2 Percent Truck Traffic	42,000	84,000	126,000	168,000
HMAC Surface Course (inches)	2.0	2.0	2.0	2.5
Crushed Limestone Base Course (inches)	5.0	6.5	8.0	7.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	13.0	14.5	16.0	15.5
Design ESALs for 4 Percent Truck Traffic	84,000	168,000	252,000	336,000
HMAC Surface Course (inches)	2.0	2.5	2.5	2.5
Crushed Limestone Base Course (inches)	6.5	7.0	8.0	9.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	14.5	15.5	16.5	17.5
Design ESALs for 6 Percent Truck Traffic	126,000	252,000	378,000	504,000
HMAC Surface Course (inches)	2.0	2.5	2.5	3.0
Crushed Limestone Base Course (inches)	8.0	8.0	9.5	8.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	16.0	16.5	18.0	17.5

Notes:

1. Minimum thicknesses of hot mix asphalt concrete were determined utilizing minimum thickness tables outline in the 1993 AASHTO design guide and in Figure 14 - *Suggested Minimum Thickness of Asphalt Concrete Pavement* in TEX-117-E, September 1995.
2. The stabilized subgrade was assumed to be 6 inches for all conditions.
3. Structural layer coefficients used in calculations were 0.44 for HMAC, 0.13 for flexible base, and 0.08 for stabilized subgrade.
4. The existing subgrade soils below the flexible pavement sections were assumed to have an effective CBR value of 5.
5. Summary of other design inputs: $S_o = 0.5$, $R = 80\%$, $P_i = 4.2$, and $P_i = 2.0$.

Table 4.3.2 Limited Flexible Pavement Analysis Based on Variable Traffic Frequencies, Magnitudes of Loading, and Design Periods (ADT = 5,000 VPD)

ADT = 5,000 vehicles per day (Minor Collector)				
Pavement Layers	Design Period			
	10 years	20 years	30 years	40 years
Design ESALs for 2 Percent Truck Traffic	95,000	190,000	285,000	380,000
HMAC Surface Course (inches)	2.0	2.5	2.5	2.5
Crushed Limestone Base Course (inches)	8.5	9.0	10.5	11.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	16.5	17.5	19.0	20.0
Design ESALs for 4 Percent Truck Traffic	190,000	380,000	570,000	760,000
HMAC Surface Course (inches)	2.5	2.5	3.0	3.0
Crushed Limestone Base Course (inches)	9.0	11.5	11.5	12.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	17.5	20.0	20.5	21.5
Design ESALs for 6 Percent Truck Traffic	285,000	570,000	855,000	1,139,000
HMAC Surface Course (inches)	2.5	3.0	3.0	3.5
Crushed Limestone Base Course (inches)	10.5	11.5	13.0	12.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	19.0	20.5	22.0	22.0

Notes:

1. Minimum thicknesses of hot mix asphalt concrete were determined utilizing minimum thickness tables outline in the 1993 AASHTO design guide and in Figure 14 - *Suggested Minimum Thickness of Asphalt Concrete Pavement* in TEX-117-E, September 1995.
2. The stabilized subgrade was assumed to be 6 inches for all conditions.
3. Structural layer coefficients used in calculations were 0.44 for HMAC, 0.13 for flexible base, and 0.08 for stabilized subgrade.
4. The existing subgrade soils below the flexible pavement sections were assumed to have an effective CBR value of 5.
5. Summary of other design inputs: S_o = 0.5, R = 90%, P_i = 4.2, and P_i = 2.25.

Table 4.3.3 Limited Flexible Pavement Analysis Based on Variable Traffic Frequencies, Magnitudes of Loading, and Design Periods (ADT = 10,000 VPD)

ADT = 10,000 vehicles per day (Major Collector)				
Pavement Layers	**Design Period**			
	10 years	**20 years**	**30 years**	**40 years**
Design ESALs for 2 Percent Truck Traffic	170,000	339,000	509,000	678,000
HMAC Surface Course (inches)	2.5	2.5	3.0	3.0
Crushed Limestone Base Course (inches)	9.0	11.5	11.5	12.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	17.5	20.0	20.5	21.5
Design ESALs for 4 Percent Truck Traffic	339,000	678,000	1,017,000	1,355,000
HMAC Surface Course (inches)	2.5	3.0	3.5	3.5
Crushed Limestone Base Course (inches)	11.5	12.5	12.5	14.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	20.0	21.5	22.0	23.5
Design ESALs for 6 Percent Truck Traffic	509,000	1,017,000	1,525,000	2,033,000
HMAC Surface Course (inches)	3.0	3.5	4.0	4.0
Crushed Limestone Base Course (inches)	11.5	12.5	13.0	14.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	20.5	22.0	23.0	24.5

Notes:

1. Minimum thicknesses of hot mix asphalt concrete were determined utilizing minimum thickness tables outline in the 1993 AASHTO design guide and in Figure 14 - *Suggested Minimum Thickness of Asphalt Concrete Pavement* in TEX-117-E, September 1995.
2. The stabilized subgrade was assumed to be 6 inches for all conditions.
3. Structural layer coefficients used in calculations were 0.44 for HMAC, 0.13 for flexible base, and 0.08 for stabilized subgrade.
4. The existing subgrade soils below the flexible pavement sections were assumed to have an effective CBR value of 5.
5. Summary of other design inputs: $S_o = 0.5$, R = 90%, $P_i = 4.2$, and $P_i = 2.5$.

Table 4.3.4 Limited Flexible Pavement Analysis Based on Variable Traffic Frequencies, Magnitudes of Loading, and Design Periods (ADT = 20,000 VPD)

ADT = 20,000 vehicles per day (Minor Arterial)				
Pavement Layers	**Design Period**			
	10 years	**20 years**	**30 years**	**40 years**
Design ESALs for 2 Percent Truck Traffic	339,000	678,000	1,017,000	1,355,000
HMAC Surface Course (inches)	2.5	3.0	3.5	3.5
Crushed Limestone Base Course (inches)	13.0	14.5	14.5	16.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	21.5	23.5	24.0	25.5
Design ESALs for 4 Percent Truck Traffic	678,000	1,355,000	2,033,000	2,710,000
HMAC Surface Course (inches)	3.0	3.5	4.0	4.5
Crushed Limestone Base Course (inches)	14.5	16.0	16.5	16.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	23.5	25.5	26.5	26.5
Design ESALs for 6 Percent Truck Traffic	1,017,000	2,033,000	3,049,000	4,065,000
HMAC Surface Course (inches)	3.5	4.0	4.5	5.0
Crushed Limestone Base Course (inches)	16.0	16.5	17.0	16.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	25.5	26.5	27.0	27.5

Notes:

1. Minimum thicknesses of hot mix asphalt concrete were determined utilizing minimum thickness tables outline in the 1993 AASHTO design guide and in Figure 14 - *Suggested Minimum Thickness of Asphalt Concrete Pavement* in TEX-117-E, September 1995.
2. The stabilized subgrade was assumed to be 6 inches for all conditions.
3. Structural layer coefficients used in calculations were 0.44 for HMAC, 0.13 for flexible base, and 0.08 for stabilized subgrade.
4. The existing subgrade soils below the flexible pavement sections were assumed to have an effective CBR value of 5.
5. Summary of other design inputs: S_o = 0.5, R = 95%, P_i = 4.2, and P_i = 2.5.

Table 4.3.5 Limited Flexible Pavement Analysis Based on Variable Traffic Frequencies, Magnitudes of Loading, and Design Periods (ADT = 40,000 VPD)

ADT = 40,000 vehicles per day (Major Arterial)				
Pavement Layers	**Design Period**			
	10 years	**20 years**	**30 years**	**40 years**
Design ESALs for 2 Percent Truck Traffic	678,000	1,355,000	2,033,000	2,710,000
HMAC Surface Course (inches)	3.0	3.5	4.0	4.5
Crushed Limestone Base Course (inches)	18.0	20.0	20.5	20.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	27.0	29.5	30.5	31.0
Design ESALs for 4 Percent Truck Traffic	1,355,000	2,710,000	4,065,000	5,420,000
HMAC Surface Course (inches)	3.5	4.5	5.0	5.0
Crushed Limestone Base Course (inches)	20.0	20.5	21.0	22.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	29.5	31.0	32.0	33.5
Design ESALs for 6 Percent Truck Traffic	2,033,000	4,065,000	6,100,000	8,130,000
HMAC Surface Course (inches)	4.0	5.0	5.0	5.5
Crushed Limestone Base Course (inches)	20.5	21.0	23.5	23.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	30.5	32.0	34.5	35.0

Notes:

1. Minimum thicknesses of hot mix asphalt concrete were determined utilizing minimum thickness tables outline in the 1993 AASHTO design guide and in Figure 14 - *Suggested Minimum Thickness of Asphalt Concrete Pavement* in TEX-117-E, September 1995.
2. The stabilized subgrade was assumed to be 6 inches for all conditions.
3. Structural layer coefficients used in calculations were 0.44 for HMAC, 0.13 for flexible base, and 0.08 for stabilized subgrade.
4. The existing subgrade soils below the flexible pavement sections were assumed to have an effective CBR value of 5.
5. Summary of other design inputs: S_o = 0.5, R = 99%, P_i = 4.2, and P_i = 2.5.

4.4 RESULTS OF LIMITED RIGID PAVEMENT ANALYSIS

The results of the limited rigid pavement analysis are presented on the subsequent pages of this report in Tables 4.4.1 thorough 4.4.5. Similar to the results presented in Sections 4.3 for flexible pavement sections, each table is meant to represent one of the five roadway functionality classes previously discussed, i.e. residential roadways, minor collectors, major collectors, minor arterials, and major arterials.

It's worth noting that the 1993 AASHTO design procedure for rigid pavements does not directly consider faulting or thermal cracking of a rigid pavement section, which will likely occur over the design life of any rigid pavement section. In addition, environmental impacts due to swelling soils were not considered in the computations. Significant distress in rigid pavement systems due to these conditions generally warrants total reconstruction of the rigid pavement.

Similar to the results previously presented in Section 4.3 for the flexible pavement analyses, the variations of the results presented in Tables 4.4.1 through 4.4.5 for various rigid pavement sections are considerable and are primarily based on the number of variables that were evaluated for this portion of the limited analysis. Nevertheless, a number of conclusions can be made based on the results obtained. Some of the most notable conclusion can be generalized as follows:

- The total design thickness of a rigid pavement section will increase with an increase in traffic frequency, magnitudes of loading, and design period.
- For a given design period, the total required thickness of a rigid pavement section (for a given roadway functionality class) will vary by as much as 2 inches (typically 1 to 1.5 inches) based on variable percentages in truck traffic.
- For a given roadway functionality class, doubling the amount of ESALs expected to travel on a given roadway will result in approximately a 1-inch increase in the required PPC surface course.

Table 4.4.1 Limited Rigid Pavement Analysis Based on Variable Traffic Frequencies, Magnitudes of Loading, and Design Periods (ADT = 2,500 VPD)

ADT = 2,500 vehicles per day (Residential Roadways)				
Pavement Layers	**Design Period**			
	10 years	**20 years**	**30 years**	**40 years**
Design ESALs for 2 Percent Truck Traffic	42,000	84,000	126,000	168,000
PCC Surface Course (inches)	4.5	5.0	5.5	6.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	10.5	11.0	11.5	12.0
Design ESALs for 4 Percent Truck Traffic	84,000	168,000	252,000	336,000
PCC Surface Course (inches)	5.0	6.0	6.0	6.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	11.0	12.0	12.0	12.0
Design ESALs for 6 Percent Truck Traffic	126,000	252,000	378,000	504,000
PCC Surface Course (inches)	6.0	6.0	6.5	7.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	12.0	12.0	12.5	13.0

Notes:

1. The stabilized subgrade was assumed to be 6 inches for all conditions.
2. The PCC slab was assumed to have a 28-day modulus of rupture of 570 psi and an elastic modulus of 3,600,000 psi.
3. The existing subgrade soils below the flexible pavement sections were assumed to have an effective CBR value of 5.
4. A load transfer coefficient of 3.6 was assumed.
5. Summary of other design inputs: S_o = 0.4, R = 80%, P_i = 4.5, and P_i = 2.0.

Table 4.4.2 Limited Rigid Pavement Analysis Based on Variable Traffic Frequencies, Magnitudes of Loading, and Design Periods (ADT = 5,000 VPD)

ADT = 5,000 vehicles per day (Minor Collector)				
Pavement Layers	**Design Period**			
	10 years	**20 years**	**30 years**	**40 years**
Design ESALs for 2 Percent Truck Traffic	95,000	190,000	285,000	380,000
PCC Surface Course (inches)	5.5	6.5	7.0	7.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	11.5	12.5	13.0	13.0
Design ESALs for 4 Percent Truck Traffic	190,000	380,000	570,000	760,000
PCC Surface Course (inches)	6.5	7.0	8.0	8.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	12.5	13.0	14.0	14.0
Design ESALs for 6 Percent Truck Traffic	285,000	570,000	855,000	1,139,000
PCC Surface Course (inches)	7.0	8.0	8.5	8.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	13.0	14.0	14.5	14.5

Notes:

1. The stabilized subgrade was assumed to be 6 inches for all conditions.
2. The PCC slab was assumed to have a 28-day modulus of rupture of 570 psi and an elastic modulus of 3,600,000 psi.
3. The existing subgrade soils below the flexible pavement sections were assumed to have an effective CBR value of 5.
4. A load transfer coefficient of 3.6 was assumed.
5. Summary of other design inputs: $S_o = 0.4$, R = 90%, $P_i = 4.5$, and $P_i = 2.25$.

Table 4.4.3 Limited Rigid Pavement Analysis Based on Variable Traffic Frequencies, Magnitudes of Loading, and Design Periods (ADT = 10,000 VPD)

ADT = 10,000 vehicles per day (Major Collector)				
Pavement Layers	**Design Period**			
	10 years	**20 years**	**30 years**	**40 years**
Design ESALs for 2 Percent Truck Traffic	170,000	339,000	509,000	678,000
PCC Surface Course (inches)	6.5	7.0	7.5	8.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	12.5	13.0	13.5	14.0
Design ESALs for 4 Percent Truck Traffic	339,000	678,000	1,017,000	1,355,000
PCC Surface Course (inches)	7.0	8.0	8.5	9.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	13.0	14.0	14.5	15.0
Design ESALs for 6 Percent Truck Traffic	509,000	1,017,000	1,525,000	2,033,000
PCC Surface Course (inches)	7.5	8.5	9.0	9.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	13.5	14.5	15.0	15.5

Notes:

1. The stabilized subgrade was assumed to be 6 inches for all conditions.
2. The PCC slab was assumed to have a 28-day modulus of rupture of 570 psi and an elastic modulus of 3,600,000 psi.
3. The existing subgrade soils below the flexible pavement sections were assumed to have an effective CBR value of 5.
4. A load transfer coefficient of 3.6 was assumed.
5. Summary of other design inputs: S_o = 0.4, R = 90%, P_i = 4.5, and P_i = 2.5.

Table 4.4.4 Limited Rigid Pavement Analysis Based on Variable Traffic Frequencies, Magnitudes of Loading, and Design Periods (ADT = 20,000 VPD)

ADT = 20,000 vehicles per day (Minor Arterial)				
Pavement Layers	**Design Period**			
	10 years	**20 years**	**30 years**	**40 years**
Design ESALs for 2 Percent Truck Traffic	339,000	678,000	1,017,000	1,355,000
PCC Surface Course (inches)	7.5	8.5	9.0	9.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	13.5	14.5	15.0	15.5
Design ESALs for 4 Percent Truck Traffic	678,000	1,355,000	2,033,000	2,710,000
PCC Surface Course (inches)	8.5	9.5	10.0	10.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	14.5	15.5	16.0	16.5
Design ESALs for 6 Percent Truck Traffic	1,017,000	2,033,000	3,049,000	4,065,000
PCC Surface Course (inches)	9.0	10.0	10.5	11.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	15.0	16.0	16.5	17.0

Notes:

1. The stabilized subgrade was assumed to be 6 inches for all conditions.
2. The PCC slab was assumed to have a 28-day modulus of rupture of 570 psi and an elastic modulus of 3,600,000 psi.
3. The existing subgrade soils below the flexible pavement sections were assumed to have an effective CBR value of 5.
4. A load transfer coefficient of 3.6 was assumed.
5. Summary of other design inputs: $S_o = 0.4$, $R = 95\%$, $P_i = 4.5$, and $P_i = 2.5$.

Table 4.4.5 Limited Rigid Pavement Analysis Based on Variable Traffic Frequencies, Magnitudes of Loading, and Design Periods (ADT = 40,000 VPD)

ADT = 40,000 vehicles per day (Residential Roadways)				
Pavement Layers	**Design Period**			
	10 years	**20 years**	**30 years**	**40 years**
Design ESALs for 2 Percent Truck Traffic	678,000	1,355,000	2,033,000	2,710,000
PCC Surface Course (inches)	9.5	10.0	11.0	11.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	15.5	16.0	17.0	17.0
Design ESALs for 4 Percent Truck Traffic	1,355,000	2,710,000	4,065,000	5,420,000
PCC Surface Course (inches)	10.0	11.0	12.0	12.5
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	16.0	17.0	18.0	18.5
Design ESALs for 6 Percent Truck Traffic	2,033,000	4,065,000	6,100,000	8,130,000
PCC Surface Course (inches)	11.0	12.0	12.5	13.0
Chemically Stabilized Subgrade (inches)	6.0	6.0	6.0	6.0
Total Thickness of Pavement Section	17.0	18.0	18.5	19.0

Notes:

1. The stabilized subgrade was assumed to be 6 inches for all conditions.
2. The PCC slab was assumed to have a 28-day modulus of rupture of 580 psi and an elastic modulus of 3,600,000 psi.
3. The existing subgrade soils below the flexible pavement sections were assumed to have an effective CBR value of 5.
4. A load transfer coefficient of 3.6 was assumed.
5. Summary of other design inputs: S_o = 0.4, R = 99%, P_i = 4.5, and P_i = 2.5.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This section of the report provides a summary of the limited analysis along with conclusions that can be drawn from the results of the limited analysis. In addition, the section also provides recommendations for future studies and practices that may be considered by the City.

5.1 OBJECTIVE OF LIMITED ANALYSIS REVISITED

As previously discussed in Section 1.0, there were two primary objectives associated with the limited analysis of flexible and rigid pavements. The two primary objectives can be summarized as follows: (1) evaluation of the existing minimum flexible and rigid pavement sections outlined in the BCSUDGSA for residential roadways and minor collector based on variable subgrade stiffness or strength; and (2) performance of a limited analysis of various flexible and rigid pavement sections based on the following factors: (a) variable traffic frequencies that are typical of the roadway classifications outlined in Table V – *Street Classification Definitions* of the BCSUDGSA, i.e. residential roadways, minor collectors, major collectors, minor arterials, and major arterials; (b) variable percentages of truck traffic that could be considered typical for each roadway classification, i.e. 2 percent, 4 percent, and 6 percent; (c) variable design periods or analysis periods, i.e. 10 years, 20 years, 30 years, and 40 years; and (d) a single subgrade soil stiffness or strength that is considered representative of the predominately cohesive subgrade soils, i.e. clays, typically encountered in the College Station area. The results of the evaluation performed for the existing minimum flexible and rigid pavement sections outlined in the BCSUDGSA are presented in Section 3.0 along with a summary of the results. The results of the limited analysis of flexible and rigid pavement sections was presented in Section 4.0 along with a summary of some of the conclusions developed from the results. The various assumptions required to perform both portions of the analysis were outline in each respective section.

5.2 CONCLUSIONS

Based on the assumptions previously outlined in Sections 3.0 and 4.0 and the results of the limited analysis, the following conclusions can be made:

- The performance of the minimum flexible a rigid pavement sections outlined in Table VIII of the BCSUDGSA for residential roadways and minor collectors will rely heavily on the effective stiffness of strength of the subgrade soils supporting the pavement section and the frequency and magnitudes of traffic utilizing the pavement section. More specifically, the maximum allowable ESALs on a residential roadway and minor collector will be approximately twice as much for a roadway founded on a subgrade with an effective CBR of

5 compared to a roadway founded on a subgrade with an effective CBR or 3. It's worth noting that larger effective subgrade stiffnesses or strengths than those considered in this limited analysis will allow for an increase in the maximum allowable ESALs that the minimum flexible pavement sections can support over a given design period.

- Based on the extended evaluation performed for the minimum flexible pavement sections outlined in the BCSUDGSA, the theoretical design life computed for flexible pavement sections (with a flexible base course of crushed limestone) founded on subgrade soils with an effective CBR of 3 ranged from approximately 6 to 10 years. This agrees with the City's previously referenced observations which concluded that some residential roadways and minor collectors constructed using the current minimum design pavement sections are requiring significant maintenance or rehabilitation shortly after construction.
- The current minimum pavement sections outlined in the BCSUDGSA for residential roadways and minor collectors are not "equivalent". More specifically, the structural capacities of the minimum rigid pavement sections are much larger than the structural capacities of the minimum flexible pavement sections.
- The required design thickness of any flexible and rigid pavement section will rely heavily on the percentage of truck traffic and magnitudes of truck traffic that travel either type of pavement system over a given period of time. As a result, it is imperative that accurate traffic information be obtained prior to the selection and design of a pavement section for a given roadway functionality class.

5.3 RECOMMENDATIONS FOR FUTURE STUDIES AND PRACTICES

Based on the results of the limited analysis and previous experience regarding the design of flexible and rigid pavement systems, CME has developed various recommendations for future studies and practices that may be considered by the City. The recommendations for future studies and practices that appear most notable for the current problems being experienced by the City can be summarized as follows:

- Consider implementing in-situ field CBR testing or dynamic cone penetration testing on subgrade soils prior to the construction or reconstruction of a roadway in order to verify existing subgrade stiffnesses or strength.
- Consider requiring that a subgrade soils stiffness or strength is verified prior to utilizing the minimum flexible pavement sections outlined in the BCSUDGSA. This would require establishing a minimum subgrade stiffness or strength for residential roadways and minor collectors. If the minimum subgrade stiffness or strength is not met, the minimum flexible pavement sections should not be utilized for a given roadway.
- Evaluate the physical properties of existing flexible and rigid pavements in the College Station area for variable roadway functionality classes based on falling weight deflectometer (FWD) testing. This evaluation should be performed on distressed and un-distressed roadways so that a determination can be made as to what is the primary source of failure or success of the pavement systems evaluated.
- Consider revising the current minimum flexible and rigid pavement sections outlined in the BCSUDGSA based on the numerous variables addressed in this report.

- Traffic studies should be performed for roadways currently in use to develop more extensive data concerning the volume and characteristics of the traffic utilizing that various classifications of roadway. In particular, CME believes that construction traffic on residential roadways and minor collectors may be contributing to the rapid failure in the minimum flexible pavement sections outlined in the BCSUDGSA. One segment of the suggested traffic studies should focus on documenting construction traffic. Another segment of the study should also focus on the characterization traffic associated with the production and operation of oil and gas wells within the City's jurisdiction...
- In addition, extended traffic studies should also be undertaken for recently constructed roadways to document initial serviceability and to track the loss in serviceability over time.
- Based on previous project experience, CME believes that traffic studies are often performed inadequately if performed at all. As previously discussed, the frequency and magnitude of traffic a roadway is subject to will have a significant impact on the total design thickness of a given roadway. As a result, CME recommends that detailed traffic studies be performed for any roadway that is desired to perform successfully over the selected design period.

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