Sacramento Transportation Infrastructure Implementation Guidance

January 2026

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1.1 COOL PAVEMENT

Purpose and Background

This document presents guidelines and considerations concerning cool pavement technologies, emphasizing the installation of high solar reflectance (high albedo) materials and reflective coatings for pavements. These guidelines offer recommendations for new pavement construction using cool pavement materials as well as for maintaining existing pavement.

Typical asphalt concrete pavements have low reflectance and absorb a high percentage of heat energy from the sun resulting in an urban heat island. Cool pavement initiatives, e.g., use of high albedo materials and reflective coatings, increase the reflectance of solar energy resulting in lower heat absorption by the pavement.

Cool Pavement Types and Uses

This section summarizes several types of cool pavement techniques, their uses and construction considerations:

1. **Treatment with reflective coating to improve solar reflectance**: Conventional asphalt pavement can be treated with thin, light-colored material after construction to improve solar reflectance. Cities in California have used various types of reflective coatings for this purpose. Some patented products for reflective coatings include ePAVE, SunShield, Endurablend, GAF- DuraShield- SR, GuardTop CoolSeal, StreetBond, etc. These treatments do not increase structural capacity of the pavement.
2. **Cool Aggregate Asphalt**: For new construction, the aggregate used in conventional asphalt concrete can be modified with high albedo aggregates to increase solar reflectance. This option can be used for new construction in low to high traffic areas.
3. **Portland Cement Concrete (PCC) Pavement**: PCC pavement generally has high solar reflectance. Moreover, the solar reflectance can be further increased using white cement. Concrete pavements are suitable for the construction of trails, parking lots, roadways, and highways. Various types of concrete pavement like Jointed Plain Concrete Pavement (JPCP), Jointed Reinforced Concrete Pavement (JRCP), Continuously Reinforced Concrete Pavement (CRCP), Roller Compacted Concrete (RCC) and Precast Concrete Pavement (PCP) can be used for new construction.
4. **Whitetopping**: Whitetopping is generally used for pavement rehabilitation/ resurfacing through application of a PCC overlay on existing or new asphalt

pavement. Whitetopping has high solar reflectance. Thicker whitetopping (4 to 12 inches) can be used for high volume applications like major highways and urban streets. However, ultra-thin whitetopping, 2 to 4 inches thick, is typically used for parking lots and low volume roads.

5. **Microsurfacing with light color or reflective pigment**: Microsurfacing is a thin sealing layer generally used for preventive maintenance on asphalt pavement to restore pavement surface conditions and extend life. Using light colored aggregate or incorporating reflective pigments into the polymer-modified asphalt emulsion can increase solar reflectance of microsurfacing. This layer is not considered a structural layer.

6. **Chip seals with light-colored aggregate**: Chip seals are generally used to resurface low-volume asphalt roadways. Similar to microsurfacing, the use of light-colored aggregates can be used for chip seals to increase the solar reflectance of the pavement surface. Chip seals are not considered a structural layer.

Summary of current findings for Los Angeles Cool Streets program

Several studies have focused on the cool pavements installed throughout Los Angeles Metropolitan area in California. Some major findings from these studies are as follows:

- In a study in Covina, California, Ko et al (2022) found 30 percent reduction in albedo of the cool pavement in a year of real-world exposure. The study found that albedo degradation was dependent on the type of cool pavement product used, as well as tire wear, which led to more rapid degradation at curved road sections, cul-de-sacs, and intersections.

- In a study in Pacoima and Sun Valley neighborhoods north of Los Angeles, Middel et al. (2020) field observations show that high albedo solar reflective coatings on asphalt concrete reduce surface temperatures of Portland cement concrete sidewalk levels, especially in the mid-to-late afternoon hours. The study also reveals that pedestrian heat load in the early evening may be slightly higher on sidewalks if the road is not separated by a vegetated setback.

- In a study in El Monte, California, located in Los Angeles County, Taleghani et al. (2016) found that cool pavements reduced surface air temperatures in the unshaded receptors, but they also increased mean radiant temperature at the mean height of pedestrians during the day reducing the thermal comfort of pedestrians. The study concluded that cool pavements also absorbed less heat during the day and therefore released less at night, leading to reductions in nighttime surface air temperatures.

- These studies found that combining cool pavement with shade trees, bus shelters and vegetated parkways yield better results than cool pavements alone.

Construction Costs

Construction costs are influenced by numerous factors, including geographic location, prevailing climate conditions, subsurface soil characteristics, anticipated traffic volumes, and the intended lifespan of the pavement. See the table below for details on cool pavement types:

Table 1. Service life and construction costs of various pavement types

Type	Service Life (years)	Approx. Cost (per ft^2) with Reference Date	Initial SRI (%)	Color	Application Rate (Gallons/ ft^2)	Product Link	Application / Target Use
ePAVE*	5-10	$0.70 - $1.40 (2023)	35-45	Light Gray	0.01 to 0.02	ePAVE Product Page	Applicable as a coating on new or existing roadways. Generally used on low-volume roads, parking lots, playgrounds and sidewalks.
SunShield*	7-10	$1.40 - $ 1.90 (2024)	38-50	Light Gray/ Gray/ Khaki	0.01	SunShield Product Page	
Endurablend*	7-10	$3.50 - $4.50 (2023)	30-50	Concrete Gray	0.01 to 0.02	Endurablend Product Page	
DuraShield-SR*	5-7	$0.85 - $1.25 (2022)	34	Gray Acrylic	0.01	DuraShield SR Product Page	
GuardTop Coolseal*	6-7	$0.60 - $1.10 (2021)	35 - 45	Phoenix Gray/ Classic Gray	0.02 to 0.035	Coolseal Product Page	
StreetBond SB 150 with Invisible Shade*	5-7	$1.00- $1.20 (2024)	30 – 45	Irish Cream/ Khaki/ Fawn	0.02	StreetBond Product Page	
Asphalt pavement modified with high albedo materials (New Construction)	>20	**	25 - 35	Light Gray (depends on aggregate)	Varies	N/A	Suitable for all types of roadways, parking lots, bike lanes, sidewalks
Portland Cement Concrete Pavement	>30	**	40 - 50	Light Gray	Varies	N/A	

(New construction)							
Whitetopping	>20	**	40 - 5 0	Light Gray	Varies	N/A	Used as overlay on asphalt pavement.
Microsurface with high albedo aggregates or reflective pigment	5-7	$2.50 - $4.50 (2024)	35	Light Gray (depends on aggregate)	Varies	N/A	Used for extending pavement life for low to medium volume roads, and parking lots.
Chip seals with high albedo aggregates	5-7	$0.85 - $1.25 (2025)	25 - 35	Light Gray (depends on aggregate)	Varies	N/A	Used for roadway maintenance generally for low volume roads and parking lots.
Traditional asphalt pave ment	>20	**	5-10	Dark	Varies	N/A	All types of roadways, parking lots, bike lanes, sidewalks

** These treatments with reflective coatings. The costs mentioned for treatment with reflective coatings are in addition to the cost of the traditional/existing pavement that is structurally supporting the reflective coating.*
*** The cost for these depends on the pavement thicknesses and requirements for base layer types and thickness. The thickness also depends upon the traffic conditions, subgrade conditions, climatic conditions, and proposed pavement properties.*

Benefits

Use of cool pavements have both direct benefits and indirect benefits, including:

- Cool pavement techniques using high albedo material and reflective coating may help with reduction in the urban heat island effect. Reducing pavement surface temperatures can reduce the heat stress on the pavement resulting in decreasing the risk of premature failure of asphalt by rutting. This may extend the pavement life and delay maintenance cycle.

- Case studies from Los Angeles, California and Phoenix, Arizona show the reduction in the overall temperature at night after implementation of the cool pavement techniques. At a large scale, this may reduce air conditioning demand and save money.

- Improved visibility at night due to the use of reflective coatings may reduce lighting requirements and save energy.

- Cool pavements may improve air quality by lowering surface temperatures that contribute to the formation of certain air pollutants, and may promote outdoor activities providing cooling when paired with other shade treatments. Similarly, cooler pavement surfaces improve water quality by decreasing the warming of water runoff from these surfaces.

Costs of cool pavements depend upon the method and technology used. Most of the cool pavement technologies can be used in place of traditional pavements at a comparable or slightly higher cost. However, due to the numerous benefits noted above, there may be sufficient benefit to justify the higher installation costs, although these listed benefits may not directly support the financial investment of pavement installation and maintenance. Lifecycle cost assessments can help evaluate the cost savings potential from cool pavement techniques.

Other Considerations

Some additional considerations for installation of cool pavement techniques are discussed below:

- Striping and safety considerations: Reflective coating can affect adhesion of striping materials and cause them to wear off more quickly. Therefore, they require more frequent restriping cycles.

  Many coatings have their own compatible striping methods. Where necessary, pavement markings can be grooved into the base material after treatment. In addition, cool pavements are typically light in color and might reduce contrast with standard white and yellow markings. Some projects in Los Angeles have used heated thermoplastic striping and/or black borders around white or yellow markings to improve longevity of the bond with asphalt and visibility.

  The striping used should follow the Manual on Uniform Traffic Control Devices (MUTCD) and Caltrans specifications for line width, color, and placement. Skid resistance testing should be conducted after the application of reflective coating. To address the safety concern due to glare issue for the vehicle traffic, the Sacramento Metropolitan Air Quality Management District (SMAQMD) recommends that the solar reflectance for roadways and adjacent walls not exceed the value of 0.35.

- Care should be taken when selecting a treatment to ensure that the local market, or national providers, will be able to procure and properly apply the materials within the desired construction window.

- Build America Buy America (BABA) constraints may exist for some potential treatments. These may be addressed through product selection, waiver request, or alternative funding mechanisms, depending on the project and the selected treatment.

- Performance monitoring and measurement: As evident from different studies, the performance of cool pavement depends on the cool pavement methods used, climate, traffic conditions, and presence of other cooling measures. Hence, it is recommended to monitor the performance of installed cool pavement types and measure the direct benefits. Performance monitoring at some pilot projects might be beneficial.

- Environmental Impacts: Cool pavements can have both positive and negative impacts on the environment.

  Positive impacts include potential reduction in cooling demand in nearby buildings resulting in lowering greenhouse gas emissions from power generation and improvement of water and air quality as an indirect benefit of lower pavement surface temperature.

  Negative impacts include potential higher initial energy and resource use for the manufacturing of light-colored coatings or additives.

Limitations

- In their cool pavement overview, SMAQMD recommends solar reflectance for roadways and adjacent walls to not exceed the value of 0.35 to avoid glare issues for the vehicle traffic. Hence, highly reflective material should not be used as the reflective coating on roadways.

- Cool pavements may not be appropriate in high pedestrian-use areas, as it may increase thermal load on pedestrians during the day.

- Numerous studies have shown that combining cool pavement techniques with urban green infrastructure, like shade trees and vegetated parkways, provides better results for reduction of heat island effects compared to cool pavement alone. Therefore, when estimating the effect of cool pavement on heat island and performing life cycle assessment, the presence of vegetation should be considered.

- The solar reflectance of cool pavement materials decreases with time.

- Some coatings may alter skid resistance of the pavement, impacting traction during wet conditions. Skid resistance tests should be conducted.

Benefit-Cost Analysis

This section provides a hypothetical example to illustrate a benefit-cost analysis (BCA) comparing the cost-effectiveness of various cool pavement options against traditional asphalt pavement. The analysis assumed a roadway segment 2,600 ft long and 24 ft wide located in Sacramento, CA. The baseline scenario used traditional asphalt pavement, while the cool pavement (referred to as “enhanced”) scenarios evaluated eight alternatives involving cool pavement applications over regular asphalt.

The primary benefit of cool pavement is its ability to reduce surface temperatures, which may extend pavement service life and lower energy demand for cooling nearby buildings. Accordingly, the benefits considered in this analysis include delayed maintenance cycles, reduced building energy consumption, and associated emission reductions.

To monetize energy and emission benefits, the roadway is assumed to be in a dense residential area with single-family homes on both sides. Based on a 50-ft lot width, 100 buildings were included in the energy benefit analysis. Each home is assumed to have an annual cooling demand of 1,600 kWh, with an average electricity price of $0.21/kWh (SMUD (2010, 2023)). The analysis assumes 532 affected hot hours per year, based on 76 days exceeding 90°F, and a cooling degree day (CDD) value of 1,700 for the Sacramento area from NHCI (2023). The average temperature reduction from cool pavement is assumed to be 1.8°F (1°C) based on literature findings (Santamouris, 2017). Emission reductions were monetized using a fixed emission factor of 0.000207 tCO_2e/kWh from Climatiq (2023) and a social cost of carbon of $265/$tCO_2e$ from UCSC (2023).

Lifecycle costs for cool pavement applications and their reapplication cycles were based on the average of the values provided in Table 1. For the enhanced scenarios, it was assumed that the annual maintenance activity was similar to that of traditional asphalt pavement while the reapplication of the cool pavement happened at the end of the service life, taking the average of values provided in Table 1. For the baseline scenario, annual maintenance costs of $0.08/ft^2 and capital preventive maintenance of $4.25/ft^2 after 20 years were applied, following recommendations from Caltrans (2025). The lifecycle BCA covered the period 2025–2050 using a 7% discount rate, as recommended by USDOT (2025). In this analysis, Benefit-Cost Ratio (BCR) represents the ratio of total monetized benefits to the additional costs of the enhanced scenario beyond the baseline. A BCR greater than 1 indicates benefits exceed incremental costs.

A summary of the results is presented in Table 2.

Table 2. Summary of lifecycle costs and benefits for different enhanced scenarios

Type	Construction Costs ($)	Maintenance Cost Difference ($)	Energy Saving ($)	Benefit-Cost Ratio
Treatment with ePAVE	71,760	21,317	12,585	0.14
Treatment with SunShield	109,200	53,541	12,585	0.08
Treatment with Endurablend	268,320	231,420	12,585	0.03
Treatement with GAF DuraShield-SR	76,128	53,528	12,585	0.10
Treatment with GuardTop Coolseal	57,408	92,046	12,585	0.08
Treatement with StreetBond	70,512	44,524	12,585	0.11
Microsurface with high albedo aggregates	227,760	296,650	12,585	0.02
Chip seals with high albedo aggregates	65,520	36,520	12,585	0.12

The main takeaways of the assessment include:

- Cost-effectiveness was relatively low. The Benefit-Cost Ratio (BCR) ranges from 0.02 to 0.14 across options. This suggests that none of the evaluated cool pavement options are cost-effective for this hypothetical scenario.
- Overall, energy savings and emission reductions are relatively small benefits compared to the net increases in costs. It should be noted that delay in maintenance for cool pavements is still under research, so actual maintenance costs may differ from assumptions.
- Additional potential benefits such as improved nighttime visibility, enhanced safety, and potential urban heat island mitigation are not captured in this analysis, meaning the true value of some treatments may be understated.

Conclusion

Cool pavement technologies offer potential for mitigating urban heat island effects and improving sustainability, but cost-effectiveness may be somewhat limited and should be evaluated case-by-case using lifecycle analysis and performance monitoring. Decision-making should also consider factors like economies of scale, maintenance uncertainty, and unmonetized benefits such as improved visibility and safety.

As a potential next step, the City could implement one of the lower-cost cool pavement treatments in a pilot location to evaluate cool pavement maintenance and everyday performance. A good pilot location would be a low- to moderate-loading area, where slower traffic reduces risk and limits impacts if failure occurs. This controlled application would generate critical performance data before broader deployment.

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1.2 PERVIOUS PAVEMENT

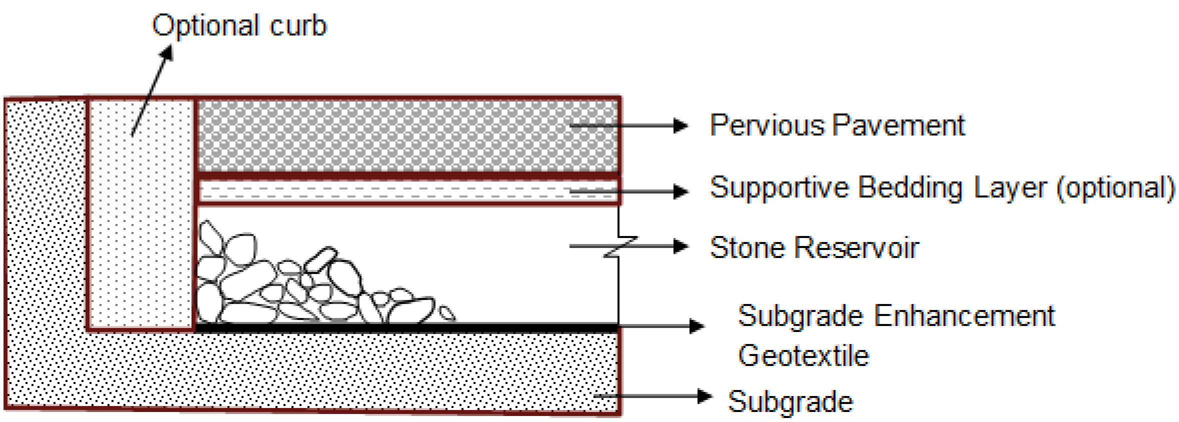
Purpose and Background

This document outlines general guidelines and key considerations for pervious pavement systems in the Sacramento area, including advantages and limitations; design, construction, and maintenance considerations; and the general cost of different methods.

Prior to implementing pervious pavement, it is important to assess both the project's functional feasibility and cost (e.g., construction and long-term maintenance and overall cost effectiveness of the pervious pavement). Currently, pervious pavements are not recommended for use on highways, high volume roads, and in close proximity to structural foundations. They can be used in areas with no-to-limited vehicular access, parking lots, sidewalks, bike lanes, rest areas, fire lanes (if Sacramento’s Fire Department allows), maintenance stations, and maintenance access roads.

Pervious Pavement Section and Types

A pervious pavement can have the following layers and elements: (1) pervious pavement including (asphalt, concrete, grass paver, or blocks), (2) Optional open graded bedding course, (3) stone reservoir, (4) subgrade enhancement geotextile, and (5) optional curb. The figure below shows a schematic of a pervious pavement.



The surface layer allows the water to flow freely into the reservoir, where the water is stored before it leaves the pavement structure.

The pervious pavements can be generally divided into the following groups:

1. Non-modular permeable pavement including Permeable Asphalt Pavement (PAP) and Pervious Concrete Pavement (PCP)
2. Modular permeable pavement: Permeable concrete pavers (Concrete Pavers, Permeable Interlocking Concrete Pavement (PICP)), Paving Blocks such as ECORASTER BLOXX and Powerblock permeable pavers,

Schematic sections of these pavement types are presented in Exhibit A.

Advantages of Pervious Pavement

Pervious pavements offer a wide range of environmental and functional benefits that make them a strong choice for sustainable infrastructure. They improve stormwater control by reducing runoff rate, infiltrating runoff into the ground, providing temporary storage of runoff, and reducing flood risk. They also improve the quality of stormwater runoff by filtering contaminants and pollutants, which reduces the water treatment burden for stormwater systems, with pervious pavement capable of removing between 13 and 99% of contaminants and suspended solids, and pervious asphalt generally having the best performance. Storing water in a pavement reservoir prior to discharge can reduce the temperature of runoff from hot rooftops and pavement surfaces, thus reducing thermal pollution.

In addition, open graded pavements—like those used in pervious pavements—may reduce tire pavement noise and enhance vehicle safety by reducing water spray and splash from moving vehicles and increasing traction through better water drainage. These combined benefits make pervious pavements a useful and effective option for a wide range of applications.

Design Guidance

Feasibility

Prior to designing the pervious pavement, a site investigation is necessary for evaluation of the functional feasibility of pervious pavements for a project site based on hydrology and hydraulic design, soil permeability, pavement thickness design, and environmental regulations. A site can be acceptable for construction of pervious pavement only if the reservoir layer can be designed to infiltrate the runoff in the appropriate drawdown time. The factors influencing the feasibility of the projects are:

- **Hydrology and hydraulic design**: Hydrology and hydraulic design are used to estimate the hydraulic storage requirements of the pavement and the amount of runoff in the project site. For using pervious pavement, the groundwater should be 2 to 3 feet below the seasonal high-water level.
- **Soil permeability**: Geology and subsurface material can play a significant role in determining the soil permeability and drainage requirements of pervious pavements. The best areas for construction of pervious pavements are within hydrological soil groups A and B (on NRCS soil survey) which have low and moderately low runoff potential.

  Soil group A includes soils such as well-drained sands or gravels with low clay content with high infiltration rates and very low runoff potential. Soil group B includes soils such as moderately well-drained soils with a mix of sand, silt, and only modest clay content, with moderate infiltration rates and moderate runoff potential. Soil groups C and D consist of soils with higher clay content, with low to very low infiltration rates and high and very high runoff potential respectively.

  The City of Sacramento lies within the Great Valley geomorphic province, a broad and relatively flat alluvial plain characterized by a thick accumulation of sediments deposited in a bedrock trough. The subsurface material includes a combination of different contents of fat or lean clay, silt, and sand. A geological map of the city is shown in Exhibit B, along with the dominant soil type encountered in the top 5 feet for a few selected projects throughout the city. Based on the available information, and due to the variability of the Alluvium Formation, site-specific subsurface investigation should be performed for each project to identify the soil permeability and drainage requirements. This subsurface investigation should include soil borings, soil classification tests, soil permeability test, and compaction test to identify the site suitability. One infiltration test (in accordance with CT 220) every 0.25 acres is recommended and any reduction in test requirements should be done with the City's approval. The test should be performed in the field on the in-situ samples, and then repeated on remolded samples compacted at multiple relative compaction levels, with the compaction range not exceeding 4 percent with acceptable infiltration rates.

- **Pavement thickness** should satisfy the pavement structural design requirements and reservoir layer design requirements as detailed in the following section.
- **Environmental regulations**, including preventing soil and groundwater contamination. Pervious pavements can be designed to reduce the concentration of contaminants such as phosphorus and nitrogen, metals, and suspended solids from the stormwater. This can be achieved by different methods such as partial infiltration design that can store water for over 24 hours, using specially coated aggregates in the joints and beddings, adding a filter layer of sand or fine aggregates under the permeable pavement, and sloping the site by intermittent berms to allow the suspended material settle.

Design Guidelines

The design of the pervious pavement includes empirical structural design of the pervious pavement and the reservoir, and estimation of the thickness of the reservoir to store the runoff (Water Quality Volume (WQV)). The following recommendations are provided:

1. Structural design: the pervious pavement and reservoir should be able to support the applied load and traffic. The structural design depends on the type of pavement, total traffic, soil strength, and environmental elements.
    - If traffic information is not available, Table 613.4A of Caltrans Highway Design Manual (HDM) can be used.
    - For Pervious Asphalt (including open graded friction course (OGFC) over asphalt treated permeable base (ATPB)), a typical thickness of 0.1 ft can be used for OGFC. The ATPB can be designed based on the empirical or Mechanistic-empirical methods provided in HDM topic 633.

- For Pervious Concrete the following minimum thicknesses are recommended based on the application of the pavement: for locations with non-vehicular loads: 4.2 inches; for parking, maintenance roads, sidewalks and bike paths where a few heavy loads are anticipated: 5.4 to 6 inches; for rest areas and maintenance roads (where Traffic Index (TI)<9): 8.4 inches; and for bus stop pads and areas where TI is 9 to 10: 9.6 inches. Dowel bars or Tie bar are not used in pervious concrete design.
- For Permeable Interlocking Concrete Pavement (PICP) thicknesses of 2-3/8 inches for pedestrian areas and 3-1/8 inches for areas with vehicular traffic are recommended. Concrete pavers must conform to ASTM C936. A two-inch layer of bedding is required between 0.35 feet Class 3 AB course and pavers.
- For the reservoir layer, Class 4 AB material should be used. A minimum thickness 0.5 ft is considered for all types of pervious pavement for constructability. The bottom of this layer should be 1 inch lower than any adjacent non-permeable pavement structure.

Caltrans pervious pavement design guidance (July 2023) section 4.3.5 provides minimum required layer thicknesses based on the application of the project.

2. Reservoir layer design: The thickness of the reservoir layer should be the maximum of (1) the thickness required for structural design of the pavement (mentioned in the previous section) (2) the thickness required to store the runoff, so that the stored water can infiltrate into the subgrade soil within a given drawdown time. For determination of this thickness the guidelines provided in Section 3.2 of Caltrans Stormwater Quality Handbooks - Pervious Pavement Design Guide, July 2023, should be followed.

Standard approaches to stormwater control should be put in place as the permeability of the pavement system will deteriorate over time. This guidance is covered in more detail in the following section.

There may be additional design requirements included in the Pervious Pavement Design Guidance by Caltrans that should be followed.

Installation/Construction Considerations

The following should be considered during construction and installation of pervious pavement:

- The **materials** used in the pervious pavement typically includes open graded aggregates that are hard, durable, and have low percentage of fine material. These materials should be in accordance with the non-standard specifications for pervious pavement bases, PCP, PAP and PICP provided by Caltrans. Care must be taken to avoid fouling of the base during construction and staging should avoid haul or traffic atop the drain bed, as it may rut easily.

- **Subgrade preparation**: The pervious pavement section cannot be placed on embankment material. Elevating the existing ground should be minimal and the reservoir layer material is recommended as the fill material. Barriers should be used when embankment materials are present on the sides of the pervious pavement installation.

  Subgrade preparation should be completed during dry weather conditions.

  The subgrade should be compacted to maintain a balance between infiltration rate and structural integrity. For this purpose, a range of compaction should be defined for the subgrade material with acceptable infiltration for the contractor to follow.

  Resilient Modulus (Mr) of the soil should be determined in accordance with HDM Topic 614. MR is required for Caltrans CalME flexible pavement design method to determine thickness of the reservoir layer and surface layers for PAP and PICP.

  A subgrade enhancement geotextile fabric should be placed on top of the subgrade soil and below the reservoir layer, if recommended by Caltrans Geotechnical Services. The geotextile can also be used between the pervious pavement and adjacent soil. The fabric can be used to reduce migration of fine materials into the reservoir.

  The slope of the subgrade should be as flat as possible. A slope reduces the storage capacity of the pervious pavement.

- **Drainage:** Pervious pavements are not designed to handle all stormwater from all storms. Further, as noted above, the permeability typically deteriorates over time. Therefore, typical drainage design required for stormwater control should be performed for any project with pervious pavement, which can include perforated drainage pipes, drain inlets, curb cut-outs, and possible additional subsurface piping.

For sites with slopes higher than 2% and/or low-infiltration soil, such as clay, additional measures may be required such as terraced subgrade and underdrain installation to intercept the water flow through the pavement. For clay material and soil groups C or D (on NRCS soil survey), it is also recommended to use a larger subbase layer and an impermeable layer (a geomembrane) between the subbase and the clay material to reduce soil expansion.

Based on the infiltration rate and subgrade condition, the pervious pavements can be divided into full, partial, and low infiltration. According to Caltrans permeable pavement design, the required infiltration is based on the thickness of reservoir layer and a drawdown time of 72 hrs. Full infiltration occurs when the stored water can flow fully through the subgrade. In this case no underdrain is required. For partial infiltration, an outlet pipe is required at the bottom of the reservoir layer. If the pavement is supported by expansive soil, fill, or is placed close to a building structure, an impermeable layer (e.g. geomembrane) should be used along with underdrain pipes to outflow the water from the reservoir layer (low infiltration).

Exhibit C shows schematic cross sections for full, partial, and low infiltration pervious pavements. The pervious area should be protected from the adjacent stormwater runoff areas (especially if unpaved and not constructed yet). The sediments from these areas can affect the performance of the pervious pavement.

- Traffic over the pervious pavement during construction should be limited as much as possible.
- For pervious asphalt, prime coat and tack coat cannot be applied prior to placement of ATPB and OGFC. However, the OGFC can be replaced if worn out.
- For pervious concrete, all the standard requirements for concrete placement applies, such as, control of water content, unconfined compressive strength testing, timing of concrete curing, extending curing membrane beyond the paved area to adequately secure the edges, and covering the pavement for full 7 calendar days to maintain structural capacity. Inspection should be performed by a National Ready Mixed Concrete Association (NRMCA) certified personnel.
- Any additional requirements or considerations mentioned in the Pervious Pavement Design Guidance of Caltrans should be followed.
- Prior to embarking on pervious pavement, it is critical to make sure that sufficient contractor and consultant knowledge and skill is present. If necessary, outreach and training can provide local confidence to foster a productive bid and construction environment.
- Build America Buy America (BABA) constraints may exist for some potential treatments. These may be addressed through product selection, waiver request, or

alternative funding mechanisms, depending on the project and the selected treatment.

Unit Costs

Permeable pavements may be able to reduce long-term expenses by minimizing stormwater infrastructures and provide environmental benefits. However, their initial cost is higher due to more complex design and requirements, special materials, and labor-intensive installation. Their initial cost depends on various factors like region, local climate, underlying soil conditions, drainage requirement, expected traffic, pavement design life, etc. Table 3 estimates the service/design life, cost, and application of different pervious pavement types.

Pervious pavements will also require regular maintenance to maintain permeability. Maintenance needs are discussed in the following section.

Table 3. Service life and construction costs of various pavement types

Type	Service/Design Life (years)	Approx. construction Cost (\$ per ft^2)[1]	Application / Target Use
Pervious Asphalt	15-25	11 to 38	Parking lots, bike paths, maintenance access roads, sloped areas (<5%)
Pervious concrete	20-40	15 to 40	Sidewalks, parking lots, maintenance access roads, pedestrian zones, sloped areas (<5%)
Permeable Interlocking Concrete Pavement	25-40	36 to 53	Driveways, plazas, fire lanes (if Sacramento's Fire Department allows), urban streetscapes, areas where vehicles turn

Notes:

[1] The cost estimates here are based on Caltrans Cost Data Base, July 2023. These values include reservoir cost.

The cost of maintenance is not included in this table. Maintenance is discussed in the following section.

The cost values mentioned in this table are subject to change based on project size, location, and any other project specific requirements.

It is possible to reduce the cost of the project by limiting the pervious pavement area to the area necessary to control the runoff and using conventional pavements in other areas. In some areas, *depending on the native soil, it might be possible to place the pervious pavement on the soil without a need for the reservoir layer.*

Based on a nearby project experience, the cost of traditional asphalt and concrete pavement can be estimated to be in ranges between $5 to $20 for asphalt, and $8 to $25 for concrete pavements. The cost values mentioned in this table are subject to change based on project size, location, and any other project specific requirements.

Maintenance

The most important maintenance concern for any pervious pavements is clogging of pavement surface, reservoir, and underlying soil with sediments. Clogging can reduce infiltration rates and long-term performance of the pavement. The sediments and fine particles can come from the adjacent sites, the traffic on site, and the atmosphere. Clogging increases with age and use of the pavement; however, it generally does not lead to complete impermeability, but can reduce the infiltration rate to 1 inch per hour.

High performance vacuum sweeping, infiltration testing, and regular maintenance are required to maintain high permeability and mitigate clogging. An infiltration rate of 10 in/hr is a sign of near-clogged condition, and surface ponding after a storm is a sign of clogging. If jointing aggregates are removed during sweeping process, the openings should be re-filled with clean aggregates. Regular, documented observation, coupled with flow testing at intervals can be used to determine best practices for cleaning and maintenance based on local conditions.

Other maintenance requirements for pervious pavements are as follows:

- Time-appropriate removal of any debris, contaminated spills, or material and required pavement repair.
- Any damage to the drainage system should be promptly repaired. Sediment control measures should be maintained.
- For repair of PAP and PCP, similar material can be used. OGFC can be replaced if worn out; however, seal coat cannot be used for maintenance. The damaged PCIP blocks can be replaced.
- Structural integrity of the pavement should also be inspected regularly to find and repair the deteriorated areas.
- Pavement maintenance and/or repairs must maintain the permeability of the asphalt, concrete, and/or pavers for long-term functioning of these systems. This may require additional in-house trainings and monitoring, and/or additional contractor requirements.

Limitations

Although pervious pavements can be very useful when used in an appropriate site, there are limitations in conditions that they can be used.

- Pervious pavements may not be appropriate for locations with cohesive and expansive subgrade (low infiltration rate). It is recommended to remove and/or replace expansive soil, stabilize these soils using lime or cement, or install underdrains to reduce or eliminate expansion. Geomembranes can also be used under the pavement to prevent water from leaving the pavement from areas other than the designed outlets. These items can increase the cost of pervious pavement installation.
- Since pervious pavements are not as strong as conventional impervious pavements, they are not appropriate for applications in high traffic areas. Use of PICP in areas where TI > 9 is not recommended.
- Due to their permeability, pervious pavements are not appropriate for areas where hazardous materials are present, and spills and fuel leakage are possible. Similarly, loading areas with high sediment or areas with high vegetation debris should be avoided.
- Pavers and blocks should comply with the Americans with Disabilities Act. Application of large openings in PICP pavers containing aggregate should be limited for areas such as bike paths, sidewalks, or parking areas where disabled persons, bicycles, and the elderly are present.

Benefit-Cost Analysis

This section presents a hypothetical benefit-cost analysis (BCA) comparing the cost-effectiveness of pervious pavement and traditional concrete pavement. The analysis assumes a 180 × 240-foot (approximately 1 acre) parking lot located in Sacramento, CA. The baseline scenario uses traditional concrete pavement, while the pervious pavement (referred to as “enhanced”) scenario incorporates pervious concrete pavement.

To quantify costs, construction costs for the baseline scenario were taken as $15.46/ft^2 based on Caltrans’ cost estimation guidance for 7-inch traditional concrete pavement with 0.25 ft of HMA-Type A base and 0.5 ft of Class 2 aggregate subbase. Construction costs for the enhanced scenario were averaged from Table 3. Annual maintenance for both scenarios included $0.025/ft^2 for minor patching and sealing (if applicable) as per Caltrans’ recommendations. For pervious pavement, an additional annual maintenance cost of $0.014/ft^2 was assumed for vacuuming and cleaning clogged particles based on the stormwater best management practices (EPA, 2021).

The major advantage of pervious pavement is its ability to reduce runoff compared to impervious pavement, which has a runoff coefficient of approximately 0.95. Stormwater runoff reduction for pervious pavement typically ranges from 25% to 100%, based on findings compiled by the EPA (2021). To account for this variability, three cases were considered: low (25%), medium (60%), and high (100%) reduction. The economic value of runoff reduction is defined as the avoided cost of providing stormwater capture systems otherwise required for urban runoff from impervious pavement. To quantify stormwater volume at the site, the precipitation depth associated with 10-year storm event for the Sacramento area from SacAdapt vulnerability assessment was used and multiplied by the parking lot area. The unit cost of stormwater capture was assumed to be $2,000 per acre-foot, based on the median value (adjusted to 2025) of proposed stormwater capture projects in California (Xie et al, 2020). It should be noted that the unit cost estimate here was based on state-wide stormwater capture projects varied in process characteristics (e.g., with or without treatment).

Using the different levels of runoff reduction, monetary benefits were calculated for each case and compared with the additional cost of the enhanced scenario beyond the baseline to estimate the benefit-cost ratio. The lifecycle BCA spans 2025–2050 and applies a 7% discount rate, as recommended by the U.S. DOT (2025). In this analysis, Benefit-Cost Ratio (BCR) represents the ratio of total monetized benefits to the additional costs of the enhanced scenario beyond the baseline.

A BCR greater than 1 indicates benefits exceed incremental costs.

Results are provided in Table 4.

Table 4. Summary of lifecycle costs and benefits for different scenarios

Type	Construction Costs ($)	Maintenance Costs ($)	Runoff Benefits ($)	Benefit-Cost Ratio
Traditional Concrete Pavement	667,872	13,666	--	--
Pervious Concrete Pavement - Low Runoff Reduction	1,188,000	21,319	1,540	0.003
Pervious Concrete Pavement - Medium Runoff Reduction	1,188,000	21,319	3,696	0.007
Pervious Concrete Pavement - High Runoff Reduction	1,188,000	21,319	6,159	0.012

The key takeaways of the assessment include:

- The construction cost for pervious concrete pavement ($1.188 million) is nearly 78% higher than traditional concrete pavement ($667,872). This large upfront cost is the primary driver of the low benefit-cost ratios across all scenarios.
- While pervious pavement requires additional maintenance for vacuuming and cleaning, the difference in lifecycle maintenance costs ($21,319 vs. $13,666), if following best management practices, is relatively small compared to the construction cost gap. This suggests that maintenance is not a major factor in overall cost-effectiveness. However, required maintenance costs may prove higher than this estimate annual maintenance cost from EPA.
- Even under the high runoff reduction scenario (100%), the monetary benefit ($6,159) is small compared to the incremental cost of adopting pervious pavement, indicating that stormwater benefits alone cannot justify the additional investment under current assumptions.
- The analysis assumes a unit stormwater capture cost of $2,000 per acre-foot and a 7% discount rate. If these values change (e.g., higher stormwater capture costs or lower discount rates), the BCR could improve, but likely not enough to exceed 1 without substantial policy or market shifts.

Beyond stormwater runoff reduction, pervious pavement may provide additional benefits that were not monetized in this analysis but can influence decision-making. These include improved water quality by filtering pollutants during infiltration and enhanced groundwater recharge, which is critical in water-scarce regions. Pervious surfaces may also support regulatory compliance and reduce flood risk by lowering peak runoff volumes during heavy rainfall events.

Conclusion

The benefit-cost analysis shows that pervious pavement is generally not cost-effective when based solely on stormwater runoff reduction. However, decisions should also consider broader benefits such as improved water quality, groundwater recharge, and reduced flood risk. Pervious pavement applications that are strategically located to mitigate localized flooding—particularly for bicycle, pedestrian or transit facilities—may provide a sufficient benefit to justify the cost. Additionally, pervious pavements can be especially suitable in areas with sandy subgrade conditions that support infiltration.

Costs vary by design and maintenance, influencing feasibility. Interlocking pervious pavers may have a different BCR than pervious pavement and have been successfully used in private developments in Sacramento (e.g., The Mill).

Grant funding (e.g., from water quality and flood mitigation programs, in addition to climate and transportation programs) may be able to fund higher construction costs associated with pervious pavement. Additionally, pervious pavements and pavers may be an appropriate tool for private development as needed to meet requirements for on-site stormwater management.

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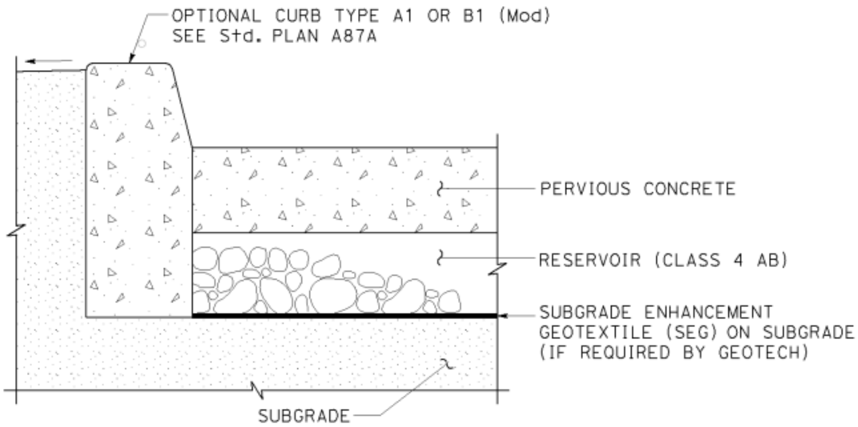
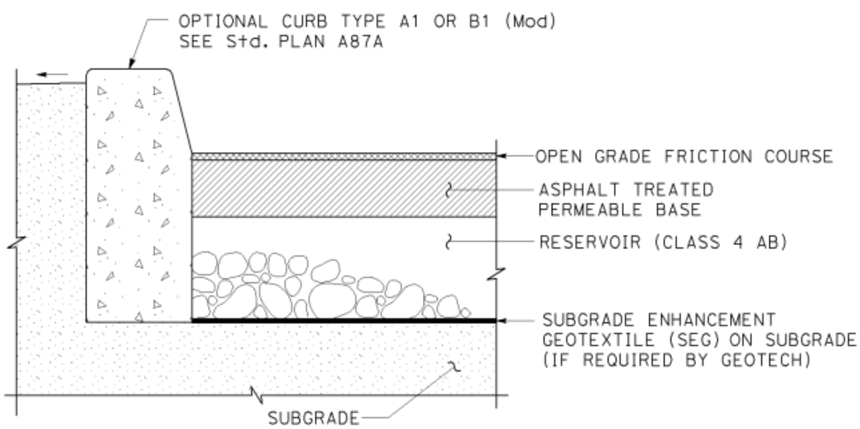
Exhibits

Exhibit A

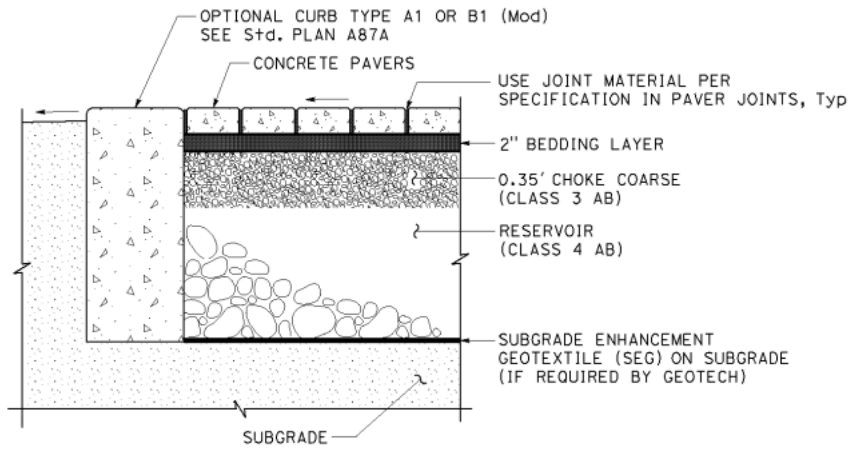
Selected Pervious Pavement Cross Sections



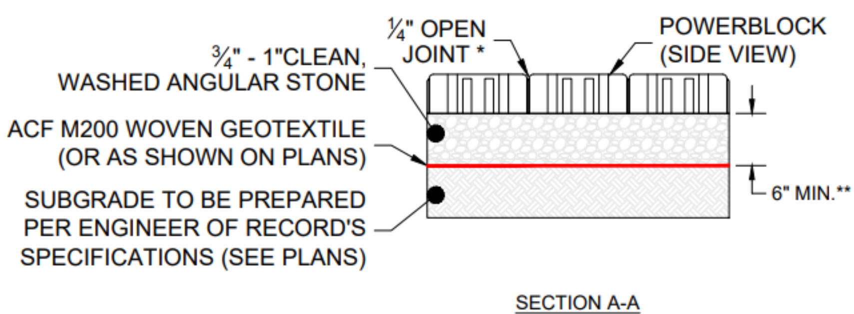
Pervious Concrete Pavement (PCP) Typical Section



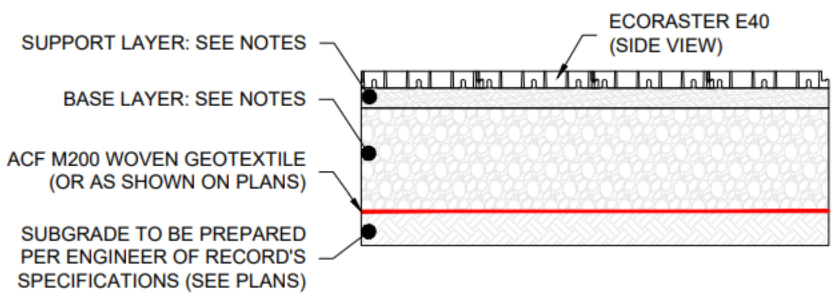
Pervious Asphalt Pavement (PAP) Typical Section



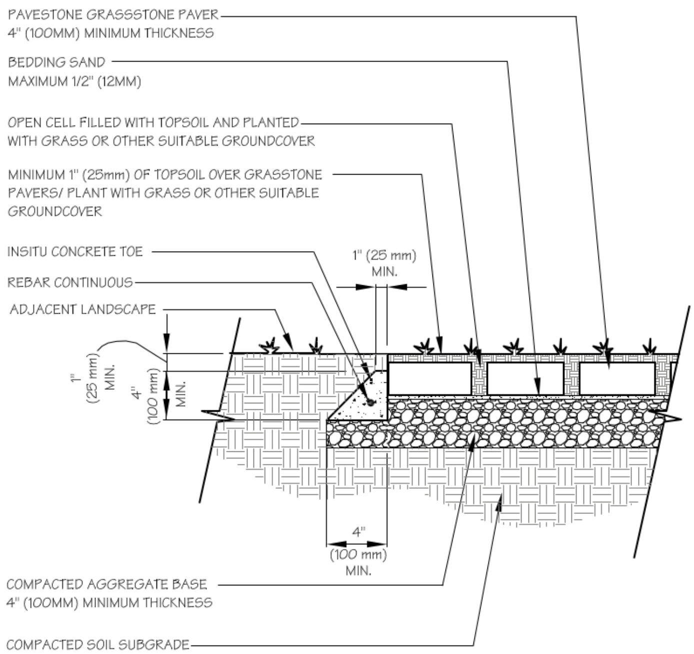
Permeable Interlocking Concrete Pavement (PICP) Typical Section



PowerBLOCK Permeable Paver Typical Section



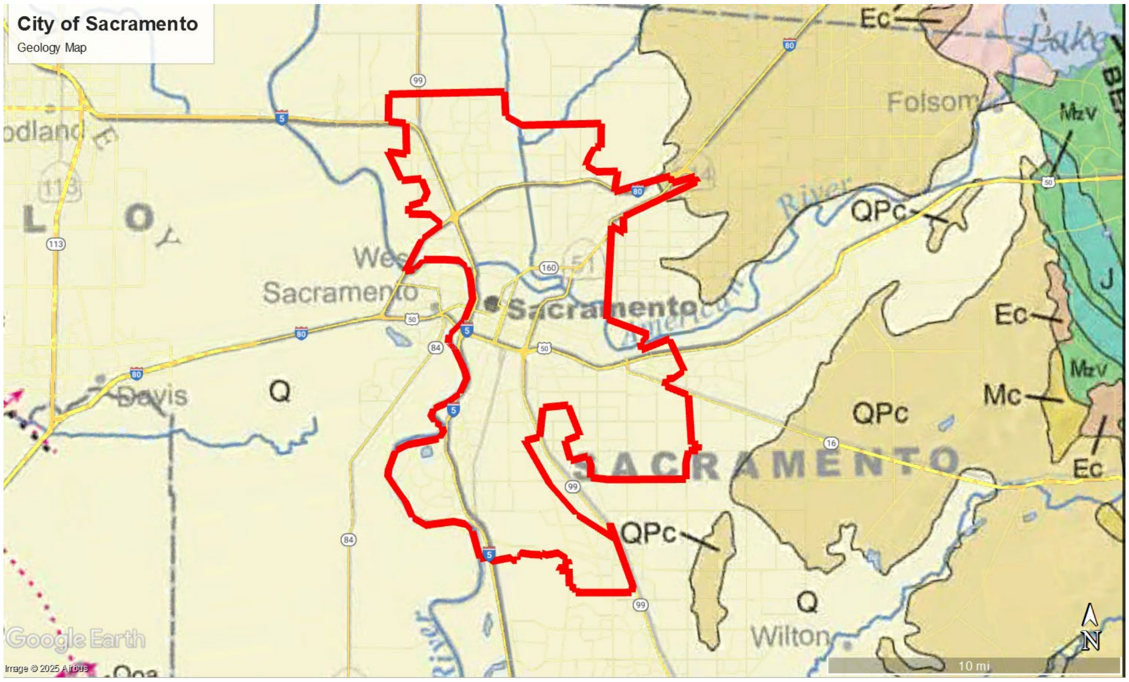
ECORASTER® and Bloxx Typical Section



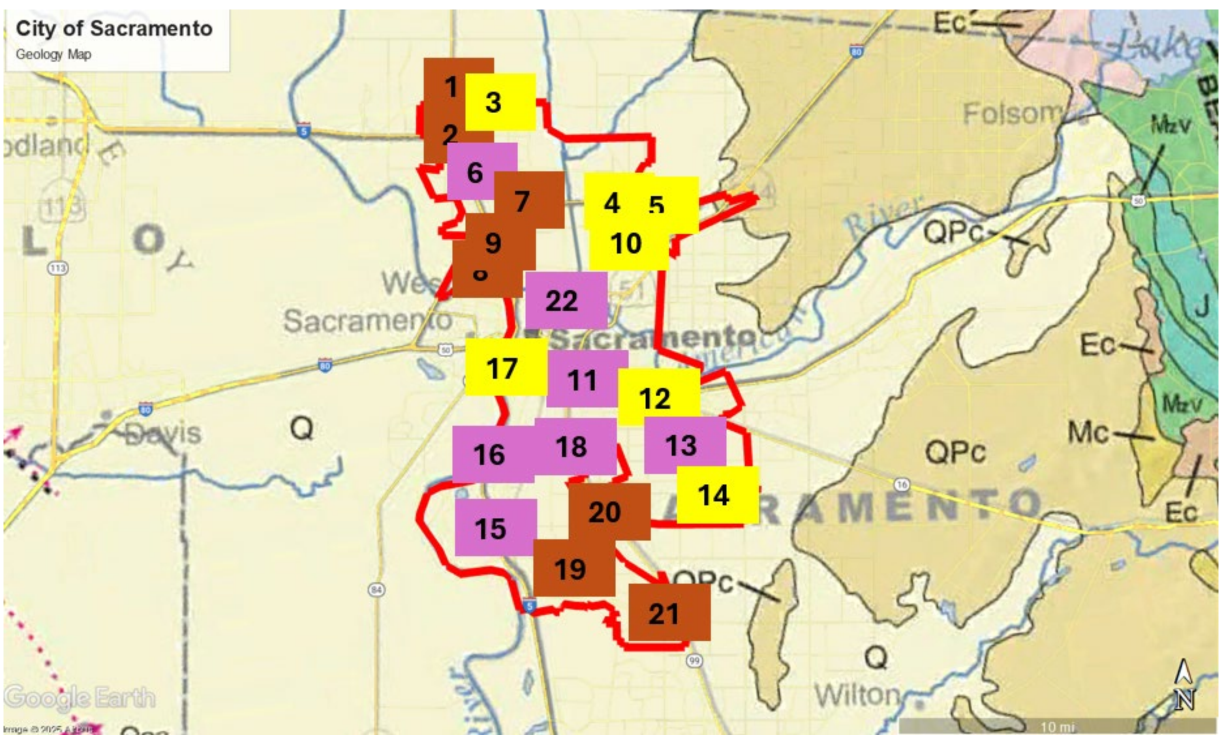
Grassstone Pavers Typical Section

Exhibit B

Geology map of Sacramento



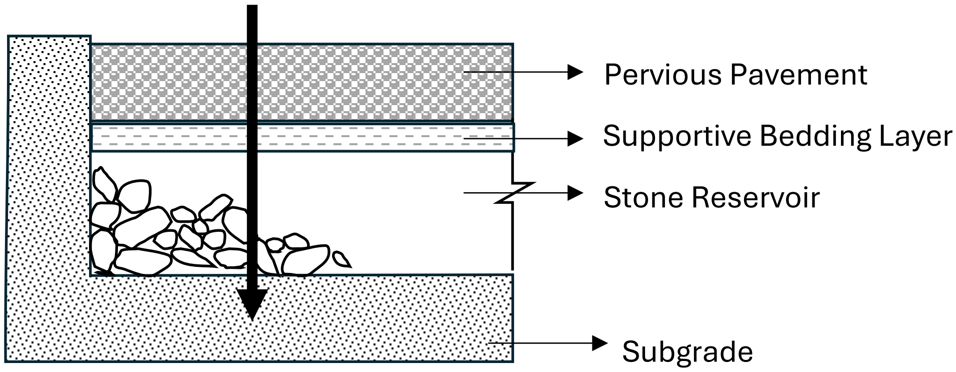
Predominant soil type for selected projects



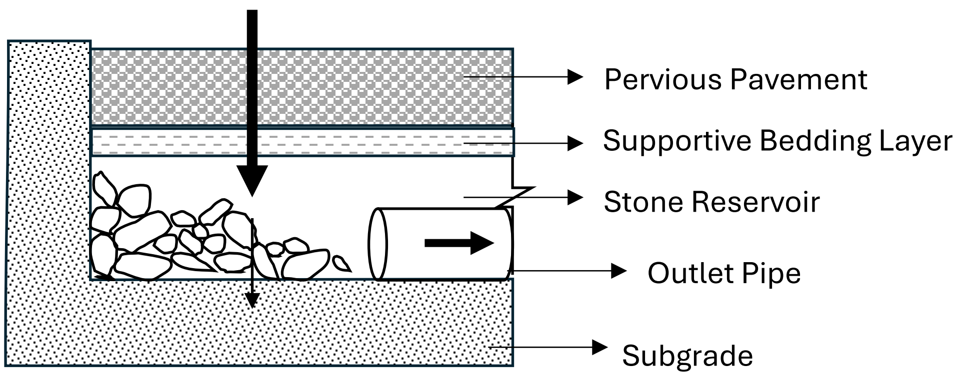
Predominant soil types for selected projects: Red: Clay (Class C or D), Pink: Silt (Class B or C), Yellow: Sand (Class A or B). (https://geodog.dot.ca.gov/)

Exhibit C

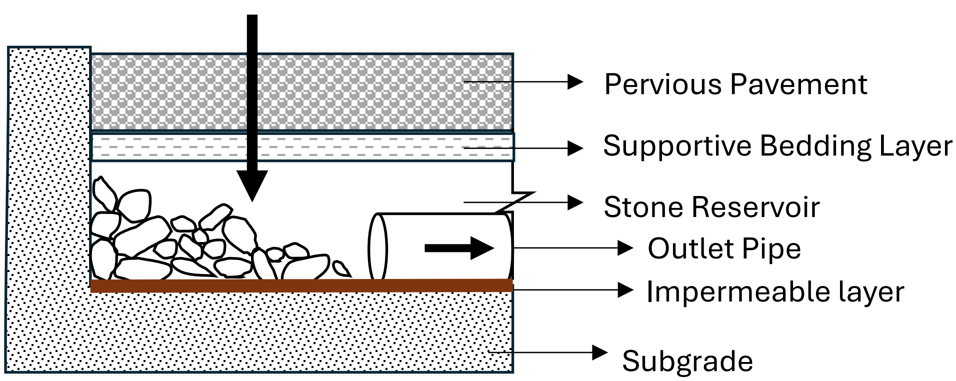
Subgrade Permeability



(a) Full infiltration (Group A and some group B soils)



(a) Partial infiltration (Some groups B and C soils)



(b) Low infiltration (Some group C and group D soils)

1.3 **PAVEMENT BINDER GRADES**

Purpose and Background

Sacramento's pavement performance was evaluated using two approaches: the original SHRP (Strategic Highway Research Program) Superpave method, which the city currently uses, and the updated FHWA (Federal Highway Administration) Long-Term Pavement Performance (LTPP) method. Both methods estimate the temperature extremes that pavement binders must withstand to prevent cracking in winter and rutting in summer. These temperatures are then translated into binder grades, expressed as two numbers (e.g., PG 64-10), where the first represents high-temperature resistance (64°C in this case) and the second represents low-temperature resistance (-10°C in this case) in degrees Celsius.

Historically, Sacramento's high-temperature pavement grade values are around 70-71°C, and low-temperature values range from about -9°C to -11°C, depending on the method.

The City's current Standard Specifications for Public Construction (Section 22-2) require:

> Unless otherwise indicated on the Plans or in the Special Provisions, asphalt binder to be mixed with aggregate shall be steam-refined paving asphalt: PG 64-10 or PG 64-16 for residential and collector streets and PG 70-10 for on/off ramps, Intersections, arterials, and thoroughfares. Use ARHM-GG (Asphalt Rubber hot Mix – Gap Graded) with PG 64-16 for overlays, unless otherwise indicated.

Looking ahead, climate projections for the 2050s and 2080s show a gradual increase in high temperatures and a slight warming of low temperatures (meaning less severe cold). By the 2080s, high pavement temperatures could reach 74-76°C under the most extreme emissions scenario (SSP 5-8.5), while low temperatures may rise to -6°C to -8°C. This suggests future binder grades may need to shift toward PG 76-10.

SHRP & FHWA Methods

The SHRP method uses air temperature alone, while FHWA incorporates pavement surface temperature, rut depth, usage, and reliability factors. As a result, FHWA generally produces slightly warmer high-temperature values and slightly warmer low-temperature values compared to SHRP. For Sacramento, this difference is modest but important for long-term planning given that FHWA's approach anticipates more extreme heat impacts.

These results highlight the need to prepare for hotter pavement conditions in the coming decades. While current binder grades like PG 70-10 may suffice today, future projects – especially those with long design lives – should consider higher grades such as PG 76-10 to maintain performance under projected heat stress. The FHWA method provides a more robust framework for accounting for uncertainty and reliability, which may be valuable for critical infrastructure.

Table 5. Results for City of Sacramento

Method (°C)	**Historical**	**2050s SSP 2-4.5**	**2050s SSP 5-8.5**	**2080s SSP 2-4.5**	**2080s SSP 5-8.5**
FHWA High	71°C	74°C	74°C	74°C	76°C
SHRP High	70°C	73°C	73°C	73°C	75°C
FHWA Low	-9°C	-9°C	-7°C	-8°C	-6°C
SHRP Low	-11°C	-10°C	-9°C	-9°C	-7°C

Given that Sacramento is located in the Inland Valley pavement climate region, as designated by Caltrans (**Figure 1**), the current binder grades used in the city (PG 64-10) for residential and collector streets are too low even for historical conditions, with a maximum of 64°C or 70°C. Binder grades are provided in increments of six – so for example, the next highest option for a PG with a high of 64°C would be a PG with a high of 70°C, then 76°C.

Based off this analysis, both historical and future conditions should be upgraded to a maximum of 76°C given that all results are above 70°C. Given that the climate is estimated to continue warming, the lows of -10°C or colder in all of the current binder grade recommendations for Sacramento's climate region will remain adequate with no changes necessary. Instead, the focus should remain on increasing the high-temperature grade.

Table 6. Asphalt binder performance grade selection for Caltrans (source: table 632.1)

Climate Region (6)	Binder Grade for Hot Mixed Asphalt (HMA)(1), (2)				
	Dense Graded HMA		Open Graded HMA		Gap and Open Graded Rubberized Hot Mix Asphalt (RHMA)
	Typical	Special(3)	Placement Temperature > 70°F	Placement Temperature ≤ 70°F	
South Coast Central Coast Inland Valley	PG 64-10	PG 70-10 or PG 64-28 M	PG 64-10	PG 58-34 M	PG 64-16

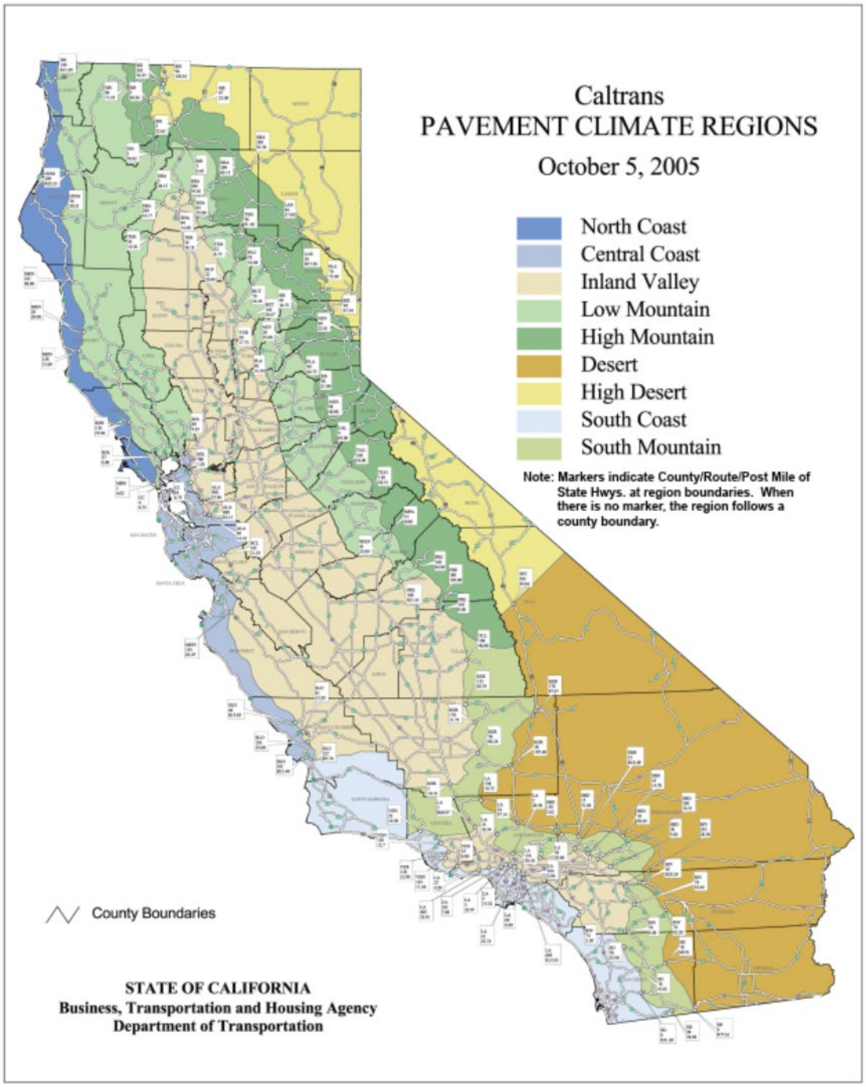


Figure 1. Caltrans pavement climate regions (source)

Conclusion

Analyses of both historical and projected pavement temperature conditions indicate that the City should transition from its current binder grades—PG 64-10 for residential and collector streets and PG 70-10 for higher-volume roadways—to a PG 76-10 binder. Historical high-temperature values already exceed 70 °C, and future climate projections estimate pavement temperatures reaching 74–76 °C by the 2050s and 2080s. The low-temperature grade of –10 °C remains sufficient, so adjustments should focus solely on raising the high-temperature rating.

Switching to a higher-temperature binder grade has implications for both cost and maintenance. PG 76-10 binders typically require polymer modification and therefore come at a higher initial cost. However, these binders offer superior resistance to rutting and thermal degradation, which can extend pavement life. In turn, agencies may experience reduced maintenance needs and potentially lower lifecycle costs despite higher upfront expenditures. Over time, the improved performance may offset early investment, particularly on heavily trafficked or heat-vulnerable corridors. Market availability and pricing are influenced by Caltrans' statewide specifications.

Because current Caltrans recommendations rely heavily on lower binder grades, suppliers have limited incentive to produce and distribute higher-grade materials at scale. To enhance availability and reduce long-term costs, Caltrans will need to reevaluate and update its statewide binder grade recommendations, which would help create market demand for higher-temperature binders such as PG 76-10. Doing so would help shift production practices, reduce price premiums, and support more resilient pavement infrastructure statewide.

2| SCOUR MITIGATION

2.1 SCOUR DEFINITION

Scour is the erosion or removal of sediment (such as sand, gravel, or silt) from bridge foundations—including piers, abutments, and embankments—due to the action of flowing water.

Scour occurs when the hydraulic forces of water (velocity, turbulence, vortices) are strong enough to dislodge and transport particles from the riverbed or banks, leading to localized deepening of the riverbed. If not properly accounted for, it can expose or undermine structural foundations and cause bridge instability or failure.

Scour is the leading cause of bridge failure worldwide. When sediment supporting the foundation is eroded, it can lead to settlement or tilting of piers, collapse of abutments or retaining walls, and complete structural failure during floods or high-flow events.

When scour is neglected, there may be sudden bridge failure (especially during floods), loss of human life, high economic costs for repair or replacement and traffic disruption.

2.2 SCOUR TYPES

Scour is generally classified into three main types:

1. **Local Scour** occurs around piers or abutments due to the turbulence and vortices created by flow obstruction. It creates scour holes at the base. Local scour is caused by mechanisms like downflow and horseshoe vortices in front of piers and wake vortices behind piers.

2. **Contraction Scour** happens when the flow is constricted (e.g., at bridge openings or narrowed river sections) and increased flow velocity leads to uniform erosion across the bed in the contracted section.

3. **General Scour (Degradation)** is long-term, large-scale lowering of the riverbed over time due to natural river evolution, changes in upstream/downstream sediment supply, and channel straightening, dam construction, or gravel mining.

2.3 FACTORS THAT INFLUENCE SCOUR

Several hydraulic, geotechnical, and structural factors affect how scour develops:

Category	Factors
Hydraulic	Flow velocity, depth, turbulence, flood frequency
Geomorphic	Sediment size and type, riverbed material, stratification
Structural	Pier shape, size, alignment to flow, foundation depth
Environmental	Vegetation, ice, debris, tides (in coastal areas)
Hydrologic Events	High flows, flash floods, rapid flow changes

2.4 COMMON SCOUR MITIGATION MEASURES FOR BRIDGES

The most common scour mitigation measures used in bridge design, construction, and maintenance are:

Structural Measures (Physical Protection):

1. **Riprap (Rock Armoring)**. Large stones or broken concrete placed around piers or abutments to absorb water energy. Most widely used and cost-effective.

2. **Gabions**. Wire mesh baskets filled with stones. Used to stabilize slopes or riverbanks near bridge foundations.

3. **Scour Countermeasures using Concrete (e.g., aprons, mats)**. Concrete aprons or collars around pier bases. Articulated concrete blocks or mats to armor the bed.

4. **Grouted Riprap**. Riprap bonded with concrete to prevent displacement during high flows.

5. **Sheet Piles or Cut-off Walls**. Driven deep into the bed around piers/abutments to block undermining.

6. **Scour-Resistant Foundations**. Spread footings placed at or below the anticipated total scour depths or founded on competent, scour-resistant bedrock. Deeper foundations (e.g., drilled shafts or piles) placed and extending below the anticipated total scour depth.

7. **Cable-Tied Blocks / Mattresses**. Precast blocks tied together with cables, flexible and conform to the bed.

8. **Catcher Bents**. Provide alternate support of the superstructure in case of total failure of an existing support or un-seating of the superstructure from the existing supports.

Hydraulic Measures (Flow Alteration):

8. **Guide Banks / Spur Dikes / Vanes**. Structures built upstream to redirect flow and reduce velocity near piers.

9. **River Training Works**. Adjusting the river course to minimize flow concentration near the bridge.

10. **Channel Linings**. Stabilize the riverbed using concrete, riprap, or other materials to reduce erosion.

Monitoring and Maintenance Measures:

11. **Scour Monitoring Devices**. Sensors or sonar to monitor scour depth in real-time.

12. **Regular Inspections**. Especially after floods or high flow events.

13. **Scour Risk Assessments**. Predictive modeling and evaluation to proactively mitigate risks.

Design Measures (Preventive Planning)

14. **Designing for Scour Depth**. Foundations placed below calculated maximum total scour depths (including safety margins) based on project specific Hydrology/ Hydraulics & Geotechnical Reports.

15. **Use of Scour-Resistant Materials**. Avoiding easily erodible soils near bridge foundations.

16. **Bridge Span Design**. Longer spans to minimize number of piers in water, reducing scour risk.

2.5 DETAILED DESCRIPTIONS OF SELECTED MITIGATION MEASURES

Cable-Tied Blocks

- These measures are typically used as armoring countermeasures (i.e., adding a protective armor layer on the bed or around foundations) rather than flow-altering devices.

- “Cable-tied blocks” are concrete blocks or slabs (often truncated-pyramidal or other shapes) that are interconnected by cables (steel, stainless steel, alloy, or synthetic) to form a mat or armor layer.

- The blocks individually might be unstable in high-velocity flows, but when tied together they act as a system or mat, resisting higher flows more effectively than loose blocks alone.
- The system is often placed on top of a geotextile or filter layer to prevent sediment migration under the mat and then placed around the foundation (pier or abutment) to reduce scour.
- Common applications: bridge piers in stream beds, abutments, spill-through abutment slopes.

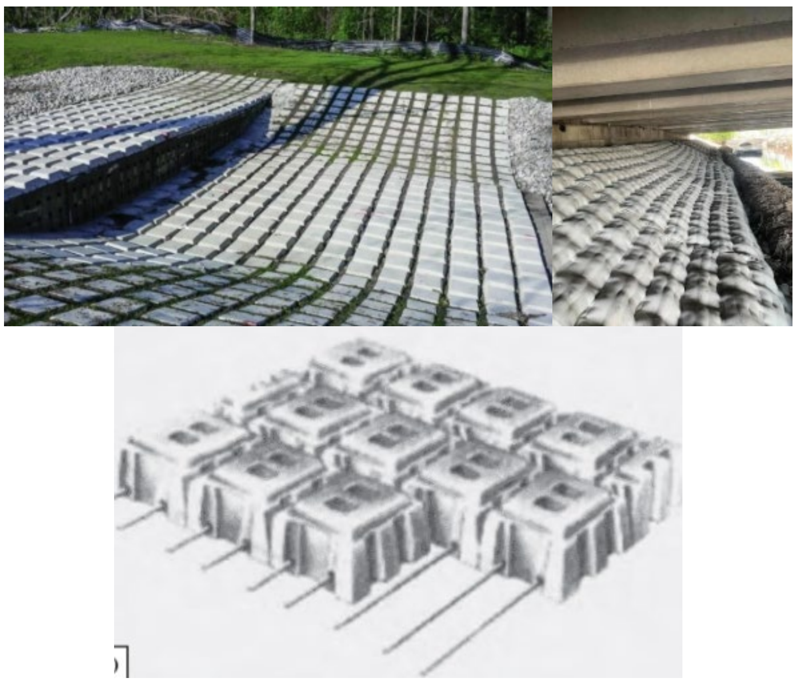


Figure 2. Example of cable-tie blocks

Advantages:
- More predictable than loose riprap in some cases, because the interconnection helps create a stronger armor.
- Flexibility: The mat can conform to bed contours and still provide protection.
- Suitable in locations where placement of large rock may be difficult (e.g., shallow approaches, tight geometry).

Limitations / Considerations:
- Less field experience compared to classic riprap for bridge scour around piers/ abutments.

- Requires careful detailing at the structure interface (seal to pier/abutment) and at edges. If the seal fails or mat edges are not secure, sediment can scour beneath, leading to undermining.

- Durability of cables: particularly in harsh or corrosive environments, cable corrosion or fatigue may be a concern.

- Cost and constructability: The mats may require prefabrication, specialized anchor systems, and precise installation compared to simple rock riprap.

- Not always suitable for very large scours, or where extreme velocities or very large bed-material movement occur (e.g., rock bed with huge bedforms). Guidelines caution about use in large cobble/rock bed streams.

Mattresses (Articulated Concrete Block Mats / Cable-Tied Block Mats)

- “Mattress” here refers to an articulated mat or blanket of interconnected concrete blocks (or pillows) that lie over the bed or channel surface, often used for bank protection, riverbed lining, scour mitigation under bridge structures.

- The blocks are interconnected (by cables or synthetic links) so that the mattress acts like a continuous protective layer rather than individual pieces. The concept overlaps with cable-tied block systems.

- They can be installed in front of abutments (particularly spill-through abutments) or around piers to suppress local scour by protecting the bed material and preventing scour hole formation.

Figure 3. Example of mattresses

Advantages:

- Uniform protective blanket that reduces the need for placing large rock pieces.

- Ability to conform to bed contours and provide a continuous cover, reducing gaps or voids through which scour could initiate.

- Effective for moderate velocities and bed movement, especially when combined with a good filter/seal. The 1998 NCHRP study stated "a mattress of cable-tied blocks underlain by a geotextile tied to the pier provides excellent protection."

Limitations / considerations:

- Similar to cable-tied blocks, performance depends heavily on proper installation: filter, sealing to structure, edge anchoring. If these are compromised, uplift or undermining can occur.

- Not always suitable for very large bed material movement or extremely high velocities; again, larger rock riprap or other heavy armoring may be needed.

Sonar / Acoustic Depth Sensor

- A sonar (acoustic pulse) transducer is mounted underwater (often on or near the pier or scour-critical element). It emits acoustic pulses toward the streambed and measures the time-of-flight to the sediment/bottom to determine bed elevation.

- Over time, as scour occurs and the bed drops, the measured depth increases (or the distance to the bottom grows) indicating the measured reduction of supporting material.

- Often combined with a data logger and telemetry system so that changes in bed elevation can be monitored remotely (even during high-flow events) (see for example the system described by NexSens).

Figure 4. Example of sonar/acoustic depth sensor

Sliding Collar / Probe Rod Device

- A rigid probe/rod is driven or embedded vertically into the bed (or fixed near the bed) at or adjacent to the pier/abutment. A "sliding collar" rests on the bed surface at installation.

- As the bed erodes (scours) and drops, the sliding collar will drop with the surface (or the collar is free to drop), triggering switches or sensors at known intervals on the rod to log the drop.
- This gives a discrete (often stepwise) measure of bed elevation change relative to the fixed reference rod.

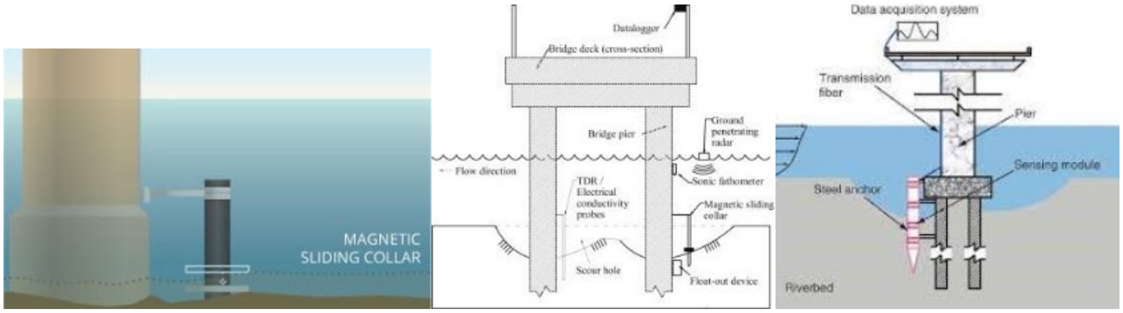


Figure 5. Schematic of sliding collar

Threshold / Float-out or Buried-Sensor Devices

- Lower cost or simpler option: sensors are installed/embedded at predetermined depths below the streambed or near the bed surface adjacent to pier. When scour reduces the bed to expose or affect the sensor, it triggers an alert (float-out, exposure, electrical contact change).
- These are often used as warning devices rather than continuous measurement. When bed drops to critical depth, sensor activates, alerting the inspector/owner that a threshold has been exceeded and remedial action may be required.

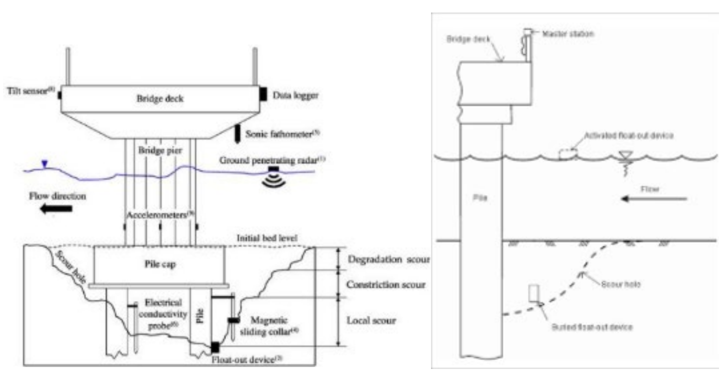


Figure 6. Schematic of float-out or buried-sensor devices

Additional considerations:

- Baseline survey: Document initial streambed elevation around each pier/abutment at installation time so future scour progression can be referenced to this datum.

- Access and safety: Provide safe access for both installation and periodic inspection/maintenance (e.g., diving, float platform, boat, pier access).
- Redundancy: Consider dual-sensor systems (e.g., one sonar + one threshold device) especially for critical bridges.
- Integration: Ensure data flows into your bridge management system: include dashboard/reporting requirements, alert protocols, inspection trigger conditions.
- Maintenance schedule: Specify periodic verification of sensor operation, cleaning of transducers/collars, calibration check.
- Environmental design: Account for high-flow debris, sediment deposition, marine/ freshwater corrosion, bio-fouling.
- In drawings: Provide elevation and plan views of sensor mounting, datum referencing, cable route, enclosure location (logger/telemetry), conduit details.

2.6 REGULATORY CONSIDERATIONS FOR LARGER MEASURES

Besides more typical scour-mitigation measures around the piers and abutments, highlighted in separate reports, this section explores reducing scour effects on the structure by modifying the creek bed and channel alignment to redirect the primary flow path away from the bridge foundations. These activities would include in-channel excavation and fill, potential bank stabilization, and channel re-grading. Realignment of the creeks reduces debris collected at piers/abutments and reduces scour impacts to structural members.

This section provides feasibility and identifies the regulatory permits and approvals potentially required for modifying the creek bed and flow regime associated with the bridge crossing. Modifications to creek beds and flow paths in California are regulated under a combination of federal, state, and local statutes. The following sections summarize the likely permits and authorizations applicable to the proposed work.

Federal Permits

U.S. Army Corps of Engineers (USACE)

Authority: Clean Water Act § 404 and Rivers and Harbors Act § 10
Administered by: U.S. Army Corps of Engineers, Sacramento District

- Applicability: A § 404 permit is required for discharge of dredged or fill material into "waters of the United States," including streams, creeks, and wetlands.

- Project Relevance: The proposed modification of the creek bed to redirect flow will likely involve placement of fill or alteration of channel morphology, triggering § 404 permitting requirements.
- Permit Type: Depending on scope and impacts, the project may qualify for a Nationwide Permit (NWP 14 – Linear Transportation Projects) or require an Individual Permit.
- Coordination: Contact USACE Sacramento District Regulatory Branch to request a Pre-Application Meeting and confirm jurisdictional status.

State Permits

California Department of Fish and Wildlife (CDFW)

Authority: California Fish and Game Code § 1602
Permit: Lake or Streambed Alteration Agreement (LSAA)

- Applicability: Required for any project that will divert or obstruct natural flow, or substantially change the bed, bank, or channel of any river, stream, or lake.
- Project Relevance: Creek bed modification involves modifying the channel and redirecting flow; therefore, an LSAA will almost certainly be required.
- Coordination: Early consultation with CDFW Region 2 (North Central Region) is recommended.

State Water Resources Control Board / Central Valley Regional Water Quality Control Board (CVRWQCB)

Authority: Clean Water Act § 401 – Water Quality Certification; Porter-Cologne Water Quality Control Act – Waste Discharge Requirements (WDRs)

- Applicability: A § 401 Water Quality Certification is required for projects needing a federal § 404 permit. If federal jurisdiction is not established, a WDR under state authority may still apply for discharges to "waters of the State."
- Project Relevance: Likely required due to in-channel work, grading, and fill.
- Coordination: Consultation with CVRWQCB (Sacramento Office) should occur concurrently with USACE coordination.

Central Valley Flood Protection Board (CVFPB)

Authority: California Water Code § 8700 et seq. and Title 23, California Code of Regulations
Permit: Encroachment Permit

- Applicability: Required for any work within a Designated Floodway or within 100 feet of a Regulated Stream or levee maintained under the State Plan of Flood Control.
- Project Relevance: Many Sacramento-area creeks fall within CVFPB jurisdiction. Mapping verification via the Best Available Map (BAM) Viewer is necessary.
- Coordination: Contact CVFPB for jurisdictional determination and encroachment permit requirements.

Local Permits

Sacramento County / City of Sacramento

Depending on the project location and jurisdictional boundaries:

- Grading Permit – Required for earthwork exceeding 350 cubic yards or work near watercourses.
  - *Administered by:* Sacramento County Department of Community Development, Site Improvement and Permits Section.
- Floodplain Management Permit – Required if project work occurs within FEMA-mapped or locally designated floodplains.
  - *Administered by:* Sacramento County Department of Water Resources.
- Environmental Compliance and Supporting Studies. Several technical studies and documents may be required to support permit applications, including:
  - Hydraulic and hydrologic modeling (to demonstrate no adverse impacts)
  - Preliminary Foundation Report
  - Biological resources assessment and habitat evaluation
  - Jurisdictional delineation (waters of the U.S./State)
  - Erosion and sediment control plan (SWPPP under the Construction General Permit)
  - Mitigation and monitoring plan (if stream impacts cannot be avoided)

Recommended Coordination Steps

1. Pre-consultation with agencies – Initiate early discussions with CDFW, USACE, CVFPB, and CVRWQCB to define jurisdiction and data needs.
2. Prepare and submit a Notification of Lake or Streambed Alteration to CDFW.

3. Request a Jurisdictional Determination from USACE to confirm federal waters.
4. Coordinate § 401 certification with CVRWQCB concurrent with USACE permit application.
5. Verify floodway jurisdiction and apply for a CVFPB encroachment permit if necessary.
6. Apply for local grading and floodplain permits through Sacramento County/City.

Summary Table of Anticipated Permits for a Creek Bed Modification Project

Agency	Permit/Approval	Legal Authority	Trigger / Applicability
U.S. Army Corps of Engineers	§ 404/§ 10 Permit	Clean Water Act / Rivers & Harbors Act	Placement of fill or work in "waters of the U.S."
CDFW	Lake or Streambed Alteration Agreement	Fish & Game Code § 1602	Modification to streambed, bank, or flow diversion
CVRWQCB	§ 401 Water Quality Certification / WDR	Clean Water Act § 401 / Porter-Cologne Act	Discharge to waters of the U.S. or State
CVFPB	Encroachment Permit	Water Code § 8700 et seq.	Work in Designated Floodway or within 100 ft of Regulated Stream
Sacramento County / City	Grading, Floodplain, and Encroachment Permits	County/City Codes	Earthwork, floodplain activity, right-of-way encroachments

2.7 PROJECT CASE STUDY – ROSEVILLE ROAD BRIDGE (BR. NO. 24C0554)

The existing Roseville Road Bridge (Br. No. 24C0554) was built in 2015, is located 0.8 miles north of Marconi Avenue crossing Arcade Creek in Sacramento, California. The bridge is composed of four (62.5’, 62.5’ 62.5’ & 62.5’) precast-prestressed (PC/PS) concrete voided slab units (12 per span) in simple spans with a continuous cast-in-place reinforced concrete (CIP/RC) topping on reinforced concrete pier caps on reinforced concrete columns with pile extensions (6 per bent) and reinforced concrete seat-type abutments with integral wingwalls (See Figure 7). The existing piers have a skew of 30 degrees that does not align with the flow of the Arcade Creek.

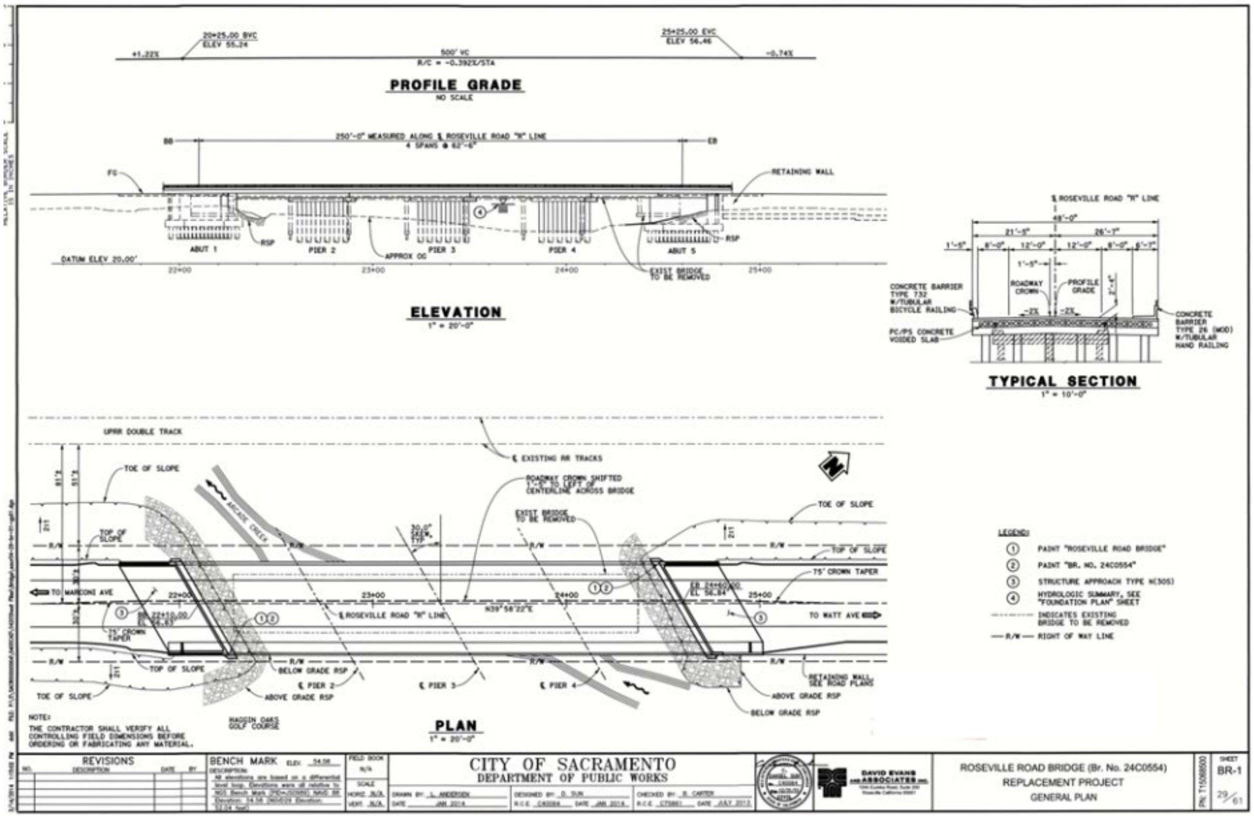


Figure 7. Roseville Road Bridge General Plan

There are ongoing scour issues with this bridge because the flow of the creek hits the bridge piers at an angle, thereby collecting debris at the bridge piers and creating significant scour issues to the concrete lined channel and scouring around the abutments (see Figures 8 and 9).

In the past, there have been repairs to concrete lining of the channel, but scour issues are still prevalent. There have been considerations in the past to realign the creek, so it flows more favorably relative to the bridge's piers, rather than its current angle. However, the recommendations were not advanced due to limited funding and permitting requirements.

Figure 8. Roseville Road Bridge – Pier 3 with accumulated debris

Figure 9. Roseville Road Bridge – Scour issues around Abutment 1

Project Case Study – Proposed Realignment Mitigation:

At Roseville Road Bridge, the creek mitigation involves modifying the creek bed and channel alignment to redirect the primary flow path away from the bridge's foundations. These activities include in-channel excavation and fill, potential bank stabilization, and channel re-grading. This type of mitigation opens up a series of environmental requirements enumerated in Section 2.6.

Project Case Study conclusions:

Because the project involves altering a creek bed and flow regime to protect bridge piers, multiple federal, state, and local permits will be required. The primary regulatory triggers include streambed alteration, discharge of fill to waters, and work within floodways or floodplains.

Early coordination with CDFW, USACE, CVRWQCB, CVFPB, and local permitting authorities will streamline environmental compliance and avoid project delays. A consolidated permitting schedule should be developed as part of project planning.

In conclusion, even though creek realignment is a viable option for scour mitigation of the existing bridge, the extent of permitting regulations and coordination makes this option prohibitive versus other localized scour mitigation options at the bridge crossing. At this location, it is recommended to implement regular debris removal (preferably during the summer months when the flows are low, and debris removal is more accessible).

3| STORMWATER MODELING

3.1 OVERVIEW

A comprehensive model of the stormwater drainage system is critical for effective stormwater management, a core responsibility of the City of Sacramento Department of Utilities (DOU). Such model would include a representation of major storm drain system components—such as pipes, channels, manholes, inlets, and outfalls, with the objective of assessing the system response during a given rainfall or storm scenario across the City.

The DOU relies on model outputs to design new drainage elements and evaluate the adequacy of existing infrastructure. Maintaining accurate and up-to-date models supports efficient and reliable operations of the stormwater management system.

However, climate change, outdated data and lack of coverage present significant challenges to the reliability of current stormwater models. Existing models at DOU cover only about 40 of the city’s 160 drainage basins and do not account for future conditions. Incorporating future scenarios is vital, as changes in precipitation patterns and land use—driven by climate change and socio-economic factors such as population growth—will directly impact model accuracy. Another challenge faced by DOU current models is that culverts and ditches are not in the model, so further data collection and incorporation is needed.

Therefore, model updates are a key adaptation strategy for the DOU. This includes simulations of hydrology models for drainage basins using new climate data and rainfall projections, as well as incorporating remaining drainage basins that have not been modeled yet. These tasks will also include updates to the current inventory of drainage system components. This document outlines potential benefits of the model update effort and provides general guidelines for implementation.

3.2 BENEFITS OF MODEL UPDATES

Updating the stormwater hydraulic models will result in the following benefits for the DOU.

Enhanced Flood Risk Management

An improved stormwater hydraulic model enables more accurate simulation of stormwater flows and flood extents under current and future climate conditions. This will help DOU to better identify vulnerable areas, prioritize upgrades, and reduce the likelihood of catastrophic failures in the system.

Flood risk management is one of DOU's most critical responsibilities. Managing this risk begins with understanding the likelihood of flooding caused by system malfunctions or stormwater overflow. Reliable stormwater models are essential for generating accurate risk metrics, which are developed by hydraulic and risk specialists to inform planning and decision-making.

Optimized Infrastructure Design and Investment

By refining models with updated rainfall projections and basin characteristics, DOU can design drainage systems and pump stations more efficiently and sustainably. Accurate estimates of demand on drainage components help prevent overdesign, leading to more effective resource allocation. Incorporating forward-looking design reduces the likelihood of costly retrofits or replacements as future conditions evolve.

The ability to identify vulnerable areas under both current and projected precipitation scenarios further supports cost-effective investment decisions. Enhanced models ensure that resources are directed toward the most critical basins and infrastructure components, maximizing the impact of each dollar spent. From an investment planning perspective, improved modeling helps guarantee that stormwater infrastructure projects deliver long-term benefits by better forecasting drainage performance throughout their service life.

Improved Operational Efficiency and Resilience

Advanced stormwater hydraulic models enable DOU to plan for redundancy and backup power at pump stations, schedule maintenance proactively, and optimize overall system performance.

These models provide critical insights into which components are most essential to system reliability and may require additional redundancy to prevent cascading failures during extreme events, helping eliminate single points of failure. They also identify elements operating near capacity, allowing maintenance efforts to be prioritized where demand is highest. Components under greater stress typically require more frequent monitoring and servicing.

Ultimately, these improvements help reduce downtime, enhance resilience during severe weather events, and minimize emergency repair costs, ensuring a more reliable and cost-effective stormwater management system.

Support for Climate Adaptation and Regulatory Compliance

Updated models that incorporate climate change scenarios will enable DOU to meet evolving regulatory requirements and advance sustainability objectives. These models provide a strong foundation for benefit-cost analyses, which are often required when seeking funding for infrastructure projects.

Current regulatory frameworks emphasize forward-looking planning, and this modeling effort supports compliance by integrating future climate and socio-economic conditions into design and decision-making. Overall, adopting a proactive approach to model updates will not only facilitate regulatory compliance but also position DOU to consistently meet future standards and sustainability goals.

3.3 BEST PRACTICES

This section provides a general three-step approach to updating the stormwater hydraulic models for DOU.

Data Gathering

The first step involves compiling and validating essential data to ensure accurate model development. This includes collecting the latest publicly available topographic information and existing storm drain network details, supplemented by as-built drawings or survey data to confirm attributes such as invert elevations, pipe lengths, and material types. Agency standards and design rainfall data are identified to align with regulatory requirements, while soil and hydrologic parameters are sourced from published resources to support reliable hydrologic analysis.

Hydrologic Modeling

Using the gathered data, drainage subcatchments are delineated based on the storm drain network and topography. Key parameters—such as soil type, land cover, impervious surface extent, storage depressions, and time of concentration—are assigned to each subcatchment. Design storm events are then applied to generate hydrographs for both existing and future conditions, enabling the assessment of runoff characteristics under varying scenarios, including anticipated changes in precipitation and land use.

Hydraulic Modeling

The hydraulic modeling phase integrates both 1D and 2D approaches to capture system and surface interactions. The 1D model represents major storm drain components—pipes, channels, manholes, inlets, and outfalls—using dynamic wave flow routing to evaluate system capacity. Concurrently, a 2D model simulates overland flow and surface flooding through a LiDAR-based computational mesh that incorporates roads, obstructions, and low-lying areas. Coupling the 1D and 2D models provides a dynamic link between subsurface and surface systems, allowing for comprehensive evaluation of combined performance under selected storm events.

3.4 CONCLUSION

Updating the City of Sacramento DOU’s stormwater hydraulic models would enhance system reliability, operational efficiency, and resilience in the face of evolving climate and urban challenges. Integrating current data, expanding model coverage, and incorporating future climate and land use scenarios will enable DOU to better predict and manage flood risks, optimize infrastructure investments, and ensure compliance with regulatory requirements. Implementing these best practices will position Sacramento to proactively address future uncertainties, safeguard public safety, and advance sustainability goals for a robust and effective stormwater management system.

4| SHADING

4.1 STRUCTURAL SHADING

Introduction

In many locations, trees cannot be planted due to available space, utilities, and other urban area restrictive elements. Structural-based shading uses solid or semi-solid materials that block sunlight. Typically, the structure includes a frame, a canopy and/or panels, and posts that are anchored to the ground.

Purpose

The purpose of this document is to outline practical strategies for selecting, locating, and maintaining shade structures in transit environments and adjacent urban corridors. Guidance is focused on early design and coordination, not construction-level detail. Emphasis is placed on solutions that perform well under Sacramento's heat conditions and can be maintained over time. Because conditions and constraints vary widely, the strategies in this document are adaptable and intended for use across bus stops, light rail stations, transit centers, walkways, and public space improvements.

Goals

This document aims to: provide direction for heat-resilient shelter and shade-structure design; support coordinated decision-making among the City, SacRT, unincorporated Sacramento county, and SMUD; and provide tools to evaluate shading approaches.

How to Use This Document

Use the guidance during planning and early design to:

- Identify types of shade structures used to aid pedestrians and transit users.
- Select materials used to construct shade structures that support heat resiliency.
- Determine strategies to be used in shade structure design that provide ventilation and protection from the sun.

Shade Structure Types

- Bus Shelters
  - Description: Bus stop shelters are small, semi-enclosed structures used to protect passengers from the elements while waiting for the bus.
  - Located: Behind sidewalks or alongside roads.

- Size: Current shelter sizes vary between 8’, 10’, and 12’ in length. Typical dimensions are 5 ft x 12 ft; 60 sq-ft to 100 sq-ft. Height clearance should be at least 8 ft.
- Functions: Protects waiting passengers from rain, wind, and sun. Provides the required ADA clearance around the shelter unit for wheelchairs to navigate and access the sheltered stop. Provides visual cue of the location of a bus stop.
- Potential integrated elements: Seating, digital informational signage, advertising (typically to generate revenue for maintenance), wind/sun-screen, roof, and lighting.

Photo: Bus Shelter in Citrus Heights, CA — Sacramento Regional Transit District

- Light Rail Station Platform Shade Structures
  - Description: Light rail station platform shade structures are semi-enclosed structures used to protect passengers while waiting for light rail trains.
  - Located: Along the station platform and boarding areas, adjacent to tracks.
  - Size: Typical dimensions 8 ft x 16 ft; 120 sq-ft to 300 sq-ft. Height clearance should be at least 9 ft.

- Functions: Protects waiting passengers from rain, wind, and sun. Provides the required ADA clearance around the unit for wheelchairs to navigate and access the station platform and boarding area. Provides visual cue of the location of a light rail station.
- Potential integrated elements: Seating, digital informational signage, advertising (typically to generate revenue for maintenance), wind/sun-screen, roof, security cameras, lighting.

Photo: Light Rail Platform Shade Structure at Franklin Station, Sacramento, CA — Sacramento Regional Transit District. (Note that installing screens between the posts could provide wind protection.)

- Transit Center / Pavilion
  - Description: Transit center structures are semi-enclosed structures used to protect passengers while waiting for light rail trains, buses, and other modes of transit. This structure type is typically constructed to be more durable than a bus shelter or a light rail station platform structure.

- Located: Along sidewalks, adjacent to tracks, or parking lots.
- Size: 300 sq-ft and larger. Height clearance should be at least 9 ft.
- Functions: Protects waiting passengers from rain, wind, and sun. Provides required ADA clearance around the structure for wheelchairs to navigate and access the platform and boardings areas for both buses and trains. Provides visual cue of the location of a transit center.
- Potential integrated elements: Seating, digital informational signage, advertising, wind/sun-screen and roof or enclosed area, security cameras, lighting. May also provide enough space to include restrooms and drinking water.

Photo: Transit Center Structure at 7th & Richards / Township 9 Station, Sacramento, CA — Sacramento Regional Transit District

- Covered Walkway
    - Description: A structure that covers a walking path between two destinations.
    - The structure may be continuous or in segments between the destinations.
    - Located: Over sidewalks, for example connecting a transit stop to a park-and-ride lot or connecting two transit stops.
    - Size: The length will vary, and width should be a minimum of 5 ft. Height clearance should be at least 9 ft.
    - Functions: Protects people walking from rain and sun. Provides minimum width for pedestrians and individuals navigating in wheelchairs, with minimal columns and/or posts so as to not obstruct the walkway path of travel.
    - Potential integrated elements: digital informational signage, roof, security cameras, lighting, solar panels

Photo: Covered Walkway at Sacramento Valley Station, Sacramento, CA — City of Sacramento / Sacramento Regional Transit District

- Carport
    - Description: A carport is designed to shade parked cars and portions of the parking lot to reduce heat. The structure should cover several parking stalls. Posts should be placed so as to not obstruct car doors. Placement of carports should not overhang drive aisles or obstruct fire access (i.e. fire trucks need at

least 13’-6” height clearance). The structure is built of durable materials and designed to withstand potential vehicle impacts. The carport structural design should take into account extreme weather conditions like wind, rain, and heat. Solar panels are often mounted on top and can function as the roof.

- Located: In parking lots covering parking stalls.
- Size: Size should be based on parking stall dimensions. Larger carports may require fire sprinklers and setbacks to surrounding structure and property lines. Refer to building and zoning codes to determine size and setback requirements. Carport height clearance should be at least 9 ft.
- Functions: To shade parking stalls to reduce heat in parking lot. Provide structure to mount solar panels, which in turn can generate electricity that may feed into electric vehicle charging stations.
- Integrated elements: Roof, security cameras, lighting, and solar panels.

Photo: Solar Carport at Granite Bay High School, Granite Bay, CA — Roseville Joint Union High School District / New Era Electric

Materials and Heat-Resilience Strategies

Material Strategies

The structural components of built shade should be constructed from durable materials—such as concrete, steel, and stainless steel—to provide strength, long service life, low maintenance, and high resistance to impact and wear. Wall panels and roofing may use aluminum, aluminum composite material (ACM), and/or thermally modified wood to achieve durability, reduced surface temperatures, and minimal upkeep, with thermally modified wood reserved for locations where vandalism risk is low. Shade fabrics made from vinyl or high-density polyethylene plastic (HDPE) yarn and acrylic panels are not preferred due to their shorter service life, higher maintenance needs, and vulnerability to vandalism. Where appropriate, exposed surfaces are recommended to receive vandalism-resistant coatings, with reapplication anticipated every 5 to 20 years depending on the product type and site exposure.

Stainless Steel and Corten

Stainless steel and Corten are highly durable materials with long service lives and relatively low maintenance needs. Stainless steel may be used raw, brushed/textured, or painted, and both stainless steel and Corten are well suited to locations where corrosion is a concern or where ongoing coating maintenance is unlikely. However, both materials can become hot in direct sun and are more expensive than standard structural steel, so their use is typically strategic and limited to key elements or accents. Leaving them uncoated can help manage lifecycle costs. Corten is designed to develop a stable rust patina layer that protects the underlying steel and creates a distinctive weathered appearance, but this rust can stain adjacent paving and surfaces and should be detailed accordingly.

Concrete

Concrete is extremely durable and offers a very long service life. Cast-in-place concrete can achieve a high aesthetic quality through the use of form liners, integral color, and protective or decorative coatings. It is often relatively expensive due to material and labor costs, and it can become hot in full sun. For ground surfaces, concrete is typically preferred and should use lighter colors to reduce heat gain. Where concrete is used on vertical elements, design to minimize prolonged direct sun exposure and favor lighter finishes to limit heat buildup.

Steel

Steel is highly durable with a long service life when properly protected, and its high strength-to-weight ratio allows efficient long spans and slender structural members. It is well suited for primary structural components such as posts, beams, rafters, and bracing.

Steel should not be used as exposed roofing or infill panels in full sun where heat gain and glare can be problematic. Because steel components can be fabricated off-site and then quickly assembled on-site, it can be a cost-effective option when paired with appropriate corrosion-resistant coatings and ongoing maintenance.

Aluminum

Aluminum is slightly less durable than steel but is roughly one-third lighter, allowing slimmer members and reduced structural support. It offers good corrosion resistance, and surfaces can be left mill-finished or painted depending on aesthetic and maintenance goals. For shade structure applications, aluminum tubing and panels should generally be a minimum of ¼ inch thick to ensure durability and stiffness. Laser-cut aluminum panels can be used to provide shade, ventilation, and visual interest, turning functional elements into integral aesthetic features.

Composite and Plastic

Composite and plastic materials can offer cost savings while still providing good durability. “Composite” covers a broad range of products made from two or more materials—commonly combinations of wood fiber, fiberglass, carbon fiber, plastics, resins, concrete, or aluminum. Typical examples include fiber-reinforced polymer (FRP), wood–plastic composites, composite aluminum panels, cement-bonded wood fiber, and glass fiber–reinforced polymer. Aluminum composite material (ACM) are two thin layers of aluminum with a rigid plastic core bond between layers of aluminum. ACM are durable, lightweight, provides insulation, and reduces heat transfer using the plastic as thermal brake.

Aluminum Composite Material (ACM) panel has a very low heat transfer compared to other composite materials. Performance and cost vary significantly based on the specific materials and manufacturing methods, and many products are designed to mimic the look of natural materials while improving durability, reducing maintenance, or simplifying installation. Any proposed composite or plastic product should be evaluated for structural performance, ultra-violet (UV) stability, vandal resistance, and expected service life before being specified.

Polycarbonate and Acrylic Panel

Acrylic panels offer good clarity and strong UV resistance but tend to be more brittle, while polycarbonate panels are significantly stronger, more impact-resistant, and less prone to scratching. Both acrylic and polycarbonate can be manufactured as translucent or with varying levels of opacity, and when clear or low-opacity, they admit substantial sunlight, often creating a greenhouse effect within a shade structure. Polycarbonate does require a UV coating to prevent discoloration and weakening from sun exposure over time, whereas acrylic maintains UV resistance without additional treatment. Because both materials transmit sunlight and can contribute to heat gain, tinted or frosted options may be used to reduce thermal buildup, and in all cases the panels should be specified with sufficient thickness to withstand impact.

Thermally Modified Wood

Thermally modified wood is natural lumber that is treated with heat and steam to improve durability, increase hardness, enhance resistance to decay and pests, and reduce moisture movement, which can also improve fire performance. It offers many of the benefits associated with tropical hardwoods such as teak and ipe, but is typically produced from more sustainable species. The material can be oiled to retain its original color or left unfinished to weather to a silvery grey. Although thermally modified wood is more expensive than species like redwood or cedar, it generally provides a longer service life with reduced maintenance needs. Where a real-wood appearance is desired, thermally modified wood is the preferred option.

Tensile Fabric

Tensile fabric shade structures rely on substantial steel posts and foundations, which can make them relatively expensive to construct. They also require ongoing maintenance: at a minimum, quarterly inspections of the structure, cables, and fittings to check for tension loss, wear, and damage, plus annual re-tensioning to maintain performance and safety. Fabric membranes should be cleaned each year, which can be challenging on larger or higher canopies. HDPE yarn fabrics are breathable and allow some light and rain to pass through, providing shade without full weather protection. PVC-coated fabrics are non-breathable and waterproof but can trap heat beneath the canopy; their durability improves with material weight, and a minimum of 32 oz fabric is recommended for extended service life.

Shade Structure Materials Matrix

Table 7. Material matrix of shade structures

Materials	Expected Service Life (Years)	Durability	Maintenance	Vandal Resistance	Heat Transfer Resilience	Cost
Stainless Steel/ Corten	50+	5	5	5	2	5
Concrete	50+	5	4	5	2	4
Steel (powder coated)	40-50	5	3	5	2	3
Aluminum	30-40	4	4	4	3	3

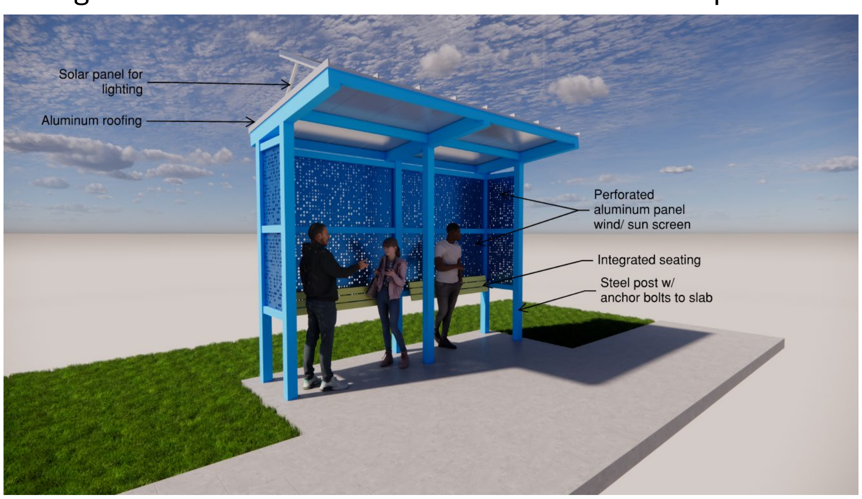
Composite/ Plastic	20-30	3	4	3	2*	2
Polycarbonate Panel	20-30	4	4	3	3	3
Thermal Modified Wood	20-25	3	2	2	4	3
Shade Fabric PVC coated	15-20	3	3	3	4	4
Acrylic Panel	15-20	3	3	2	3	2
Shade Fabric HDPE Yarn	10-15	2	3	2	5	3

Notes:
Scale (1–5): 5 = Excellent / High, 1 = Poor / Low.
Expected Service Life: Approximate years under typical outdoor urban exposure with proper maintenance and recoating.
Heat Transfer: Higher = lower heat transfer and absorption.
Cost: High = higher cost. Relative initial material + installation cost (not lifecycle).

Heat Resilient Bus Shelter Typologies and Solar Orientation

Bus Shelter with North or East Exposure

This shelter design uses perforated aluminum panels to maximize sun screening and allow ventilation. The structure has sides open from below to the optimal height to allow ventilation. The aluminum roof has a high Solar Reflective Index and is elevated high enough to reduce heat transmission to shelter occupants.



Bus Shelter with South or West Exposure

This shelter design uses perforated panels and louvers to maximize sun screening and allow ventilation. The structure has sides open to the greatest extent possible to allow ventilation. The roof has a high Solar Reflective Index and is elevated high enough to reduce heat transmission to occupants.

Retrofitting Bus Shelter

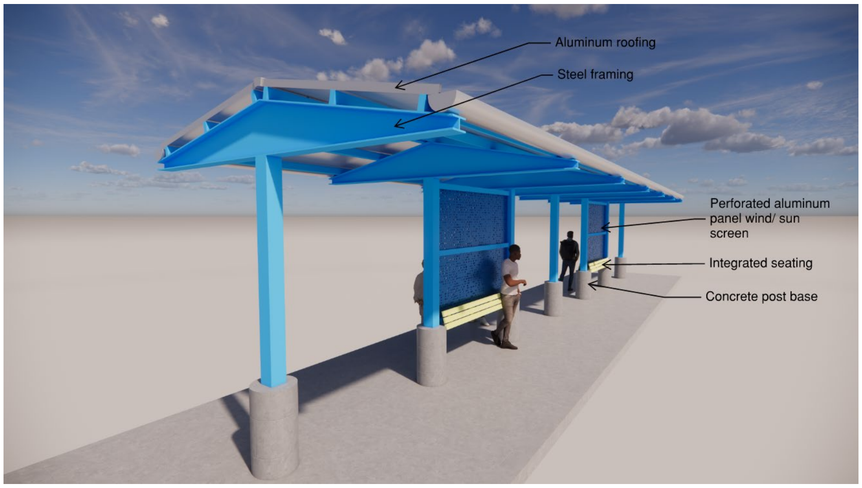
Existing bus shelters with glass and/or polycarbonate side panels and roofs can be retrofitted with aluminum panels to improve heat resilience. Replacing solid glazing and increasing open area or perforation improves airflow and reduces heat buildup. Perforated aluminum side panels provide ventilation while still offering shade and low-angle sun protection, and solid aluminum roof panels increase shade and reflect solar gain. A structural review of the shelter frame is required before adding or replacing panels, and the original shelter manufacturer should be consulted to confirm compatibility with aluminum replacement panels and roofing. When selecting new materials, prioritize light-colored finishes with a high Solar Reflectance Index (SRI); for low-slope roof surfaces, LEED recommends an SRI of 78 or higher.

The shelter should have lighting that meets the code requirements of the city or county and meets State Energy Code (Title 24). The SacRT design guidelines require lighting in and around light rail stations and bus stops and have a light level requirement. Where electricity is not available, the use of solar panels and battery storage should be used. Occupancy sensors should be considered and may be required by code. Lighting at shelters should be adequate for public safety, low glare, easily maintained, and vandal resistance.

Advertising on shelters should be integrated into the overall shelter design versus being an afterthought. All advertising panels should be constructed from durable, vandal-resistant materials and positioned so they do not block airflow or trap heat within the shelter. Advertisement signage should not dominate the aesthetic of the shelter and be scaled appropriately to the structure. Advertisement signs should not impede public safety of the shelter by reducing visibility.

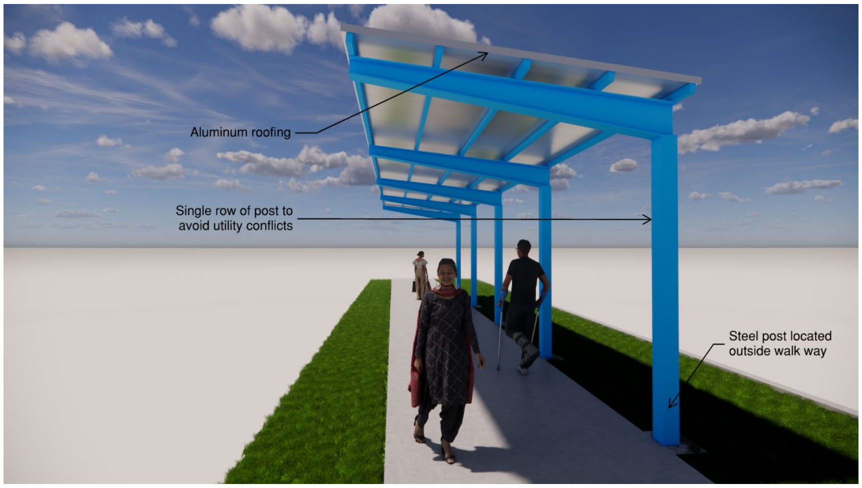
Light Rail Station- Platform Structure

These structures have sides open to the greatest extent possible to allow ventilation and use perforated panels to maximize sun screening. The roof has a high Solar Reflective Index and is elevated high enough to reduce heat transmission to occupants.



Covered Walkway

This structure has sides open to the greatest extent possible to allow ventilation. The posts are located out of the walkway to the greatest extent possible and the roof has a high Solar Reflective Index and is elevated high enough to reduce heat transmission to occupants.



Transit Center/ Pavilion

This structure has a large roof area with large spans between columns. The structure uses a roof form to allow ventilation through the roof and limit sun exposure. The roof has a high Solar Reflective Index and is elevated high enough to reduce heat transmission to occupants.

Best Practices for Shelter and Structure

The design of shelter and shade structures should prevent people from being able to climb them. Roof height should be kept above 10'. Avoid using posts that allow hand holds like a wide flange steel. Beams and braces should be kept at heights above 9' to avoid climbing. Other practice that can avoid climbing are post spacing greater than 42" apart, placing seating or low wall that can be used to access structure, and posts that have rough texture or groves that can be used hand holds. Post should be on a concrete base or made of reinforced concrete to greater durability and prevent base plates for rusting in standing water.

Shade Structure Cost Estimate

Table 8. Cost estimates for various types of shade structures

Shelter type:	Bus Shelter 5'x12'	Covered Walkway 8'x50'	Light Rail Structure 12'x50'	Pavilion/ Transit Center 30'x60'
Structure size (square feet)	60	400	600	1,800
Shelter infrastructure (per unit)	$17,500.00	$44,000.00	$75,000.00	$207,000.00
Shelter labor	$1,000.00	$12,000.00	$12,000.00	$15,000.00
Site material	$1,500.00	$2,500.00	$5,000.00	$16,000.00
Site labor	$5,500.00	$17,500.00	$17,500.00	$38,500.00
Total (per unit)	$25,500.00	$76,000.00	$109,500.00	$276,500.00
Price per square foot	$425.00	$190.00	$182.50	$153.61

Notes:
Cost estimate does not include concrete pad construction, landscaping, drainage, lighting, and signage
Cost estimates assume bus shelter to be fully assembled when delivered to the shelter-ready site. Shelter labor is the cost to anchor the assembled structure to the foundation. New 6" concrete slab or pier footing would be constructed to accommodate a bus shelter.
Cost estimates for site material and site labor cover construction of concrete pad and/or foundation for the structure.
Covered walkway, light rail structure, and pavilion are partially assembled and delivered to the site. Pier footing would be constructed on site for the structure.

Benefit-Cost Analysis

This section provides a hypothetical example illustrating a benefit-cost analysis (BCA) to evaluate the cost-effectiveness of installing a bus shelter in the city of Sacramento. The baseline scenario represents a typical bus stop without shelter, while the enhanced scenario considers adding a shelter to that bus stop.

For the baseline scenario, only installation cost was considered that included bus stop materials, landing pad, and site labor of $325, $1,130, and $137, respectively, based on Utah Transit Authority (UTA)'s Bus Stop Master Plan adjusted to 2025 values (UTA, 2023). For the enhanced scenario, the bus shelter infrastructure, shelter labor, site material, and site labor was taken from Table 8. Annual maintenance cost for the shelter beyond the baseline bus stop was assumed to be $109 (using the cost difference in maintaining bus stop with and without shelter from the City of Poway as a peer comparison).

The primary benefit of the bus shelter is its ability to provide shade and protection from the elements, making riders feel more comfortable during their wait time and retain riders on hot days. Therefore, the benefits considered in this analysis include perceived time savings and revenue loss reduction due to retention.

To quantify ridership retention, the daily individual trip rate was assumed to decrease by 27% on very hot days. This figure was estimated using the SacAdapt public survey results; 27% of regular transit riding respondents said that hot weather-related improvements would have a high impact (i.e., multiple times per week) on their mode choice. The annual number of very hot days was taken as 58, based on historical data from the vulnerability assessment report using where the Heat Index reached Extreme Caution or higher. Daily bus trips for a typical bus stop were calculated using SacRT data of 8.5 boarding trips per day on average across 2,766 bus stops without shelters. Considering a 27% reduction, a bus stop would lose 3 trips on each very hot day. Revenue was estimated at $1.20 per trip in 2025 (FTA, 2023). Hence, the retention benefit was to avoid annual revenue loss of $209 on very hot days at a bus shelter.

To monetize perceived time savings, Fan et al. (2016) found that waiting time at no-amenity bus stops was perceived as 1.3 times the actual waiting time, while perceived waiting time at bus shelters was close to actual. Assuming an actual waiting time of 18 minutes (half the average headway for Sacramento buses), the perceived time loss in the baseline case was 5.4 minutes. The value of time at transit waiting was taken as $40.20 per person per hour (USDOT, 2025). Using annual SacRT bus trips of 2,210per bus stop, the annual value of perceived time saved at a bus shelter was estimated at $7,996, assuming 260 workdays to be conservative.

Using these benefits of the bus shelter and comparing them with the additional cost of the enhanced scenario beyond the baseline, the benefit-cost ratio was calculated. The lifecycle BCA spans 2025–2045 and applies a 7% discount rate, as recommended by USDOT (2025). In this analysis, Benefit-Cost Ratio (BCR) represents the ratio of total monetized benefits to the additional costs of the enhanced scenario beyond the baseline. A BCR greater than 1 indicates benefits exceed incremental costs.

Results are provided in Table 9.

Table 9. Summary of lifecycle costs and benefits for different scenarios

Scenario	Costs ($)		Benefits ($)		BCR
	Installation	Maintenance	Ridership Retention	Time Saving	
Bus Stop without Shelter	1,592	--	--	--	--
Bus Stop with Shelter	25,500	1,266	2,421	92,703	3.78

The main key takeaways of the assessment include:

- Shelter installation significantly increases lifecycle costs compared to a basic bus stop, primarily due to higher capital and replacement costs.
- Maintenance costs for a shelter are only moderate.
- Benefits far outweigh costs for the enhanced scenario, with a Benefit-Cost Ratio (BCR) of 3.78, indicating strong cost-effectiveness.
- Largest benefit driver is perceived time savings, valued at $92,703 over the lifecycle, accounting for 97% of total benefits.
- Retention benefit contributes only 3% to the total benefits.
- Shelters improve rider comfort and resilience, reducing vulnerability to extreme weather and supporting sustainability goals.
- Actual costs may vary depending on shelter design, materials, and site conditions.

Conclusion

The benefit-cost analysis indicates that installing bus shelters can be highly cost-effective. While initial capital costs are significantly higher than an unsheltered bus stop, the long-term benefits outweigh these costs under current assumptions. Additional benefits such as heat resilience and emission reductions further strengthen the case for deploying shelters. Costs vary based on design, materials, and site conditions, which should be considered in planning. Bus shelters are most suitable in high-ridership or heat-vulnerable areas where enhanced amenities can improve transit rider experience and support sustainability goals.

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4.2 VEGETATION-BASED SHADING

Introduction

Sacramento's hot-summer climate creates challenging conditions for people walking, biking and taking public transit. Increasing shade through trees is one of the most effective ways to reduce heat exposure and improve the comfort of bicycle and pedestrian facilities, and transit stops and stations. Trees provide natural cooling, improve comfort through evapotranspiration, and create shade that grows in effectiveness over time. In many locations, trees offer the most cost-effective and visually integrated long-term shading strategy.

This document provides planning-level guidance to help the City of Sacramento, SacRT, and partner jurisdictions integrate vegetation-based shading consistently and effectively across the city.

Purpose

The purpose of this document is to outline innovative strategies for underground support systems and maintaining shade trees in urban corridors. Guidance is focused on early planning, not construction-level detail. Emphasis is placed on solutions that perform well under Sacramento's heat conditions and can be maintained over time. For tree selection and placement, readers are referred to Sacramento Urban Forest Plan (City of Sacramento, 2024) as well as permits and ordinances from the City for up-to-date information.

Context

Many transit locations and urban corridors in Sacramento receive long hours of direct sun and have limited planting space due to utilities, narrow sidewalks, and paving. Because conditions and constraints vary widely, the strategies in this document are adaptable and intended for use across bus stops, light rail stations, transit centers, walkways, and public space improvements.

Water Establishment and Maintenance

Establishment Period

The tree establishment period is critical to achieving mature size and long-term health. For most trees, this means providing supplemental irrigation through the first two dry seasons and staking through the first two winters to protect against wind. A dry winter or hotter-than-normal summer may require additional watering. During establishment, watering frequency should gradually decrease while the amount of watering increases to encourage deep rooting. The goal is to develop an extensive root system capable of accessing water during drought conditions.

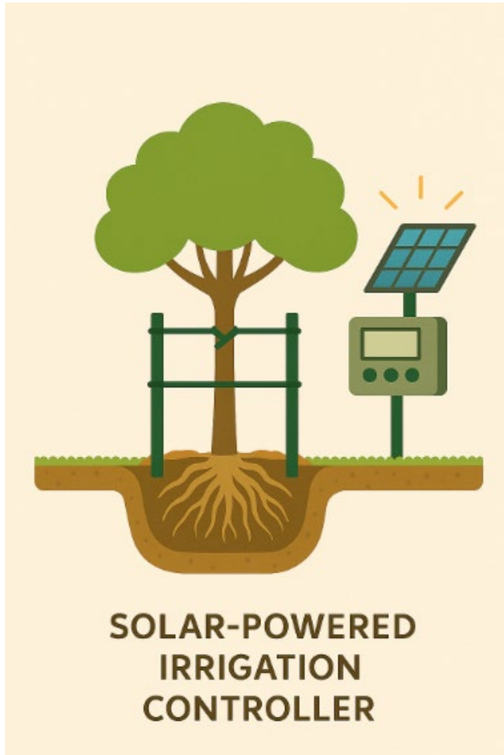
Water Requirements

Trees will require supplemental watering during the establishment period and, in some cases, beyond, depending on species-specific water needs. Drought-tolerant trees with well-established root systems can generally withstand the dry season with minimal stress. During establishment, provide consistent irrigation through an automatic system or a structured weekly hand-watering schedule. Where permanent irrigation is not available, select low water use species appropriate to the region, using the Water Use Classification of Landscape Species (WUCOLS) database for guidance.

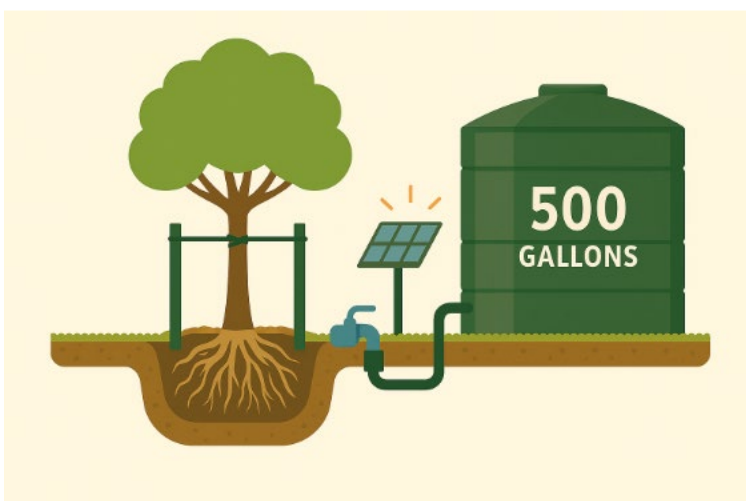
Irrigation Methods & Strategies

Newly planted trees will need additional water during the first 3 dry seasons. Apply water 2 to 3 times per week and monitor soil moisture to confirm it is reaching the root zone. Trees that are not drought tolerant will require permanent supplemental irrigation through the dry season. This water can be supplied by an automatic irrigation system or hand watering.

Automatic irrigation is the preferred method for both tree establishment and long-term watering. It requires a reliable water source and an electric irrigation controller that complies with all applicable state and local codes. Where conventional power is not available, a solar-powered controller may be used. Locate solar controllers away from the tree to avoid shading panel and position them for optimal sun exposure.



Where a permanent water source is not available, use a storage tank for tree watering. If electrical power is also unavailable, a solar-powered pump can be used to deliver water from the tank to the trees. Size the tank based on tree water demand and the anticipated frequency of refilling.



Irrigation should use low-flow emitters, generally at or below 15 gallons per hour (0.25 gallons per minute) per emitter. Place emitters near the tree root ball at installation and move them outward as the tree and root system expand. Install emitters and all related irrigation hardware where they are protected from vandalism, mowers, and regular foot traffic.

For drought tolerant trees, hand watering may be used where automatic irrigation is not feasible. Water can be supplied from a quick coupler, hose bib, or water truck. Use a slow-release watering bag to make hand watering more efficient and to allow the soil to absorb water gradually. However, hand watering and watering bags come with challenges, including labor demands, potential vandalism, the need for removal and disposal at the end of use, and the risk that the bag will not last the full establishment period. When selecting a watering bag, consider water capacity, release rate, ease of filling, and durability. *Note*: Slow-release watering bags are most practical as a temporary establishment tool for a limited number of trees, especially in locations where permanent irrigation is delayed or not available, where access for trucks or hoses is available, and crews can reliably monitor, refill, and eventually remove the bags. They should not be relied on as the default long-term solution.

Ongoing Tree Maintenance

Tree maintenance is required for the entire life of the tree. The level of maintenance will depend on species selection, placement, and the amount of soil volume provided.

Pruning is necessary to develop strong structure and reduce the risk of limb failure. For the first 10 years, trees should be pruned approximately every 2 years. After 10 years, a pruning cycle of about every 5 years is generally appropriate.

Tree stakes are to be removed after the second winter to allow the trunk to strengthen and to prevent damage as the tree outgrows the supports. During the establishment period, inspect stakes and ties regularly and repair or replace any damaged components to avoid rubbing, girdling, or instability.

Permanent irrigation serving newly planted trees should also be inspected regularly during the establishment period to ensure proper function and adequate watering. Once trees are established, irrigation checks can be reduced to monthly during the dry season, while still verifying that systems are functioning correctly and trees are not exhibiting stress.

Apply a layer of mulch in each tree planter to promote water retention, suppress weeds, moderate soil temperatures, and add organic matter as it breaks down. Use an organic mulch made from recycled or post-consumer materials where possible. Maintain a depth of 3 to 4 inches, keeping mulch pulled back from the root crown to prevent decay. Refresh or top up mulch every two to three years.

Trees should be routinely monitored for overall health, including signs of drought stress, insect damage, fungal or bacterial infection, and vandalism. Maintenance staff should address issues promptly and use preventive practices to support long-term tree health. Trees that have died or are unlikely to recover should be removed and replaced with a new tree. When possible, schedule new plantings between October and March, when establishment stress is reduced. After removal, the root crown or stump should be fully extracted or ground out to allow successful replanting.

Paving Around Trees and Underground Support Systems

Constraints & Overview

Urban areas and parking lots often have limited planter space for trees. Large planters may not be feasible because of paving, drive aisles, and walkways. In these situations, alternative approaches—such as suspended paving (soil-cell) systems or structural soil back-fill beneath pavement—can be used to increase rooting volume. These options add cost and come with design constraints, so they are most appropriate where traditional planters cannot provide enough soil for the desired tree size.

Traditional Tree Pits/Native Ground

Traditional tree pits use existing native soil without structural soil or soil-cell systems. They work best where planters are large enough for trees to mature—generally around 1,200 cubic feet or more—and where soils have not been heavily compacted or previously paved over.

In these conditions, trees can develop full canopies, roots can spread naturally, and long-term health is typically good. This is also the lowest-cost option, making it appropriate for corridors and sites that already have generous open-soil areas.

Where the tree planter soil was previously paved over or compacted, the entire planter should be amended by removing soil or tilling to a depth of 24”. Soils should be tested for fertility and amend per recommendation of soil fertility report.

Where planters are small and rooting volume is limited, traditional tree pits alone are unlikely to meet shade or longevity goals, and soil-cell systems should be considered.

Soil-Cell / Suspended Paving Overview

Suspended paving, also known as soil-cell systems, are modular structural frames—typically recycled-polypropylene lattices—installed beneath hardscape so pavement and vehicular loads are carried by the deck while trees grow in a protected rooting zone below. The frames interlock to form work around utilities. The deck of the soil cell provides air and water to soil below paving. Planting soil is placed within the system in ≤12-inch lifts and lightly compacted to preserve porosity while controlling settlement. The upper 24 inches of the profile is an amended topsoil over screened structural fill, with all soils lab-tested before placement. Where stormwater treatment is part of the program, the fill may be a bioretention mix per the local LID manual. An underdrain system is recommended and should be connected with storm drain system or use of a drywell where drain system is not available. A graded aggregate (gravel) base supports the modules and the approved pavement section. Soil cells are designed for a load rating of H20 and with some products the load rating can be increased. This allows vehicles to drive and park over the soil cells.

Graphic: GreenBlue Urban's RootSpace soil-cell system providing structured soil volume and utility space beneath paving in a street tree application.

Soil-Cell Components

A typical soil-cell assembly includes:

1. Prepared subgrade with geotextile and/or aggregate base per the approved pavement section.
2. Modular cell frames (polypropylene lattice modules) stacked to design depth with interlocks/connectors and load-spreading lids/decks engineered to the project's load rating. Manufacturers of soils cells include Deep Root Silva Cell, GreenBlude Urban RootSpace, and Citygreen Stratacell.
3. Utility corridors/sleeves routed through the matrix to keep conduits serviceable.
4. A manufacturer specified top soil placed in ≤12-inch lifts inside the cells with light compaction.

5. Aeration/inspection inlets at the surface for gas exchange, moisture checks, and maintenance access.

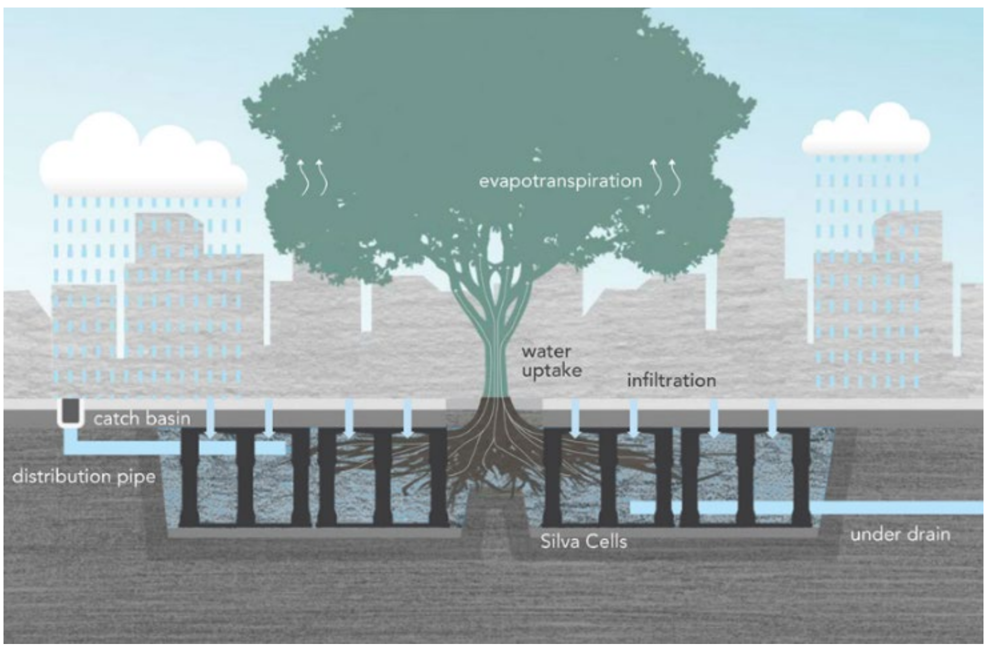
6. Drip irrigation both in planter and under pavement using perforated pipe and serviceable access point on ends.

7. Recommend perforated drainpipe connection to storm drain or drywell.

8. Root-management barriers at hardscape edges/utilities to encourage root growth into the vault.

9. Edge restraints curbs or root management barrier at pavement section.

10. The tree opening with mulch in planter.



Graphic: DeepRoot Silva Cell system showing how stormwater is captured and stored in structured soil beneath pavement to support a large street tree.

Targeted Soil Volume for Soil-Cells

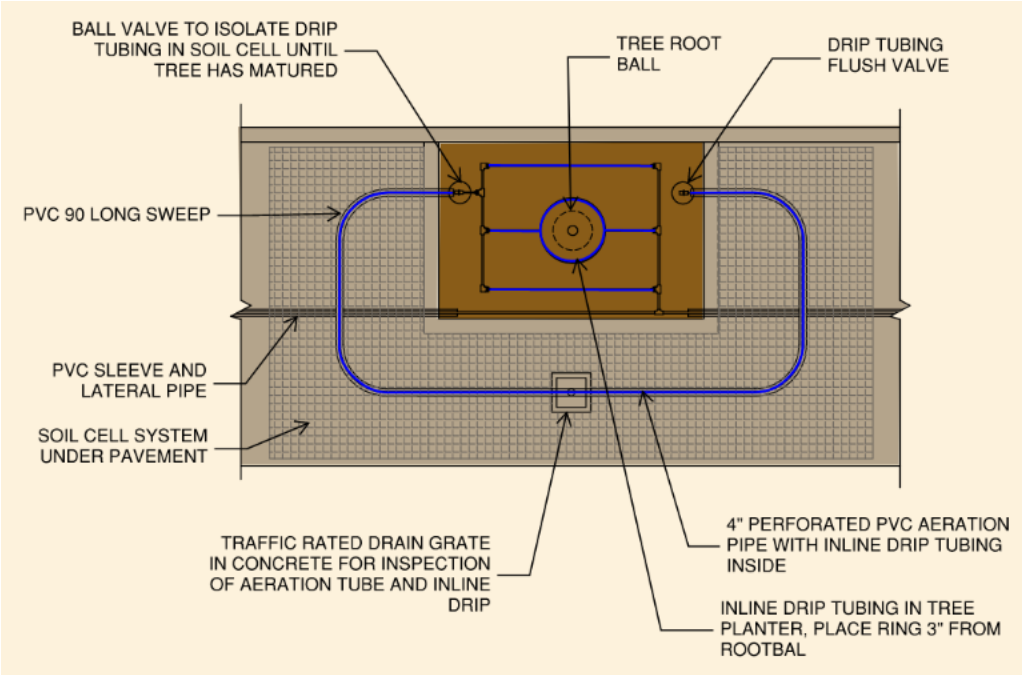
Tree performance tracks closely with soil volume. As a planning target, provide about 1,200 cubic feet per large shade tree, or about 400 square feet and 3 feet of soil depth. This typically supports a large canopy under urban conditions (species dependent). Linking tree planters and allowing roots to share space can help reduce total required soil volume. Soil cell manufacturers may have additional guidance for soil volume sizing.

Soil-Cell Backfill

Use a loam-based planting topsoil with organic matter and a controlled fraction of fines (silt and clay) to balance structure, moisture retention, and aeration. Lab-test each source for texture, organic matter, pH, EC/salts, and nutrients. Place backfill in lifts no thicker than 12 inches, lightly compacted by foot in each cell, and use limited water to help settle soil into cells. During placement, protect porosity by not working soil when wet. Soil compaction should not exceed 85% compaction. Keep fertility data-driven: add compost or targeted amendments only when lab results call for it, and re-test if sources change. If soil cells are greater than 30" deep, then a fill soil layer should be used below 30". The screened fill soil should have less than 5% organics and be compacted using the same methods as the topsoil. Soil cell manufacturers will provide soil specifications that best support their product ability to grow healthy trees.

Soil-Cell Irrigation and Aeration Methods

Provide a dedicated low-flow drip zone for the soil-cell area so flow, runtime, and scheduling can be controlled independently from surrounding landscape planting. Use pressure-regulated valves with filtration at each control zone, and do not tie soil-cell trees to turf or spray irrigation programs. Route mainline and lateral piping through designated utility corridors within or just below the soil-cell layout so lines stay accessible and do not displace planting soil. From these corridors, run distribution tubing to each tree opening. Place emitters or dripline at the top of the root ball and across the soil-cell zone where roots are expected to develop. Provide surface aeration/inspection inlets at appropriate locations so air can move in and out of the vault and maintenance staff can check moisture, flush lines, and observe performance. When irrigating trees, make sure to use deep irrigation with infrequent watering cycles that wet the full soil-cell profile and encourage deep rooting for trees.



Graphic: Soil-cell irrigation and aeration layout showing drip tubing looped through the vault, a drip ring at the tree root ball, and a surface grate for inspection and maintenance.

Root Barriers at Pavement and Utilities

Use linear root-barriers that are 30” deep where pavements, utilities, walls, or foundations need protection. Place root-barriers at paving edges to guide roots down into the soil-cell system instead of outward beneath the paving profile. Keep the rooting zone inside the soil-cell field as continuous as possible, and avoid ringing the tree or segmenting the internal soil volume with unnecessary barriers unless protecting a utility or other elements that need protection from roots.

5| BIKE/PEDESTRIAN BRIDGE INSPECTIONS

5.1 PURPOSE

Bike/pedestrian bridges are typically lighter structures than vehicular bridges and often include unique features such as timber decks, handrails, and architectural elements. Inspections ensure public safety, structural integrity, and user comfort, while also accounting for non-vehicular load types, vandalism or misuse.

5.2 INSPECTION FREQUENCY

Type of Inspection	Frequency	Notes
Initial (Baseline)	After construction completion	Establish baseline condition
Routine Inspection	Every **24 months (2 years)**	Shorter intervals (12 months) may be recommended for timber or corrosion-prone materials
Special Inspection	As needed (after flood, impact, fire, vandalism, or seismic event)	Focused on affected areas
In-Depth Inspection	Every **4–6 years** or when deterioration is suspected	Hands-on, detailed
Fracture-Critical Inspection	Every **24 months**, if applicable	For non-redundant members in steel truss or tied-arch systems
Underwater Inspection	Every **5 years**, if applicable or as needed after flood events if there has been visible damage above water from vessel impact, or build-up of debris at piers or abutments	For bridges located in deep water ways

Note: Pedestrian bridges owned by cities or parks departments may follow less formal schedules, but documentation and consistency are key.

5.3 INSPECTION CHECKLIST

A. General Information

- Bridge name, bridge number, location and owner
- Bridge type and material (steel, concrete, timber, aluminum, composite)
- Span configuration and support type
- Foundation and abutments type
- Year built / last rehab / last modification
- Load rating (if available)
- Deck width and ADA compliance

B. Approach and Site Conditions

Item	What to Look For	Notes
Approaches	Settlement, erosion, alignment issues	Trip hazards or abrupt grade changes
Drainage	Clogged inlets, ponding, undermining	Standing water accelerates decay
Vegetation	Overgrowth, root intrusion, visibility issues	Can hide defects or damage
Embankments	Erosion, scour, slope stability	Particularly after storms or flooding

C. Substructure (Abutments, Piers, Footings)

Item	What to Look For	Notes
Concrete	Cracking, spalling, delamination	Check near joints and base
Steel	Corrosion, section loss, loose connections	Pay attention to anchor bolts
Timber	Rot, insect damage, fastener loosening	Probe suspect areas
Foundations	Scour, settlement, undermining	Verify bearing alignment

D. Superstructure (Main Load-Carrying Elements)

Item	What to Look For	Notes
Girders / Trusses	Cracks, corrosion, deformation, unsound concrete, voids, honeycombing	Fatigue-prone areas at welds
Connections	Bolt tightness, weld quality, rust	Watch for vandalism or missing hardware
Bearings	Movement, corrosion, frozen condition	Often overlooked in small bridges

E. Deck System

Item	What to Look For	Notes
Deck Surface	Cracks, delamination, potholes, unevenness, unsound concrete, voids	Evaluate for ADA compliance and tripping hazards
Deck Material	Timber decay, delamination (FRP), corrosion (metal)	Non-slip surface condition
Drainage	Blocked scuppers or trapped moisture	Important for long-term durability

F. Rails, Barriers, and Fencing

Item	What to Look For	Notes
Railings / Handrails	Loose, bent, corroded, missing elements or non-compliant height	User safety concern
Fencing / Screens	Vandalism, damage, sharp edges	Especially on overpasses
Connections	Missing bolts, weld cracks	Critical to fall prevention

G. Lighting, Signage, and Accessories

Item	What to Look For	Notes
Lighting	Functionality, wiring damage, vandalism	Ensure safety for nighttime users
Signage	Missing, faded, or incorrect	Include clearance and load limit signs
Utilities	Exposed conduit, leaks, missing/damaged utility covers	Especially if combined with lighting cables

Striping / Markings on Deck Surface	Check for peeling or fading, missing markings	Encourage safe use

H. Surface / User Experience

Item	What to Look For	Notes
Skid Resistance	Worn surface, algae/moss growth	Common hazard on timber or composite decks
Expansion Joints	Gaps, misalignment, debris, missing covers or seals	Can trip pedestrians or cyclists
ADA Compliance	Slopes, surface smoothness, detectable warnings	Evaluate per PROWAG/ADA standards

I. Environmental and Aesthetic Elements

Item	What to Look For	Notes
Coatings / Paint	Peeling, fading, corrosion underneath	Preventive maintenance indicator
Drainage Systems	Leaks, plugged drains	Accelerates structural decay
Landscaping / Context	Root intrusion, visibility	Important for safety perception

J. Documentation and Photos

- Take photos or video of all structural members and any noted defects
- Record dimensions, crack widths, corrosion depth, etc.
- Note vandalism or graffiti that could conceal defects

5.4 KEY DIFFERENCES FROM VEHICULAR BRIDGE INSPECTIONS

Aspect	Bike/Pedestrian Bridge Focus	Vehicular Bridge Focus
Loads	Pedestrian, cyclist, maintenance vehicle (light loads)	Heavy vehicular loads
Deck Materials	Concrete, timber, composite, aluminum, FRP common	Concrete, steel typical

User Safety	Handrails, slip resistance, ADA compliance	Guardrails, vehicle impact protection
Frequency	Often similar (every 2 years) but may vary by ownership	FHWA-mandated (every 2 years for NBI)
Vandalism Risk	Higher—fencing, lighting, graffiti	Lower priority
Aesthetic / Architectural Features	Often integral to design	Secondary
Dynamic Effects	Vibration and comfort for pedestrians	Fatigue and heavy live loads

5.5 REFERENCES AND STANDARDS

- FHWA Bridge Inspection Reference Manual (2024)
- NBIS (23 CFR 650 Subpart C) — National Bridge Inspection Standards
- AASHTO LRFD Guide Specifications for Design of Pedestrian Bridges (2nd Ed.)
- FHWA-HRT-05-130: Pedestrian Bridge Inspection Guide
- Manual for Bridge Evaluation (AASHTO)
- ADA / PROWAG Guidelines for accessibility

6| CNG INFRASTRUCTURE

6.1 OVERVIEW

Sacramento Regional Transit District (SacRT)'s fueling infrastructure relies on compressed natural gas (CNG) compressors supported by a programmable logic controller (PLC)-based control system and supervisory control and data acquisition (SCADA) for automation and monitoring. The compressors are designed to deliver high throughput fueling for transit fleets, operating in parallel to provide redundancy and meet peak demand. The PLC system coordinates compressor sequencing, storage bank management, and dispenser operations, while SCADA provides system-wide visibility, logging, and remote monitoring of pressures, flows, alarms, and operational status.

However, the current equipment and control systems present significant challenges. The three Gemini compressors in operation are past their useful life, and sourcing parts have become increasingly difficult due to reliance on a single distributor. As these compressors age, maintenance costs continue to rise, creating financial and operational strain. Additionally, the existing PLC and SCADA systems are outdated and do not provide comprehensive sensor data, limiting the ability to detect issues early and implement predictive maintenance strategies. This reactive approach increases the risk of major faults and unplanned downtime.

Climate conditions further compound these issues. During summer months, compressors run hotter, and the lack of adequate cooling leads to a higher likelihood of high-heat faults. These faults occur more frequently in summer than in winter, disrupting fueling operations and increasing maintenance demands. As conditions continue to get hotter, disruptions are expected to increase. Together, aging equipment, outdated controls, and seasonal stressors pose a growing risk to reliability, safety, and operational efficiency.

6.2 BENEFITS OF MODERNIZATION

Upgrading aging compressors and PLC systems delivers significant operational and resilience benefits:

- **Improved Reliability**: Modern compressors combined with advanced PLC and monitoring systems enable real-time diagnostics and condition monitoring that support proactive maintenance and reduce unplanned outages. Federal research has shown that diagnostics- and prognostics-based maintenance strategies improve equipment availability and reduce downtime by allowing faults to be identified and addressed before failure occurs, extending overall asset life and improving maintenance planning (NIST, 2020; NIST, 2024).
- **Enhanced Safety**: Modernized control architectures with integrated sensors, alarms, and supervisory monitoring improve early detection of abnormal operating

conditions and support automatic placement of the system into a safe state. For CNG fueling facilities, safety codes explicitly require gas detection systems to initiate compressor shutdown and stop gas flow, with manual verification required before restart, demonstrating the critical role of updated controls and safety logic in preventing escalation and catastrophic failures (NFPA, 2022).

- **Energy Efficiency**: Optimized sequencing and load management are widely recognized as energy-efficiency measures. DOE guidance identifies control systems as a critical determinant of overall compressor energy performance and recommends quantifying energy and cost savings achieved through improvements in control logic and operational strategies (DOE, 2003).
- **Climate Resilience**: Resilience improvements include specifying control panels and components rated for ambient temperatures above the common 40 °C (104 °F) baseline, unless explicitly marked otherwise, and deploying control and monitoring systems to detect abnormal conditions and enable rapid, safe recovery. Elevated temperatures are widely recognized to accelerate failure mechanisms through Arrhenius-type behavior (NIST, 2023), underscoring the importance of heat mitigation strategies and appropriate component ratings.

6.3 REPLACEMENT STRATEGY

- **Full-System Replacement**: Recommended when compressors and controls are past their useful life or incompatible with modern PLC and SCADA platforms. This approach ensures uniform technology, reduces lifecycle costs, and simplifies maintenance.
- **Piecemeal Upgrades**: Lower upfront cost but may lead to integration challenges, uneven performance, and higher long-term maintenance expenses. Retrofit kits can offer short-term relief but often lack full compatibility with advanced monitoring and sequencing features.

Given SacRT's aging compressors, limited parts availability, and outdated SCADA system, a full-system modernization may be the most cost-effective and resilience-focused option.

6.4 RESILIENCE AND ADAPTATION MEASURES

CNG fueling facilities that support transit fleets face growing exposure to climate-driven stressors such as extreme heat, flooding, and power disruptions. Integrating resilience and adaptation measures into compressor systems and PLC-based controls is essential to maintain fueling reliability and protect fleet availability under current and future climate conditions.

Extreme Heat and Thermal Stress

High ambient temperatures reduce compressor efficiency, elevate discharge temperatures, and accelerate wear on seals, lubricants, and electronic components. Heat stress also impacts PLC panels, variable frequency drives (VFDs), and communication hardware, increasing the likelihood of nuisance trips or premature failures. Heat mitigation options include:

- Shaded or enclosed compressor skids, along with noncombustible canopy structures, can reduce surface temperatures by 15–45°F (UNH, 2024; Al Tahir et al., 2025), lowering thermal stress on compressors and electrical panels. Ensure the material is appropriately fire-rated and that it is designed in a way to prevent build-up of ignitable vapors.

- Enhanced ventilation, high-temperature-rated electrical components, and control logic that modulates compressor loading during peak heat conditions further improve resilience.

- Adaptive PLC sequencing—such as rotating lead compressors or limiting simultaneous starts—reduces thermal stress while maintaining fueling throughput.

Flooding, Stormwater, and Site Conditions

Flooding and inadequate drainage can damage compressors, electrical panels, and underground piping, particularly at older facilities not designed for intense precipitation. Adaptation measures include elevating critical equipment above projected flood levels, sealing conduit penetrations, and incorporating flood sensors tied to PLC alarms (EPA, 2015). Early detection and controlled shutdowns reduce the risk of catastrophic equipment damage and extended fueling outages.

Power Reliability and Grid Disruptions

CNG stations are highly dependent on grid power for compressors, dryers, controls, and dispensers. Extreme weather events underscore the vulnerability of fueling infrastructure to prolonged outages. Resilience strategies include integrating backup generation or microgrids, prioritizing critical loads within PLC logic, and implementing controlled shutdown/startup sequences to prevent equipment damage during power loss and restoration. PLC-based monitoring and alarms accelerate recovery by identifying system states and faults after outages.

Role of PLC and SCADA in Adaptive Operations

PLC and SCADA systems are central to climate resilience, enabling condition-based operations rather than fixed schedules. Temperature and pressure trends, runtime, and fault data supports predictive maintenance and informed operational decisions during extreme events. When integrated with agency emergency response plans, these systems help ensure fueling capacity aligns with service priorities during climate-driven disruptions.

6.5 BENEFIT-COST CONSIDERATIONS

At the planning level, climate-resilient upgrades to CNG compressor and PLC systems can be assessed through a benefit–cost analysis that weighs incremental capital and operating costs against avoided service disruptions, reduced equipment damage, and faster recovery during extreme events. Benefits are typically monetized through avoided fuel-supply outages (e.g., missed trips or bus pull-outs), emergency repairs, premature equipment replacement, and reduced labor or contractor costs, as well as avoided safety incidents (USDOT, 2025). Additional advantages include lower energy consumption from optimized compressor sequencing and load management, and reduced risk of prolonged fleet downtime during heat waves, flooding, or power outages. Federal guidance recommends using probabilistic hazard exposure, expected annual damage reduction, and avoided downtime metrics to quantify these benefits at a screening level, especially when detailed failure data are limited (Filosa, 2017). For transit fueling infrastructure, even modest reductions in outage frequency or duration can yield favorable benefit–cost ratios given the high operational and societal costs of lost transit service during extreme weather events.

6.6 CONCLUSION

SacRT's aging compressors and outdated PLC/SCADA systems pose growing risks to system reliability, safety, and cost efficiency. Rising maintenance demands, limited diagnostics, and seasonal heat-related faults highlight the need for modernization. Upgrading to modern compressors and advanced control systems will improve reliability through predictive maintenance, enhance safety with integrated monitoring, and boost energy efficiency. A full-system replacement may be the most cost-effective, long-term solution—reducing lifecycle costs, simplifying maintenance, and ensuring operational resilience to support SacRT's transit service under evolving conditions.

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