CHAPTER 6. USE-PHASE CONSIDERATIONS

Introduction

This chapter reviews environmental and social impacts of pavements in the use phase, which includes the influence of the pavement on vehicle operations and the interaction between the pavement, the environment, and humans. This chapter identifies use-phase impacts and considerations, provides current information regarding their effects, and describes current efforts to better quantify them in order to improve pavement sustainability. Figure 6-1 indicates various pavement characteristics and their potential impacts on the use phase.

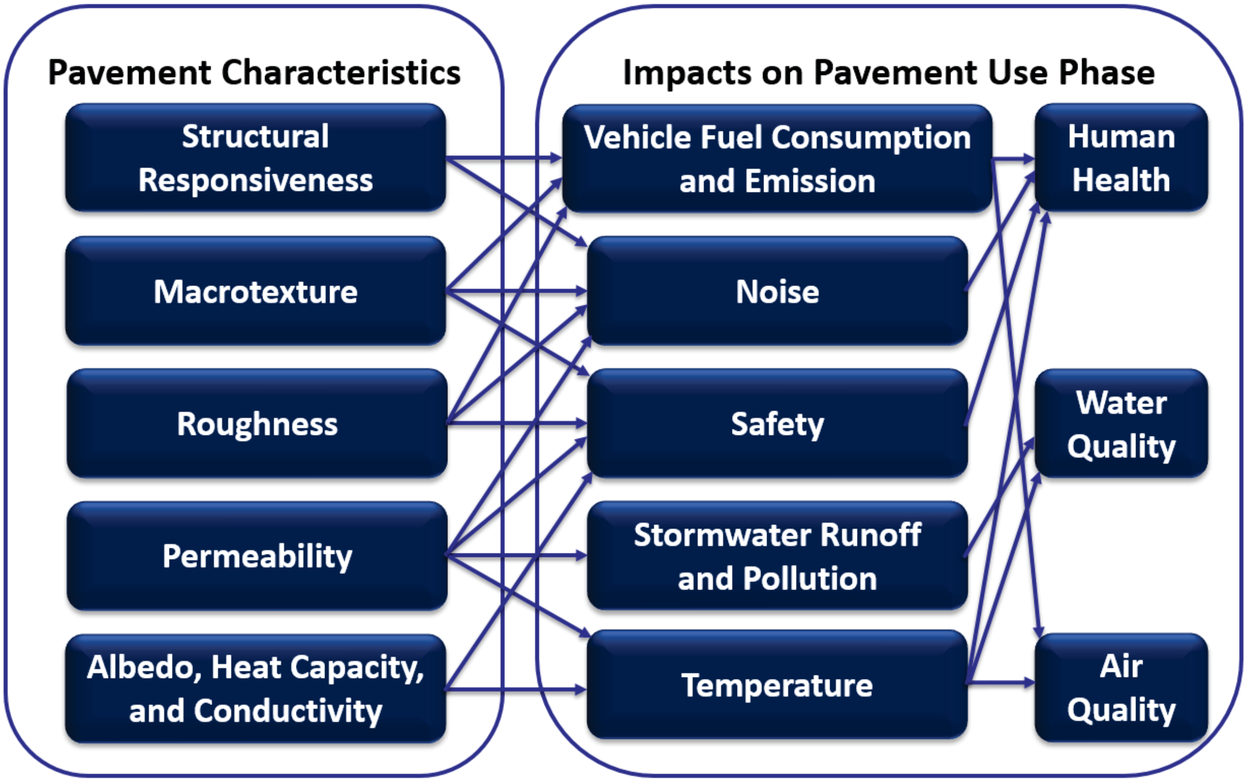

Figure 6-1. Pavement characteristics and influences on use-phase objectives.

As shown in figure 6-1, pavement roughness (or smoothness), structural responsiveness (related to stiffness, damping, and deflection under traffic), and macrotexture have all been identified as affecting vehicle fuel consumption, and as a result can have significant economic and ecological implications on vehicle operating costs and emissions. In addition, those same factors may contribute to freight damage while impacting the safety and comfort of road users. Moreover, pavement surface texture, permeability, and other pavement surface characteristics can impact the noise generated by the tire-pavement interaction, which can affect humans both in vehicles and within the acoustical range of the vehicles operating on the pavement; they also have important safety considerations with regards to surface friction, hydroplaning, and wet-weather crashes.

The permeability of the pavement system can influence stormwater runoff and surface friction, and potentially the costs associated with stormwater treatment. Pavements that are partially or fully permeable can flatten flow-duration curves to reduce the peak flow rate and can also affect pollution flow into receiving water bodies and their water temperatures.[1]

The albedo (reflectivity), heat capacity, and thermal conductivity of the pavement all affect the absorption of energy from the sun and the emission of reflected and thermal energy from the pavement, which can potentially affect energy consumption of building cooling and lighting systems, vehicle cooling systems, air quality, and human health (depending on a number of factors). The global balance of energy (radiative forcing) is also influenced by surface albedo. For some applications, the luminance of the pavement may also have an effect on the energy needed for roadway lighting for nighttime safety, visibility of objects, and the ability for drivers to see pavement markings and obstacles. Some of the decisions regarding use-phase effects that can affect sustainability are made at the network level and can be implemented through effective pavement management systems (PMS), while others can only be implemented at the project level through design and construction decisions. There are trade-offs that may be considered within many of these decisions, including important safety issues. As is discussed in this chapter, many of these trade-offs are sensitive to project context, particularly traffic levels and climate. Project context also often has a large influence on the relative importance of environmental impacts of different phases of the pavement life cycle; for example, use-phase impacts on routes with heavy traffic are often much greater than material production and construction phase impacts, while the opposite may be true for low-traffic routes.

Major Issues:

- ✓ *Trade-offs between negative effects of material production and construction activities during maintenance and rehabilitation versus use-phase benefits.*
- ✓ *Consideration of smoothness over the entire life cycle and achieving highest level of smoothness possible during initial construction and subsequent maintenance and rehabilitation activities.*
- ✓ *Consideration of pavement structural responsiveness to loading*
- ✓ *Preserving smoothness in locations with utilities (avoiding utility cuts when possible)*

Only those use-phase effects that can be changed by pavement decisions are considered in this chapter, and it must be recognized that many of these effects are not currently well quantified. Other impacts that occur from the use of the pavement but are outside the control of pavement engineers, managers, and decision makers—such as the addition of new lanes to existing roads, the selection of new road locations and alignments, and the impacts of vehicle operation that are not influenced by pavement decisions—are also not considered in this chapter. In addition, safety is a critical concern and is addressed in this chapter where decisions regarding pavement-related environmental impacts also have safety implications. However, this chapter is not intended to be comprehensive in its treatment of safety issues, and the reader is referred to a series of highway safety reports available from NCHRP for additional information.[2]

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[1] Permeable pavements can refer to pavements constructed with permeable pavers, porous asphalt, or pervious concrete, but the terms "permeable," "pervious," and "porous" are used interchangeably in this chapter.

[2] NCHRP Report 500, *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*. (http://www.trb.org/main/blurbs/152868.aspx)

Vehicle Fuel Consumption and Pavement Characteristics

Background

Vehicle fuel consumption and associated emissions from combustion are influenced by a large number of factors including vehicle and cargo mass, engine size and type, fuel type, tire type and inflation, driving behavior, vehicle maintenance, grades and curves, traffic congestion, traffic control, wind, and several other factors, as well as the number of miles traveled. In fact, many of these have a greater influence on fuel economy than pavement characteristics. However, pavements can influence the fuel efficiency of vehicles—and therefore the associated GHG and air pollution emissions as well—through three mechanisms that together are called *pavement-related rolling resistance*. A discussion of the basic concepts of rolling resistance considering the total system of the vehicle components, pavement and road geometry, and measurement techniques is included in a report edited by Sandberg (2011). Another report (Jackson et al. 2011) also includes a summary of the principles of rolling resistance and its measurement. The pavement influences on these rolling resistance mechanisms are summarized as follows:

1. Roughness—consumption of vehicle energy through the working of shock absorbers and drive train components, and deformation of tire sidewalls as the wheels pass over deviations from a flat surface in the wheelpath with wavelengths greater than 1.6 ft (0.5 m) and less than 164 ft (50 m). The working of these vehicle components converts mechanical energy into heat that is then dissipated into the air, requiring greater work by the engine than would be necessary to propel it along a flat surface. Roughness is both built into the pavement during construction and materializes over time as the pavement ages and distresses develop, and is further influenced by subsequent maintenance and rehabilitation treatment applications and timing. Roughness on some pavement types can undergo relatively small changes with daily temperature fluctuations. For a given roughness condition, this rolling resistance mechanism affects all vehicles all the time.
2. Macrotexture—consumption of vehicle energy through the viscoelastic working of the deformable tire tread rubber in the tire-pavement contact patch as it passes over positive surface macrotexture and converts it into heat dissipated into the rest of the tire and into the air. Positive macrotexture is produced by stones or other texture protruding above the average plane of the pavement surface with wavelengths of 0.2 to 2 inches (5 to 51 mm). It is the primary pavement characteristic controlling surface friction at high speeds under wet conditions and the associated potential for hydroplaning (Anderson et al. 1998; Panagouli and Kokkalis 1998; Flintsch et al. 2002). Pavements serving high-speed vehicles must have a minimum amount of surface macrotexture and/or sufficient permeability to remove water films from the pavement surface so that frictional resistance is maintained for steering and braking. Macrotexture is provided by the characteristics of the surfacing materials (primarily relevant to asphalt surfaces) and texturing (primarily relevant to concrete surfaces), as well as subsequent maintenance and rehabilitation timing and treatment type. Macrotexture does not change due to daily or seasonal temperature and moisture conditions, although it can increase or decrease with age depending on the pavement surface materials, texture type, traffic, climate and use of chains or studded tires. For a given macrotexture, this rolling resistance mechanism affects all vehicles all the time.
3. Structural Responsiveness—consumption of vehicle energy in the pavement itself through deformation of pavement materials under passing vehicles, including delayed deformation of viscoelastic materials and other damping effects that consume energy in

the pavement and subgrade. This mechanism has also been characterized in terms of the delayed deformation of the pavement under the wheel such that the moving wheel is continually on a slope (Flugge 1975; Chupin, Piau, and Chabot 2013). Pavement structural responsiveness to loading is determined by layer thicknesses, stiffnesses and material types that determine viscoelastic and elastic pavement response under different conditions of wheel loading and vehicle speed, and temperature and moisture conditions. For a given pavement structure, the effect of this mechanism on viscoelastic materials such as asphalt can be highly dependent on daily and seasonal changes in pavement temperatures (particularly near the surface), and is more sensitive to vehicle speeds and loading than are roughness and macrotexture. Structural responsiveness can change with time.

As noted above, roughness, macrotexture, and structural responsiveness can change over the life of the pavement surface. In addition, roughness and structural responsiveness can change under daily and seasonal temperature and moisture conditions depending on pavement type and other conditions. The effects of these mechanisms over the life cycle are controlled by decisions regarding design, construction, and maintenance and rehabilitation applications.

High levels of roughness can be built into the pavement during construction because of poor practices and lack of specifications controlling constructed roughness. Roughness typically increases after construction due to the development of pavement distresses, such as rutting and cracking on asphalt surfaces and faulting and cracking on concrete surfaces. Smoothness can be improved with some maintenance and rehabilitation treatments and through greater attention to achieving smoothness during construction.

Initial macrotexture depends on the surface texture created during construction of the new pavement or later maintenance or rehabilitation treatments. Some surface types, such as some open-graded asphalt mixtures, chip seals with large aggregates, and improperly textured concrete, can exhibit high positive macrotexture from the time of construction. Positive macrotexture can increase over time due to raveling of asphalt surfaces or where concrete surfaces lose the paste around the large aggregates. Studded tires and chain wear can rapidly increase the macrotexture of both asphalt and concrete surfaces. Positive macrotexture can be reduced with time if the aggregate is susceptible to polishing under traffic, sometimes even to unsafe levels such that surface friction under wet weather conditions is compromised. Macrotexture can be changed through replacement of the surface materials for asphalt or concrete pavements, and through grinding or grooving for concrete surfaces.

The pavement structural responsiveness at the time of construction under different conditions of temperatures, traffic speeds, and wheel loadings is determined by the pavement type, the materials used, and the design of the structural section. The overall deformation of the pavement structure is controlled by the stiffness and thickness of the layers, and the extent of viscoelastic (delayed elastic) stiffness behavior that the layer materials exhibit under different temperatures and at specific times of loading. Together, these factors determine the energy dissipated in the pavement and the effect on vehicle fuel economy. Thicker and stiffer layers reduce the deformation response of the pavement, with a given percent change of thickness generally having a greater effect than the same percent change in stiffness.

Most concrete and cement-stabilized materials demonstrate elastic response and do not change stiffness under the range of temperature and traffic loading conditions typically experienced by in-service pavements. Concrete generally exhibits stiffness values in the range of about 4.3 to 7.3 million lb/in^2 (30,000 to 50,000 MPa). Fatigue damage in concrete is generally localized and does not decrease the stiffness much, if at all. Somewhat higher deflections occur at concrete pavement joints with poor load transfer under cold temperatures when the joints are open (Snyder 2011; Harvey et al. 2003).

For asphalt layers and asphalt-stabilized layers, the stiffness and extent of delayed elastic response is dependent on the type of asphalt binder, the temperature, and the traffic speed, with stiffness decreasing under hotter temperatures and slower moving wheel loads, and increasing under colder temperatures and faster moving wheel loads. The stiffness of new asphalt concrete under these conditions can vary between about 43,000 and 4.3 million lb/in^2 (300 and 30,000 MPa), corresponding to hottest temperatures/slowest moving loads and coldest temperatures/fastest moving loads, respectively. The interaction of variations in temperature profiles through the asphalt layers and variations in traffic loading and speeds with the materials properties determines the structural responsiveness of the asphalt layers throughout the year. Because temperatures change more at the surface, these effects are most important near the surface. Asphalt materials tend to "age" over time, increasing in stiffness and having less viscoelastic and more elastic response, which reduces deflections but is also associated with increased risk of top-down cracking. Aging occurs most rapidly over the first 5 years after placement, and is also greater near the surface due to increased exposure to heat, UV light from the sun, and atmospheric oxygen. The stiffness of asphalt layers in the wheelpaths can be reduced towards the end of their structural life as a result of fatigue damage caused by repeated loading.

The stiffness of unbound granular layers depends on the applied stress (both magnitude and duration) and the saturation of the material. Subgrade materials can also be a source of damping. High moisture contents in the subgrade and granular pavement layers, due to unsealed surface cracking or poor drainage, can cause significant reductions in their stiffness.

The additional fuel use for on-road vehicles caused by different levels of roughness, macrotexture, and structural responsiveness can have an environmental impact. From a life cycle perspective, these impacts must be balanced with consideration of the environmental impacts of building, maintaining, and rehabilitating pavements in order to maintain a smooth condition, minimize excessive positive macrotexture, and elicit lower levels of structural responsiveness. For example, as can be seen in figure 1-1 for sources of GHG emissions in the U.S., the transportation sector is a leading source of emissions, but it must be remembered that the production and transportation of pavement materials such as asphalt, cement, steel, lime and aggregate, as well as the consumption of fuel by construction equipment, also produce emissions. The construction of longer life pavements and the application of more frequent pavement maintenance and rehabilitation treatments can reduce pavement roughness, provide positive surface texture, and therefore reduce vehicle fuel consumption and GHG emissions over the life cycle. At the same time, constructing longer life pavements and applying more frequent maintenance and rehabilitation treatments also requires additional energy and produces additional emissions. Maintenance and rehabilitation treatments can also influence structural response depending on changes in thickness, stiffness, and properties of the treatment. Optimization of the longevity of the pavement design and of the maintenance/rehabilitation treatment type and frequency must take into consideration all of the life-cycle phases (materials production, construction, use and end-of-life), but is also highly dependent on the level of traffic using the pavement.

The relative impact of pavement-related rolling resistance on fuel economy and vehicle emissions depends primarily on the level of roughness, surface texture, and structural responsiveness. Vehicle types, traffic volumes and speeds, and climatic conditions also play an important role. For two pavements sharing similar characteristics, the total impact of the pavement on energy use and vehicle emissions then depends on the number and type of vehicles using it. If there are relatively few vehicles using the pavement, then all of these mechanisms (i.e. roughness, macrotexture, and structural responsiveness) will produce fewer emissions and other environmental impacts (resulting from materials production, construction, and maintenance and rehabilitation of the pavement) will play a larger role. For very heavily trafficked pavements, the cumulative effects of roughness, macrotexture, and structural responsiveness can become much greater than those produced by materials production and construction.

The relative impact of changing an agency's practices regarding different elements of pavement-related rolling resistance depends on the starting points for roughness, macrotexture, and structural responsiveness for the network and the individual pavement sections in the network. For example, if the network is already particularly smooth, then those practices should be continued, and additional changes in practice to further improve smoothness will likely have a small effect. On the other hand, if the network has high roughness, particularly on high-volume routes, then improvements in smoothness may result in high returns in reduced environmental impacts. Similar analyses can be applied to the other factors influencing pavement-related rolling resistance.

Roughness and Macrotexture Effects

There are four components of pavement texture defined based on the maximum dimension of their deviation (wavelength) from a true planar surface: roughness (also called unevenness, with wavelengths of 1.6 to 164 ft [0.5 to 50 m]), megatexture, macrotexture (wavelengths of 0.02 to 2 inches [0.5 to 51 mm]), and microtexture. The relative scale between each component is shown in figure 6-2 (Sandberg 1997). As part of network-level pavement management, agencies routinely collect profile data in the wheelpaths on a regular cycle (typically annually or bi-annually) using high-speed vehicles equipped with laser profilers (different laser technologies need to be used for asphalt and concrete pavements to avoid an upward bias in IRI caused by directionally textured concrete surfaces). A roughness index, the most common being the IRI, is calculated from the collected profile data. The IRI is one parameter for characterizing roughness and was primarily developed to consider the riding comfort of vehicle occupants. Although IRI was not primarily developed to capture the effects of pavement roughness on fuel consumption—and there are likely better parameters for that purpose—IRI does correlate with vehicle fuel use for all vehicle types, and is used by most highway agencies.

Macrotexture can be measured on asphalt-surfaced pavements and concrete pavements that do not have directional textures (tining, grooving, grinding) using the same profiler vehicles when equipped with high-speed profilers, and can be measured for directionally textured concrete pavements using other measurement techniques. The relationships between different types of concrete directional textures and vehicle fuel economy are not as clear as it is for asphalt-surfaced pavements.

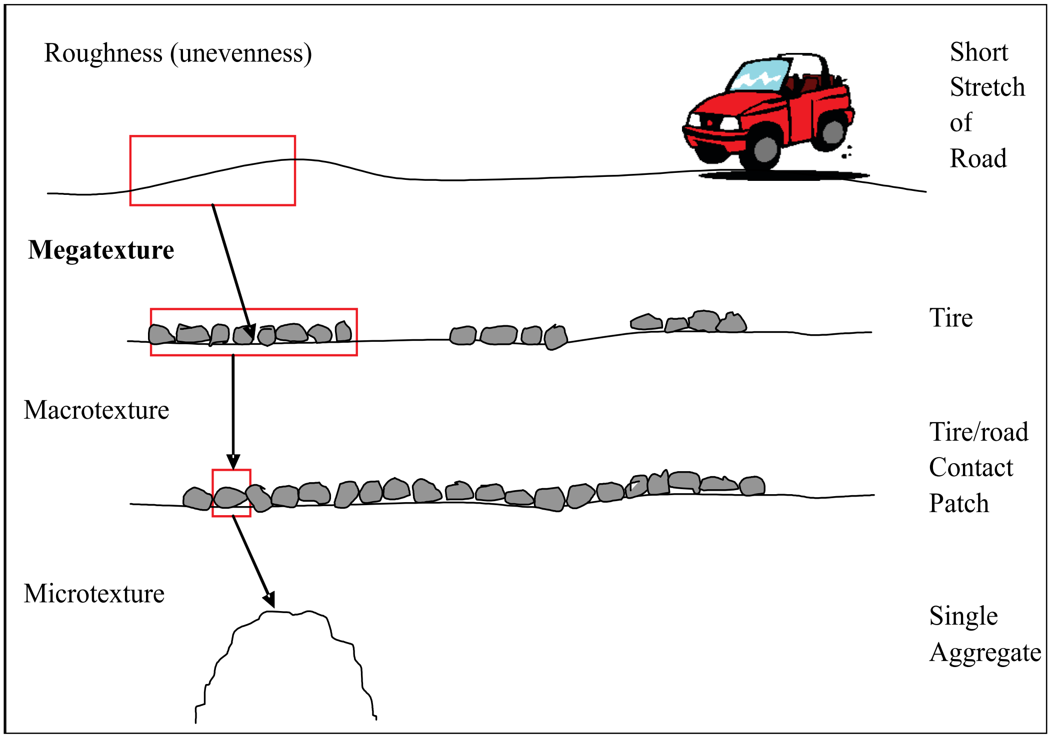


Figure 6-2. Pavement texture and wavelength (Sandberg 1997).

A recent evaluation/calibration of the World Bank's HDM-4 model (PIARC 2002) for vehicle operating costs, using measurements made with a fleet of representative North American vehicles, found the following when comparing roughness and macrotexture without consideration of the structural response (Chatti and Zaabar 2012):

> *For fuel consumption, the most important factor is surface roughness (measured using IRI). An increase in IRI of 1 m/km (63.4 in/mi) will increase the fuel consumption of passenger cars by about 2% irrespective of speed. For heavy trucks, this increase is about 1% at normal highway speed (96 km/hr or 60 mph) and about 2% at low speed (56 km/hr or 35 mph).*

In another study of fuel consumption, measurements were made at WesTrack using two automated heavily loaded articulated trucks traveling around a closed circuit track for many hours a day over a 7-week period both before and after rehabilitation on a set of test sections (Sime and Ashmore 2000). The results showed that the fuel efficiency was about 4.5 percent higher when trucks traveled on a smoother pavement (the IRI was reduced from 150 in/mi [2.3 m/km] to 75 in/mi [1.2 m/km] through the placement of an overlay). The winds and temperatures were similar during the two periods, and the grade was controlled. This is the most extensive testing regarding the effect of IRI that has been documented. Most other recent experimental results are based on less than 10 replicate runs, possibly repeated several times over a year.

Regarding surface texture, the effect is generally less than that of roughness for typical ranges of roughness and macrotexture in the U.S., with Chatti and Zaabar (2012) reporting that:

> *…the effect of surface texture is statistically significant at [the] 95 percent confidence interval only for heavier trucks and at low speed. An explanation of this observation is that at higher speeds, air drag becomes the largely predominant factor in fuel consumption. The increase in rolling resistance (i.e., fuel consumption) due to texture is masked by the increase in air drag due to speed.*

Chatti and Zaabar (2012) include coefficients for surface texture, measured by mean profile depth (MPD), in the recommended model and found that for heavy trucks *"an increase in MPD of 1 mm (0.039 in) will increase fuel consumption by about 2% at 56 km/hr (35 mi/hr),"* with no statistically significant effect for other vehicles or for heavy trucks at highway speeds. Positive macrotexture (stones and texture protruding up from the average surface elevation of the pavement) is expected to have a much greater effect on fuel economy than negative texture (downward gaps below the average surface elevation of the pavement).

On pavements carrying high volumes of traffic, the effects of pavement smoothness on fuel economy and the resulting impacts on energy use and GHG emissions in the use phase can be much greater than any differences caused by different materials or construction techniques during the material production and construction phases. This can be seen in figure 6-3 (Wang et al. 2012), which shows for an example segment of highway the relative effects on energy use (in terms of MJ and equivalent million gallons of gasoline) of applying a pavement preservation treatment (materials and construction), and the resulting savings from vehicle use on the smoothened pavement compared to letting the pavement remain rough.

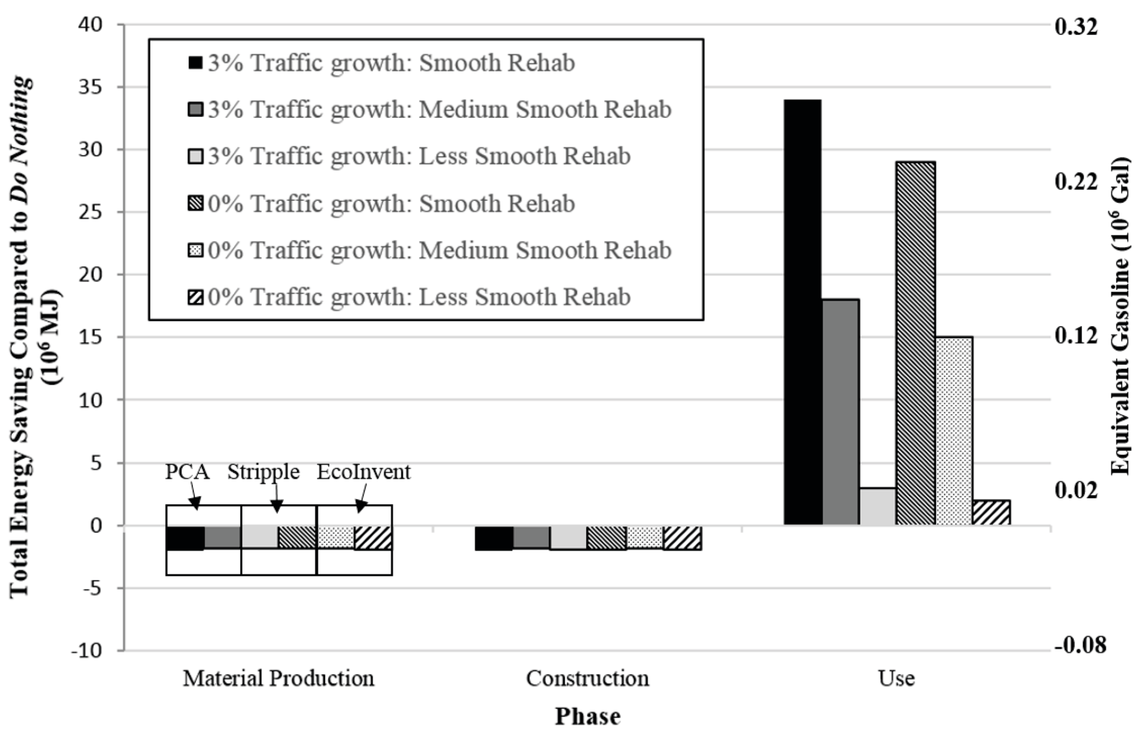


Figure 6-3. Energy savings in MJ and equivalent gallons of gasoline for a medium-to-high-volume route over 10-year analysis period for preservation treatment versus leaving the pavement rough (Wang et al. 2012). (Note: material production values calculated using three alternative sources of information shown [PCA, Stripple, EcoInvent] in order to test sensitivity of results to data source).

The example shown in figure 6-3 is for one direction of a 5-mi (8-km) segment of a medium-to-high-volume two-lane highway carrying 5,600 vpd with about 29 percent trucks. The current IRI is about 190 inches/mi (3 m/km), and the average (Medium Smooth Rehab) reduction in the IRI to about 105 inches/mi (1.7 m/km) was simulated by typical results achieved at initial construction consisting of grinding and some slab replacements followed by increases in IRI under traffic over the 10-year period. The results were calculated using the HDM-4 models calibrated by Chatti and Zaabar (2012) and coupled with emissions models in the EPA's MOVES software (EPA 2010a). Similar simulations were analyzed for asphalt overlays on asphalt pavement in the same study. Models for changes in macrotexture (measured as mean texture depth [MTD] for concrete) caused by the treatment and later traffic and their effect on fuel consumption are included in the simulation shown in figure 6-3 and in other simulations in the study, but had a much smaller effect than the change in IRI for both the concrete and asphalt cases. The structural responsiveness to vehicle loading was assumed to not change with the treatments because the pavement structures did not change much. Additional benefits of the preservation-type treatments simulated in the study due to extension of the life of the underlying pavement were not considered in the analyses.

The sensitivity analysis shown in figure 6-3 indicates that the smoothness achieved by the contractor has a major impact on the benefits. The figure shows analysis results for high-quality (Smooth Rehab = mean IRI minus two standard deviations, 57 to 72 inches/mi [0.9 to 1.2 m/km]), and low-quality (Less Smooth Rehab = mean IRI plus two standard deviations, 140 to 144 in/mi [2.2 to 2.3 m/km]) smoothness from construction of the treatment based on historical data from similar projects, in addition to the average (Medium Smooth Rehab) result. These results indicate that a strong construction smoothness quality assurance program can have a significant effect on vehicle fuel use for high-volume routes with high roughness. The changes in IRI over the life of the pavement after construction also significantly affect the net impact of the preservation treatment. Also shown in the figure are scenarios for 0 and 3 percent growth in total traffic over the 10-year analysis period. It can be seen that the construction smoothness had a much larger effect than the differences in the traffic growth rate and, paradoxically, there are greater relative savings when more traffic uses the smoother pavement, although the overall impact is greater for the higher traffic growth. Again, in terms of optimizing fuel economy on a network, construction smoothness is most important on higher volume routes and is not as important on lower volume routes (of course, smoothness is still important to the users of those lower volume routes).

The effects of vehicle speed have some interaction with roughness, but it does not change the overall trends or have much effect on the sensitivities of fuel economy to roughness (Chatti and Zaabar 2012). Modeling results also indicate that the effects of pavement roughness on fuel economy under stop-and-start congested traffic are similar to those under steady-state traffic, even including stop-and-start traffic in congested areas (Wang, Harvey, and Kendall 2013).

Since fuel economy goes down as driving speeds increase above 45 mi/hr (72 km/hr), one question that arises in discussions regarding the effectiveness of keeping pavements smooth is whether improving smoothness results in faster driving speeds under free-flow conditions that can reduce the fuel economy benefits of smoothness. Modeling by Hammarström et al. (2012), using driver speed behavior measurements from Sweden (Ihs and Velin 2002), indicated that increased driver speeds essentially cancel out the benefits of improved smoothness. On the other hand, a recently completed study in California (Wang, Harvey, and Lea 2013), using a large number of traffic speed measurements before and after pavement maintenance (on the same concrete sections with grinding plus slab replacements or asphalt overlays, and on the same asphalt sections with asphalt overlays), indicated that a reduction of IRI of 63 inches/mi (1 m/km) leads to only about a 0.3 to 0.4 mi/hr (0.48 to 0.64 km/hr) change in free-flow speed on freeways, which has a negligible effect on vehicle emissions or energy consumption.

In urban areas, pavement roughness is often affected by the quantity of utility cuts and the quality of the repairs. Poorly constructed utility cuts can immediately cause large increases in roughness in an otherwise smooth pavement. Even if utility cuts are initially constructed with a smooth surface, they can adversely affect the pavement smoothness if they are not well compacted or well bonded to the existing pavement, leading to an increase in vehicle fuel use. An alternative for new pavement construction is to place utilities in locations on the right of way outside of heavily trafficked portions of the paved areas. The timing of utility upgrades should be scheduled before maintenance or rehabilitation, as it will otherwise affect the pavement life. Utility cuts causing roughness are of greatest concern on higher volume routes.

With respect to the costs of timely application of maintenance and rehabilitation treatments, research has shown for asphalt pavements that applying a pavement maintenance treatment before a pavement reaches an advanced level of cracking can potentially reduce the life-cycle cost compared with waiting until the pavement damage reaches a critical level that a major rehabilitation is required (Lee, Rezaie, and Harvey 2012).

Pavement Structural Responsiveness to Loading Effects

Pavement structural response to loading, the third mechanism of rolling resistance that can affect fuel consumption, has been modeled as two phenomena:

1. Dissipation of energy in the pavement due to the pavements structural response under traffic loading.
2. Pavement surface structural responsiveness modeled as a change in geometry between the tire and the surface.

For both phenomena, larger deflections and greater delayed elasticity (more viscous damping as opposed to elastic behavior) will increase the pavement rolling resistance. The first pavement structural responsiveness phenomenon, dissipation of energy in the pavement structure due to the viscoelastic nature of asphalt materials, has been the subject of recent model development by the LUNAM University/IFSTTAR (Chupin, Piau, and Chabot 2013), the University of Lyon, France (Pouget et al. 2012), and by the University of Nottingham (Thom, Lu, and Parry 2010). There have also been a number of previous studies employing various approaches to model structural responsiveness (e.g., Kelly 1962; Perloff and Moavenzadeh 1967; Huang 1967; Hopman 1993; Hajj, Sebaaly, and Siddharthan 2006) that consider viscoelastic properties for some or all layers.

The second phenomenon is the subject of recent and ongoing model development at the Massachusetts Institute of Technology (Akbarian et al. 2012). Flugge (1975), Chupin, Piau, and Chabot (2013), and Loughalam, Akbarian, and Ulm (2013) have derived or reviewed relationships between the energy needed to move vehicles forward based on the position of the wheel in the deflection basin as it is affected by the delayed elasticity of viscoelastic deflections (the second structural responsiveness phenomenon described above) and the energy dissipated in the pavement (the first phenomenon).

It is interesting to note that the work by Akbarian et al. (2012), Chupin, Piau, and Chabot (2013), Pouget et al. (2012), and Thom, Lu, and Parry (2010) produce somewhat similar results for energy consumption for the distinct pavement structure, traffic speed, and temperature conditions that come from their modeling, yet draw opposite conclusions as to the overall importance of energy dissipation due to structural response under loading. This is because the researchers have not applied their results for the combined effects of traffic speed, temperature, structure and hourly traffic volumes as they occur together over a year for a given pavement, or for a range of different pavement structures. For example, Pouget et al. (2012) modeled an 8.7-inch (220-mm) thick asphalt structure with a 2.4-inch (60-mm) polymer-modified asphalt surface (and the rest conventional asphalt) as it was subjected to uniform temperatures throughout the asphalt; the results of the model (which was not calibrated with field data) indicated that, for a 7,300 lb (32 kN) truck wheel loading condition, reductions in fuel economy occur when the speed is reduced from 60 mi/hr (100 mi/hr) to 30 mi/hr (50 km/hr). The estimated reductions in fuel efficiency were approximately 0.1 percent at an asphalt temperature of 50 ^{o}F (10 ^{o}C), 1 percent at 95 ^{o}F (35 ^{o}C), 3 percent at 122 ^{o}F (50 ^{o}C) and 5.5 percent at 140 ^{o}F (60 ^{o}C) (Pouget et al. 2012). It is emphasized that this result is for one structure, one type of heavy truck, one truck wheel load, and for the two vehicle speeds over the described range of temperatures. The net result for a road section would depend on the joint occurrences of vehicle travel and pavement temperatures across each day and night and across all the seasons of the year.

A number of field studies have also been performed to measure the effects of pavement type on vehicle fuel economy, including those by Zaniewski et al. (1982), Taylor and Patten (2006), Ardekani and Sumitsawan (2010), Bienvenu and Jiao (2013), and Hultqvist (2013). For automobile traffic, the study by Zaniewski et al. (1982) showed no measureable difference in fuel economy between asphalt and concrete pavement. The study by Taylor and Patten (2006) had limited results for an automobile driven over 11 test sections that included concrete, asphalt, and composite (asphalt surface over concrete) paved roads in Ontario and Quebec; two seasons (winter and summer) and two travel speeds (37 and 62 mi/hr [60 and 100 km/h]) were included. All of the pavement sections had IRI values less than 126 inches/mi (2 m/km) and the IRI was considered directly in the results, but the study did not control for or measure pavement surface texture. Of the statistically significant results, the study showed a small increase in fuel use for asphalt pavement compared to concrete pavement for one season, and a small increase in fuel use for concrete pavement compared to composite for one season (the opposite was observed for the other season). The pavements considered by Ardekani and Sumitsawan (2010) consisted of four rough to extremely rough urban streets (IRI values of 170 to 325 inches/mi [2.7 to 5.2 m/km]) tested using a Chevy Astro van with a relatively small number of replicate runs and no consideration of texture or roughness. The study by Hultqvist (2013) showed about a 1 percent difference in fuel economy for cars when tested on one asphalt and one concrete pavement on the same route in the Swedish summer. However, the authors concluded that these results were primarily due to the higher macrotexture from studded tire use on the asphalt pavement based on modeling results. The pavement structures were not characterized for their stiffnesses.

Noting possible problems with measurements in two earlier phases of their work, Taylor and Patten (2006) performed a Phase III study on the Canadian pavements listed above using a heavy articulated truck outfitted with different weights and running at two travel speeds (37 and 62 mi/hr [60 and 100 km/h]) to establish if loading was a contributing factor to truck fuel consumption differences among the three different pavement types (concrete, asphalt, and composite). Testing was performed under different seasonal conditions in eastern Canada. The study found statistically significant fuel use savings for trucks traveling on concrete pavements for most of the five seasons and day/night conditions across the range of vehicle loadings, with greater differences noted at 37 mi/hr (60 km/hr) (1.3 to 3.9 percent) than at 62 mi/hr (100 km/hr) (0.8 to 1.8 percent). The study also found statistically significant fuel saving results for most of the seasonal and day/night conditions for concrete pavements compared to composite pavements, again with larger differences at 37 mi/hr (60 km/hr) (1.9 to 6.0 percent) than at 62 mi/hr (100 km/hr) (0.8 to 3.1 percent). Interestingly, statistically significant results under the hottest conditions on summer days found the opposite result, with the trucks consuming less fuel on composite pavements than on concrete pavements, with larger differences at 37 mi/hr (60 km/hr) (2.4 to 3.0 percent) than at 62 mi/hr (100 km/hr) (about 1.4 percent). The models developed in the Phase III study also noted that "The insensitivity of the fuel consumption differences to temperature, load and speed is somewhat counterintuitive to the engineering physical models"; however, no explanation for this lack of sensitivity was identified in the study. Thicknesses of the pavement structures were noted, but no structural evaluation or characterization of the pavements (other than being classified as asphalt, concrete or composite) was included in the analyses of the fuel consumption results. Texture was not measured or considered.

Coast-down measurements were also performed as part of the Taylor and Patten (2006) study on the asphalt and concrete sections to measure rolling resistance. Coast-down tests consist of measuring how far a vehicle (the loaded truck in this case) will roll without braking and after shutting off the engine and putting the transmission in neutral. The results showed no significant differences between the asphalt and concrete structures included in the fuel economy studies.

The truck results from the study by Hultqvist (2013) showed up to a 5 to 7 percent difference in fuel efficiency for heavy vehicles operating on hot days on one concrete and one asphalt pavement. The differences were attributed to a combination of structural responsiveness and macrotexture, with macrotexture levels higher on the asphalt pavement while the IRI was slightly higher on the concrete pavement. The effects of texture and structural responsiveness were not separated for the truck measurements, and the authors expressed concern about the presence of relatively strong winds during testing. As noted previously, the pavement structures were not characterized for their stiffnesses. The Swedish study is unique in that the sections were used to check a mechanistic model of pavement energy consumption from vehicles called VETO (Hammarström et al. 2012), which showed results similar to the measurements for the test sections. Many of the models in VETO are similar to those in HDM-4.

A field study by Bienvenu and Jiao (2013) along 28 mi (45 km) of Interstate 95 in Florida indicated that passenger vehicles on a concrete pavement use 3.2 percent less fuel compared to asphalt pavement. The study also showed that, along the same corridor, loaded tractor trailers traveling on the concrete pavement experienced 4.5 percent better fuel economy than on the asphalt pavement. The asphalt pavement consisted of 9.25 inches (235 mm) of asphalt (including an open-graded friction course) on 5 inches (125 mm) aggregate base and 12 inches (300 mm) of treated subgrade. The concrete pavement consisted of a 13-inch (330 mm) JPCP resting on a 1-inch (25 mm) asphalt-treated permeable base and 4-inch (100 mm) asphalt base. The pavement structures were not characterized for their structural responsiveness nor were the surface textures measured or considered.

The previously cited study by Chatti and Zaabar (2012) had as a secondary objective the evaluation of fuel economy for vehicles traveling on asphalt and concrete pavements. It included 11 pavement sections in Michigan divided between asphalt and concrete, five types of vehicles operating at different speeds, daytime winter and summer measurements (for most vehicles), and ranges of roughness and texture levels. As with the other studies cited, there was very little characterization of the pavement structure besides being noted as being either asphalt or concrete. The results of the study indicated that "pavement type [does] not affect the fuel consumption of any vehicle class except for heavy trucks." More detailed analysis of the same data indicated that articulated (heavy) trucks and light trucks had statistically significant higher fuel consumption, with about a 4 percent difference for the heavy trucks when operated on asphalt pavements included in the study at 35 mi/hr (56 km/hr) in the daytime in the summer, but there no statistically significant difference at speeds of 45 or 55 mi/hr (72 or 88 km/hr) or when the trucks operated during the winter. As noted there was no characterization of the pavement structures in terms of the structural responsiveness to vehicle operating conditions and temperature that would permit generalized application to other structures and other temperature and loading conditions.

From the review of the various studies noted here, it can be said with reasonable certainty that the influence of structural responsiveness on fuel economy and associated environmental impacts has not been comprehensively validated with an experiment that has accounted for the broad range of environmental conditions or the various types of pavement structures used in the nation's highway network (e.g., composite pavements, semi-rigid pavements, rubberized and polymer modified mixtures, doweled and nondoweled JPCP, and CRCP). The field studies conducted to date to measure the effects of dissipated energy on vehicle fuel efficiency suffer from a serious lack of characterization of the pavement structures in terms of their structural responsiveness to loading as a function of the stiffness and thickness of the pavement layers or the viscoelastic nature of the materials under different conditions of temperature and traffic speed. Without consideration of those variables, it is difficult to use the results for model validation, and, without validated models, it is difficult to calculate the net results of all of the variables affecting this mechanism. The structural responsiveness to vehicle loading of pavements depends on subgrade, subbase, and base support conditions, and, particularly for asphalt pavements, the temperature and time of loading. To complicate matters, these responses change as the pavement materials age and deteriorate. Therefore, consideration of pavement structural responsiveness effects must be analyzed separately for each project considering the intersection of structural responsiveness, traffic levels, traffic speeds and pavement temperatures, and the moisture conditions in the underlying unbound layers, which may vary widely with daily and seasonal climatic fluctuations.

Although deflection testing using a falling weight deflectometer (FWD) does not replicate the effects of a vehicle moving across the pavement, deflection testing has been used to help understand the effects of structural response and energy consumption. Studies that considered FWD testing include those performed by Ullidtz et al. (2010) and by Faldner and Lenngren (2012).

While it is known that water, snow, and ice on the pavement will also impact rolling resistance, the fuel economy studies cited above were all carried out under dry pavement conditions (Karlsson, Carlson, and Dolk 2012). Modeling results from Sweden (Hammarström and Karlsson 1987) indicate that water depths of 0.039, 0.078, and 0.156 inches (1, 2 and 4 mm) can increase vehicle fuel use by 30 percent, 90 percent, and nearly 80 percent, respectively, compared to dry pavement (Karlsson, Carlson, and Dolk 2012). These results indicate that pavement designs and materials that can remove water from the pavement surface quickly may contribute to substantial reductions in fuel use and environmental impact, particularly in areas with high rainfall; they will also contribute positively to overall safety. In general, open-graded friction courses and directional texturing are used on asphalt and concrete surfaces, respectively, to reduce water depths under tires. Some of these textures also tend to increase macrotexture and might slightly reduce fuel consumption. It should be noted that these modelling results are also not yet validated.

It must be again emphasized that none of the effects on vehicle fuel consumption and pavement characteristics matter much if only a few vehicles are using the pavement, and that these effects should only be considered for higher traffic volume locations from the standpoint of environmental impact on the network. This is borne out for the case of IRI as described in the next section of this chapter.

Network-Level Considerations

As has been noted previously, the effects of a pavement on vehicle fuel economy and the associated energy and environmental impacts are controlled by the number of vehicles using the pavement. The previously cited study by Wang et al. (2012) analyzed the net effects of several pavement preservation treatments on the GHG emissions and energy use as a function of traffic level, with the materials production and construction effects being the same and the reductions in GHG emissions and energy use depending on traffic flow during the use phase. The study included consideration of pavement deterioration after the treatment, and showed that the net effect can be positive or negative, depending on the traffic level and the constructed smoothness. Furthering this concept, another study by Wang, Harvey, and Kendall (2013) determined trigger levels for the same typical California preservation treatments (5- to 10-year design lives) on asphalt and concrete roads optimized to reduce GHG emissions as a function of traffic level. The modeling in the study did not consider changes in structural responsiveness of treatments in the use phase because the treatments did not change the pavement type (asphalt surfaces remained asphalt and concrete surfaces remained concrete) and the treatments did not significantly change the structural responsiveness of the typical existing pavement. The results indicated that optimized IRI trigger values for different traffic flows, in terms of daily passenger-car equivalent (trucks count as 1.5 cars) per direction, were on the order of (Wang, Harvey, and Kendall 2013):

- 101 inches/mi (1.6 m/km) for the highest traffic levels (directional daily traffic above 34,000 passenger-car equivalents).
- 127 inches/mi (2 m/km) for directional daily traffic levels between about 12,000 and 34,000 passenger-car equivalents.
- 177 inches/mi (2.8 m/km) for directional daily traffic flows between 2,500 and 12,000 passenger-car equivalents.
- Use-phase savings from treatments to reduce roughness were generally less than the GHG emissions from materials production and construction regardless of IRI for directional daily traffic flows below about 2,500 passenger-car equivalents.

As can be seen from these values, the optimum IRI trigger level decreases as the traffic level increases, and emissions from construction and materials used in the treatment could not be recovered in the use phase for low traffic flows. Although specific trigger values would be expected for different agencies and treatments (preservation, rehabilitation, reconstruction), the overall trends are expected to be the same.

Summary

A general summary of the effects of pavement characteristics on vehicle fuel economy, and the resulting environmental impacts of fuel economy changes, is presented below:

- Roughness as measured by IRI generally has the greatest effect on fuel economy for typical ranges of IRI on U.S. highway networks, compared with structural responsiveness and macrotexture. The effect is essentially linear, with sensitivity depending on the vehicle type. According to recently calibrated models (Chatti and Zaabar 2012), an increase in IRI from 63 inches/mi (1 m/km) to 190 inches/mi (3 m/km) increases passenger car fuel consumption by 4.8 percent at 86 ºF (30 ºC), 55 mph (88 km/hr) with zero grade, and an MPD (macrotexture) value of 0.04 inches (1 mm). For heavy articulated trucks the same change in IRI increases fuel consumption by 2.9 percent under the same conditions. SUVs show a change of 4.1 percent, and light trucks and vans show changes of 1.6 and 1.8 percent, respectively Although the effects of roughness vary somewhat with temperature and vehicle speed (Chatti and Zaabar 2012), it has an effect on fuel economy for every vehicle throughout the year. Given its impact, pavement roughness can be controlled by three methods:
  - Consideration of smoothness performance (smoothness over time) and having smoothness over the life cycle as a key parameter in the pavement design process.
  - The implementation of effective smoothness specifications, since pavements "born rough" will start rough and only get rougher with time.
  - The timely application of maintenance and rehabilitation strategies that restore and promote smoothness before the pavement gets too rough, including consideration of traffic volume when determining IRI trigger values for treatment.
- Macrotexture as measured by MPD on asphalt and MTD on concrete (MPD and MTD are generally considered interchangeable in terms of values for fuel economy models) has a linear effect on vehicle fuel economy. The effect of macrotexture is generally much smaller than that of IRI, to the point that it is statistically insignificant for all but heavy trucks at slow speeds for typical ranges of well-maintained pavement occurring on state highway networks in the U.S. According to the recently calibrated models (Chatti and Zaabar 2012) an increase in MPD or MTD of 0.04 inches (1 mm) will increase heavy truck fuel consumption by about 2 percent at 35 mi/hr (56 km/hr), when IRI is held constant at 63 inches/mi (1 m/km), while for other vehicles and heavy trucks at highway speeds the effect was statistically insignificant. Macrotexture is controlled by pavement surface type selection (minimizing positive texture for both concrete and asphalt) and timely maintenance (e.g., repairing raveled asphalt surfaces, degraded concrete surfaces, chain wear). However, sufficient macrotexture must be maintained to provide a pavement with adequate surface friction. Macrotexture improves wet-pavement surface friction by providing drainage between the tire and the pavement; this reduces the risk of hydroplaning, which is the phenomenon in which a film of water develops between the moving tire and the pavement surface leading to the tire losing contact with the pavement. The risk of hydroplaning increases as vehicle speed increases. Increased macrotexture may help with wet-weather fuel economy by reducing water film thicknesses, which for some pavement textures could otherwise consume vehicle energy by increasing rolling resistance (particularly in wet climates). Macrotexture is primarily controlled by surface materials selection and maintenance practices.

- Structural responsiveness and its effect on vehicle fuel economy is the subject of several models that have been developed, and a number of field studies have been performed measuring vehicle fuel economy on different pavement structures under different conditions. These studies provide indications that under certain conditions the structural responsiveness of different pavements to vehicle loading can have a measureable effect, which like that of roughness and macrotexture, is variable depending on vehicle type and operating conditions. Unlike roughness and macrotexture, the effect of structural responsiveness is highly variable, depending on temperature and the underlying support conditions which undergo daily and seasonal fluctuations. In general, the effects of different pavement structures range from approximately no difference under some conditions of vehicle type/operation and climate conditions to effects of the same order of magnitude as high levels of highway roughness under the most extreme temperature and loading conditions at certain times of the year. This effect also depends on the viscoelastic properties of the pavement materials, primarily the type and age of asphalt materials located near the surface.

  In general, modeling and measurements to date indicate that lighter and faster vehicles, as well as colder conditions, result in the least differences in rolling resistance between different pavements whereas heavier and slower vehicles under hotter conditions result in larger differences. The frequencies at which these conditions occur in combination with traffic patterns control the net effect on fuel economy of structural responsiveness for a given structure.

  However, the influence of structural responsiveness on vehicle fuel economy has not yet been comprehensively validated with any experiment that has characterized the pavement structures in terms of their responsiveness under different conditions. As a result, the available models have not been calibrated with the type of data that allows the general application of the models to evaluate in-service pavements under the range of traffic and climatic conditions that occur daily, seasonally, and from location to location. Research is needed that uses field measurements of fuel economy for a range of vehicles, climates, and pavement structural responses, controlling for roughness and macrotexture, to complete calibration and validation of models that can be used to make design and management decisions.

- Environmental impacts and energy use from all three rolling resistance mechanisms are a function of the number of vehicles using the pavement in the use phase. Beneficial environmental impacts from managing roughness, macrotexture, or structural responsiveness decrease as the number of vehicles using the pavement decrease.

- The relative impact of decisions affecting the different vehicle use phase mechanisms discussed in this section are highly context sensitive, with the benefits from changing existing practices dependent on the baseline conditions in terms of existing roughness, macrotexture conditions, and pavement structures. For example, a network with generally low roughness on high traffic routes will not see much improvement in emissions from focusing on improving roughness, although keeping the pavement smooth to avoid increasing emissions will be important. The relative effects of the different mechanisms also depend on vehicle types, loads, and speeds, daily and seasonal pavement temperature fluctuations, and interaction with the distributions of vehicle variables listed above across the years.

Strategies for Improving Sustainability

Practices that are available to pavement managers, designers, and specification developers that might be optimized to help meet GHG emission, energy use, and other environmental objectives associated with the influence of pavement characteristics on vehicle fuel economy are summarized in table 6-1.

Table 6-1. Summary of strategies for improving vehicle use phase fuel consumption and potential trade-offs.

Vehicle Fuel Consumption and Pavement Objective	Vehicle Fuel Consumption Sustainability Improving Strategy	Economic Impact	Environmental Impact	Societal Impact
Reduce Fuel Use Due to Roughness	Implement pavement design process that considers smoothness over the pavement life as a key design parameter, especially for high traffic volume routes.	Potential for small to moderate increases in initial costs but reduced life-cycle costs due to longer pavement lives. Reduced vehicle operating costs for road users.	Reduced environmental impact due to less fuel use, particularly on high traffic volume routes.	Improved economic efficiency.
	Implement construction specifications to incentivize maximum possible smoothness, especially for high traffic volume routes.	Potential for small increases in construction costs, reduced life-cycle costs due to longer treatment lives from reduction in dynamic loading. Reduced vehicle operating costs for road users.	Reduced environmental impact due to less fuel use, particularly on high traffic volume routes.	Improved economic efficiency.
	Optimize timing of maintenance and rehabilitation based on IRI trigger value and traffic volume.	Potentially increased agency initial costs if results in earlier treatment than current practice. Potentially reduced agency life-cycle cost from pavement preservation. Reduced vehicle operating costs for road users as pavements are kept in smoother condition.	Increased environmental impact of materials production and construction when treatments are more frequent; reduced environmental impact due to less fuel use. Benefit can be offset if vehicle speeds increase because of improved smoothness.	Emphasis on maintaining high-volume routes in smoother condition may improve economic efficiency and average road user cost, but may result in neglect of lower volume routes depending on funding levels.
	Minimize pavement roughness due to utility cuts through regulation, construction practice enforcement and better planning.	Reduced pavement maintenance costs. Increased enforcement costs. Reduced vehicle operating costs for road users.	Reduced environmental impact due to less fuel use when poorly repaired utility cuts cause roughness, particularly on high traffic volume routes.	Improved economic efficiency. Improved urban aesthetics.

Table 6-1. Summary of strategies for improving vehicle use phase fuel consumption and potential trade-offs (continued).

Vehicle Fuel Consumption and Pavement Objective	Vehicle Fuel Consumption Sustainability Improving Strategy	Economic Impact	Environmental Impact	Societal Impact
Reduce Fuel Use Due to Macrotexture (where impact is significant)	Avoid high positive macrotexture on routes with high heavy truck traffic volumes at slow speeds while maintaining safety.	May result in less use of some low-cost maintenance treatments with high positive macrotexture over the life cycle on high-volume heavy truck routes.	Reduced environmental impact due to less fuel use on high traffic volume heavy truck routes.	Improved economic efficiency, reduced tire wear. Potential for increased crashes due to reduced surface friction if also high speed traffic.
Calibrate and Validate Models for Fuel Use Due to Structural Responsiveness to Vehicle Loading (use them once research is completed)	Perform research to calibrate and validate models for vehicle fuel use as a function of pavement structural responsiveness to vehicle loading. Calibration requires experiments that characterize responsiveness of pavement sections and then measure fuel use on same sections. Calibrated models can be used to determine where structural responsiveness is significant and develop appropriate strategies based on those results.	Calibrated models will permit evaluation of alternative structures considering traffic, climate and other variables which will allow consideration of both road user and agency costs versus environmental benefits for designs.	Optimization may reduce environmental impact due to less fuel use, particularly on high truck traffic volume routes in certain climates.	Optimization may improve economic efficiency particularly on high truck traffic volume routes.

Future Directions and Emerging Trends

Highway agencies are moving towards construction smoothness specifications based on IRI for new pavement construction and rehabilitation and maintenance activities. The implementation of improved methods for quality assurance for as-built smoothness will have a great impact not only on pavement serviceability but also on fuel consumption. These improvements and the potential for maximizing the specified smoothness on high-traffic volume routes should result in decreases in fuel use and decreases in its associated environmental impacts.

As pavement management systems become more sophisticated, they can be used for explicit consideration of the timing of maintenance, rehabilitation, and reconstruction treatments to optimize net reductions in energy use and environmental impacts considering the pavement life cycle (materials production, construction, use, and end-of-life phases). Improvements in life-cycle inventories (LCI) for each of these phases are needed to improve the ability to optimize. Requirements in the federal transportation legislation (MAP-21) for pavement management systems to track the performance of pavement management decisions may help push implementation of this type of approach.

Improved mechanistic-empirical models for predicting pavement smoothness over the life cycle of the pavement will aid in making design decisions that result in reduced vehicle fuel use. At the same time, improved models that consider the effects of pavement structural responsiveness on vehicle fuel use, and the calibration/validation of those models with experimental data, will provide pavement designers with better information for selecting pavement structures that reduce vehicle fuel use.

Improvements in pavement deflection measurement technologies, such as rolling wheel deflectometers that measure deflections at highway speeds, will likely result in greater consideration of structural responsiveness as part of network-level monitoring. Measurement methods for texture using high-speed lasers (for pavements that do not have directional texture) and deflection using rolling wheel deflectometers (FHWA 2011a) have been developed and are being evaluated by a number of different state agencies. Methods for directly measuring pavement rolling resistance due to texture and structural responsiveness are also being developed (Bergiers et al. 2011; FHWA 2011a).

Tire-Pavement Noise

Background

Noise can be defined as unwanted or unpleasant sound. All sound is produced by vibrating objects and transmitted by pressure waves in a compressible medium such as air. Sound waves are often characterized in terms of amplitude (strength of the wave) and frequency (speed of their variation) (Snyder 2006). Sound pressure or sound intensity levels are used to quantify the loudness of an ambient sound. The frequencies of sound audible to humans range from 20 to 20,000 Hz, and sound pressures range from 20 micropascals (µPa), the threshold of hearing, to 120 pascals (Pa), the threshold of pain (Norton 1989).

Major Issues:

- ✓ *Noise effects on humans and wildlife.*
- ✓ *Noise is partly controlled by pavement surface characteristics, but tire characteristics are typically more important.*
- ✓ *Methods available to measure tire-pavement noise.*

The broad range of sound pressures important to human noise perception (seven orders of magnitude) has led to the common use of a logarithmic scale for sound pressure levels (SPL), which is normalized to a reference standard of 2×10^{-5} Pa and has units of decibels (dB). Sound intensity, which is a measure of energy flow through a unit area, is also typically discussed using a logarithmic scale with units of Watts/m^2, normalized to a reference standard of 10^{-12} W/m^2. The unit of the linear sound intensity scale is also the decibel. The reference standards for SPL and sound intensity have been chosen to obtain the same reading in decibels regardless of whether SPL or sound intensity is used to define the sound wave, and irrespective of whether pressure or intensity in an acoustic free field is measured. Because of the logarithmic scale for noise, the emissions from multiple noise sources cannot be added linearly. For example, two noise sources, each emitting at 70 dB, produce a noise level of 73 dB, not 140 dB (Ongel et al. 2008). Noise is usually adjusted to reflect human sensitivity, the units of which are expressed in terms of adjusted decibels (dBA).

Human perception of changes in sound energy is also non-linear. Most observers perceive an increase or decrease of 10 dB in the sound pressure level as doubling or halving of the sound, as shown in table 6-2 (FHWA 2011b). It can also be seen in the table that a change of 3 dBA is barely perceptible to most people. For this reason, changes in highway noise of less than 3 dBA are generally considered to be relatively insignificant. However, the information shown in table 6-2 is based on laboratory studies of humans listening to pure tones in a laboratory setting, such as in a common hearing test. Many people can hear differences in tire-pavement noise less than 3 dBA and can perceive differences in the frequency content of two tire-pavement noise sources that have the same sound intensity as measured in dBA, with different sound patterns and frequencies of sound being more irritating than others.

Table 6-2. Decibel changes, energy loss, and loudness (FHWA 2011b).

Sound Level Change (dBA)	**Change in Sound Energy (%)**	**Human Perception**
0	0	No change
-3	50	Barely perceptible
-5	67	Readily perceptible
-10	90	50% as loud
-20	99	25% as loud
-30	99.99	12% as loud

Noise levels are also affected by the distance from the source, with near-ground sources spreading out over a hemispherical volume. Noise wave energy is conserved with the result that sound intensity variation is proportional to the square of the distance from the source as it is spread over a wider surface. Therefore, the sound intensity level is decreased by a factor of four when the distance from the source is doubled.

Noise pollution has become an increasing concern in the U.S. and worldwide. Highway noise affects people in adjacent residences and businesses as well as people in vehicles; road noise effects on wildlife have also been identified (Clevenger et al. 2002). Various health and quality of life effects on humans from noise pollution have been identified by the World Health Organization (WHO 2013). Although somewhat controversial, attempts have been made to calculate the economic consequences of noise (Berglund, Lindvall, and Schvela 2000).

Public awareness of road noise has increased over the past 40 years and most industrialized countries have introduced noise emission regulations. In the U.S., regulations have been developed by the FHWA and other agencies for dealing with highway noise. For example, as required by the Federal-Aid Highway Act of 1970, the FHWA developed Regulation 23 CFR 772, *Procedures for Abatement of Highway Traffic Noise and Construction Noise*, which applies to highway construction projects where a DOT has requested federal funding for participation in the project. The regulation requires the highway agency to investigate traffic noise impacts in areas adjacent to federal-aid highways for proposed construction of a highway on a new location or for the reconstruction of an existing highway to either significantly change the horizontal or vertical alignment or increase the number of through-traffic lanes (FHWA 2013).

The FHWA states that effective control of undesirable highway traffic noise requires a three-part approach: noise compatible planning, source control, and highway project noise mitigation

(FHWA 2013). If the highway agency identifies impacts, it must consider abatement and must incorporate all feasible and reasonable noise abatement measures into the project design. FHWA cannot approve the plans and specifications for a federal-aid highway project unless the project includes adequate noise abatement measures to comply with the standards (FHWA 2013).

Modeling of noise level contours around a highway project is performed using the FHWA Traffic Noise Model (TNM) (see www.fhwa.dot.gov/environment/noise/traffic_noise_model/). The TNM has the capability to consider different pavement types when modeling noise, although an assumed pavement type has typically been used in practice.

The regulations contain noise abatement criteria, which represent the upper limit of acceptable highway traffic noise for different types of land uses and human activities, as presented in table 6-3 (FHWA 2011b). The regulations do not require meeting the abatement criteria in every instance, but instead require the agency to make every reasonable and feasible effort to provide noise mitigation when the criteria are approached or exceeded. Abatement typically consists of noise barriers (sound walls), although other measures are also included. Quieter pavement surfaces are not considered adequate for abatement because the long-term performance of many of those surfaces has not yet been fully demonstrated, and there is the possibility that surfaces will not retain their low-noise characteristics if they are not sufficiently maintained.

Table 6-3. FHWA noise abatement criteria in dBA (hourly A-weighted sound level) (FHWA 2011b).

Activity Category	NAC, L_{eq}(h)*	Description of Activity Category
A	57 (exterior)	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B	67 (exterior)	Residential
C	67 (exterior)	Active sport areas, amphitheaters, auditoriums, campgrounds, cemeteries, day care centers, hospitals, libraries, medical facilities, parks, picnic areas, places of worship, playgrounds, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, recreation areas, Section 4(f) sites, schools, television studios, trails, and trail crossings
D	52 (interior)	Auditoriums, day care centers, hospitals, libraries, medical facilities, places of worship, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, schools, and television studios
E	72 (exterior)	Hotels, motels, offices, restaurants/bars, and other developed lands, properties or activities not included in A-D or F.
F	-	Agriculture, airports, bus yards, emergency services, industrial, logging, maintenance facilities, manufacturing, mining, rail yards, retail facilities, shipyards, utilities (water resources, water treatment, electrical), and warehousing
G	-	Undeveloped lands that are not permitted for development

* L_{eq}(h) is the sound pressure averaged over 1 hour.

Highway noise generated by passing vehicles comes from three sources: air passing over and around the vehicle (aerodynamic noise); the operation of the engine, exhaust, and drive train system (propulsion noise); and several mechanisms occurring as the tire passes over the pavement (tire-pavement noise) (Nelson and Phillips 1997; Sandberg 2001). As shown in figure 6-4, for passenger cars the tire-pavement noise dominates over propulsion noise at speeds above 20 to 30 mi/hr (30 to 50 km/hr), while at lower speeds the propulsion predominates. For heavy-duty trucks, it was found that propulsion noise dominates during acceleration from 0 to 50 mi/hr (0 to 80 km/hr), but tire-pavement noise dominates for all driving conditions above 50 mi/hr (80 km/hr) (Rasmussen et al. 2008). Tire-pavement noise depends on pavement surface characteristics, vehicle speed, environmental conditions, type of tire, and the dynamics of the rolling process (McDaniel and Thornton 2005). The tire-pavement noise level increases logarithmically with increasing speed (Sandberg 2001).

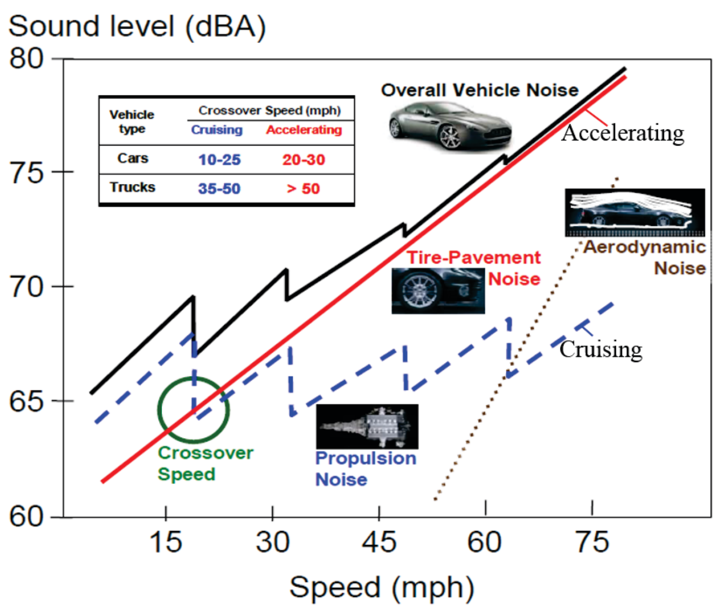


Figure 6-4. Estimate of light vehicle noise due to tire-pavement noise, powertrain noise, and aerodynamic noise at cruise speed (Rasmussen et al. 2008).

Noise at the side of the road from all of these sources is primarily measured via pass-by methods. Pass-by measurements can either be made with individual vehicles, which is referred to as the Controlled-Pass-By (CPB) method, or by measuring the total noise from all of the vehicles in mixed flow, which is referred to as the Statistical-Pass-By method (SPB) (ISO 1997). Noise measured using pass-by methods is the parameter of concern for modeling and decision making regarding the need for noise mitigation. However, such testing requires one or more days to conduct, is difficult and expensive to perform because it requires placement of microphones at different heights and at different distances from the edge of the road, and only provides measurements for small numbers of locations where this detailed arrangement can be installed.

Two test methods have been developed that permit continuous noise measurements along a roadway at highway speeds and also focus on the tire-pavement noise alone (which can be addressed through pavement design and management). The first method is called the Close Proximity method (CPX), which uses the equipment shown in figure 6-5. The CPX method involves the use of directional microphones inside of an acoustically insulated enclosed space built on a trailer that is towed behind the vehicle. This device is primarily used in Europe.

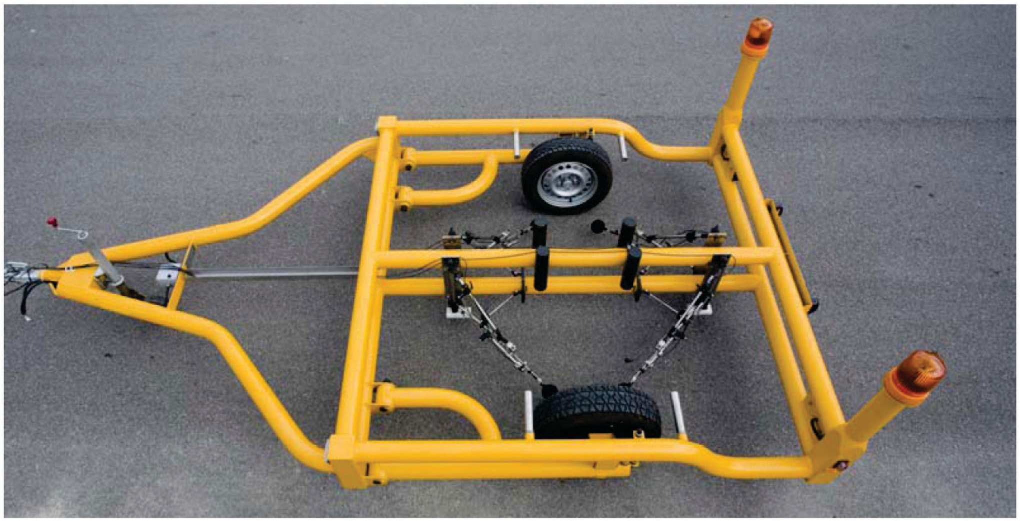


Figure 6-5. Close Proximity (CPX) test trailer (Bendtsen and Thomsen 2008).

The second method is called the On-Board Sound Intensity (OBSI) method, and is illustrated in figure 6-6. This method was developed in the U.S. based on technology originally developed by General Motors Corporation and recently introduced into the pavement community (Donavan and Lodico 2009). OBSI measurement involves the use of directional microphones placed at the leading and trailing edges of the tire-pavement contact patch, just above the pavement, and is performed in accordance with AASHTO TP-76-09. Comparisons between the OBSI and CPX methods have been performed, and show that they have similar sensitivity to pavement characteristics (Donavan 2006). The OBSI is primarily used in the U.S. because the equipment is mounted on the vehicle and it does not require the use of a trailer as does the CPX method.

Figure 6-6. On-Board Sound Intensity (OBSI) setup (photo courtesy of John Harvey).

Tire tread characteristics are major determiners of tire-pavement noise, and standard tire-pavement noise testing should include careful control of tire type and condition (Donavan and Lodico 2009; Lu, Wu, and Harvey 2011). A special type of test tire has been developed for pavement testing and other purposes called the Standard Reference Test Tire (SRTT). Comparisons have been made between OBSI and CPB noise levels (with the CPB testing performed using automobiles equipped with the SRTT), and the resulting correlations have been good, as shown in figure 6-7 (Donavan and Lodico 2009).

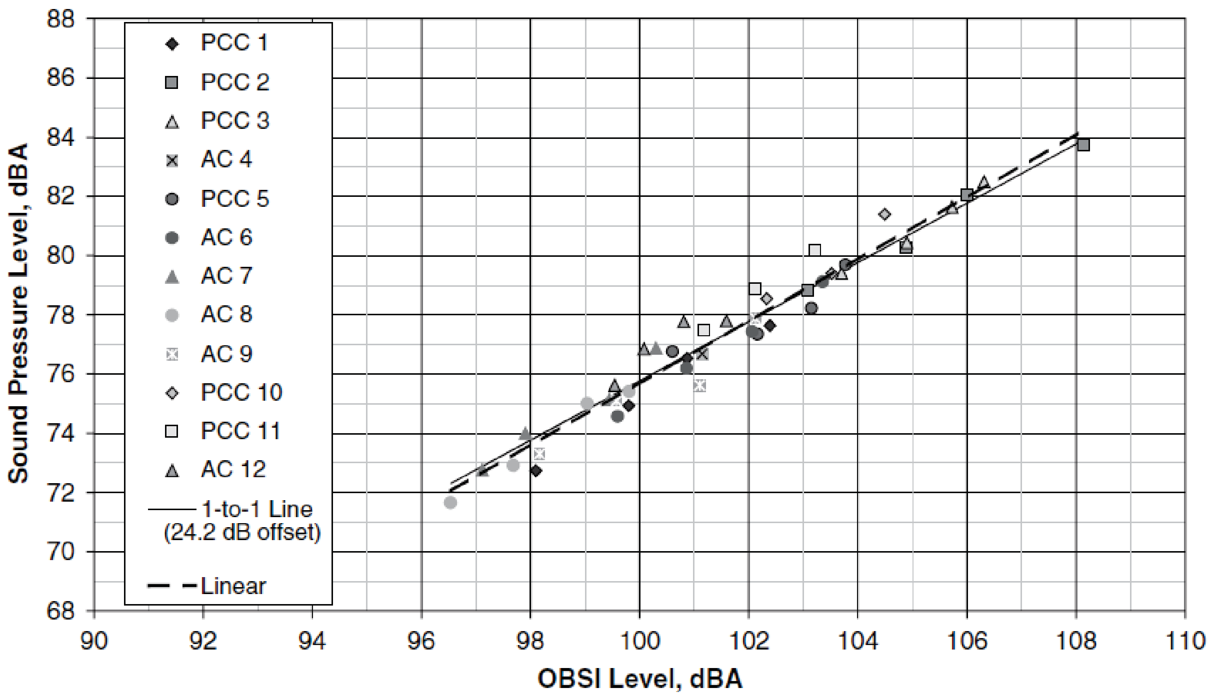


Figure 6-7. Controlled vehicle pass-by levels at 25 ft (7.6 m) versus OBSI level for the SRTT at all test sites and speeds—normalized data (Donavan and Lodico 2009).

Nelson and Phillips (1997) have further separated the phenomenon of tire-pavement noise into different mechanisms, as summarized below by Ongel et al. (2008):

- Tire tread/road surface impacts. This component of tire-pavement noise results from vibrations that occur as the tire tread initially contacts the pavement surface, and again as the tire tread breaks contact with the pavement surface and returns to its normal radius, which is referred to as "block snap out" (Bergmann 1980). These vibrations are transmitted through the tire, and from the tire to the air, creating noise. The flattening of the tire in the contact patch is resisted by friction between the tire and the pavement, which can also vibrate the tire when there is slip. The generation of vibrations on a rolling tire is dependent on the design of the tire tread, the macrotexture of the pavement (see figure 6-2, usually expressed in terms of MPD), and frictional adhesion between the tire and the pavement surface (Sandberg and Descornet 1980; Kropp 1992). In addition, Sandberg and Descornet (1980) suggested that stiffer pavements (concrete or asphalt) may generate more noise, which has also been advanced by Biligiri and Kaloush (2010). However, Beckenbauer and Kuijpers (2001) did not find that to be true, and Ongel et al. (2008) also disputed that hypothesis after accounting for other explanatory factors when comparing softer rubberized and stiffer conventional asphalt mixtures.

The noise generated due to the vibration of the tire tends to occur at frequencies up to 1,000 Hz (Nelson and Phillips 1997; Morgan, Nelson, and Steven 2003; Van Keulen and Duškov 2005), with the frequency of vibrations increasing as the tire rotation speed or the block tread length decreases. This phenomenon occurs because the tire acts as a low-frequency band-pass filter, attenuating the noise radiation at higher frequencies. Tire vibration is also increased as the tire tread pattern becomes more aggressive with deeper channels and larger lugs (or blocks) that are further apart.

- Aerodynamic processes between the tire and the road surface. Noise is generated by various mechanisms that occur as air moves in the contact patch. The most important of these mechanisms is called "air pumping," which is the sudden expelling of air that is trapped in the tread grooves or pavement texture due to the reduced groove volume when the tire makes contact with the road surface, and the sudden suction of air when the tire leaves the contact patch (Hayden 1971). The air-pumping mechanism may cause significant levels of noise in the frequency range above 1,000 Hz. Noise due to air pumping can be reduced by providing the air with more and larger pathways to move under the tire and through the pavement (Sandberg and Descornet 1980; Petterson 1988; Kropp 1992). These pathways can be provided by space between the stones due to macrotexture from stones on the surface, texturing of the surface (particularly concrete), and increasing the air permeability of the surface (particularly asphalt).
- Adhesion mechanisms. These mechanisms are caused by tire vibrations associated with the frictional forces that develop at the contact patch between the tire and the pavement surface (Nelson and Phillips 1997). The tire flattens at the contact path, causing tangential forces due to the changing radial deflections. These forces are resisted by the friction between the pavement surface and the stiffness of the tire, and the remaining forces are dissipated by the slip of the tread over the pavement surface. Friction between the tread and the pavement has two components: adhesion and hysteresis. The adhesion component is governed by microtexture of the surface, and the hysteresis component is largely controlled by macrotexture. Adhesion involves the formation and breaking of bonds at the contact patch followed by the hysteresis component of friction. This process, known as slip/stick, occurs at the contact patch and excites the tire vibration.

Noise-generation mechanisms are illustrated in figure 6-8. These general effects of the tire vibration and air pumping mechanisms are shown in figure 6-9 on a plot of OBSI measurements from a set of asphalt sections with the frequencies divided into 1/3 octave bands.

The mechanisms discussed above all assume that the pavement is dry. Phillips (2002) measured noise on wet surfaces and found an increase in the noise levels and also that the noise is dominated by the tire and pavement interacting with the water under wet conditions.

Macrotexture can be divided into two types: negative and positive texture. Positive macrotexture occurs when the texture is dominated by protrusions above the mean surface, while negative macrotexture occurs when the texture is dominated by indentations below the mean surface. From this discussion, it can be seen that positive macrotexture increases surface impact (tire vibration) mechanisms while at the same time increasing the air passages that reduces the noise at higher frequencies caused by aerodynamic processes (air pumping). Negative texture does not necessarily produce tire vibration.

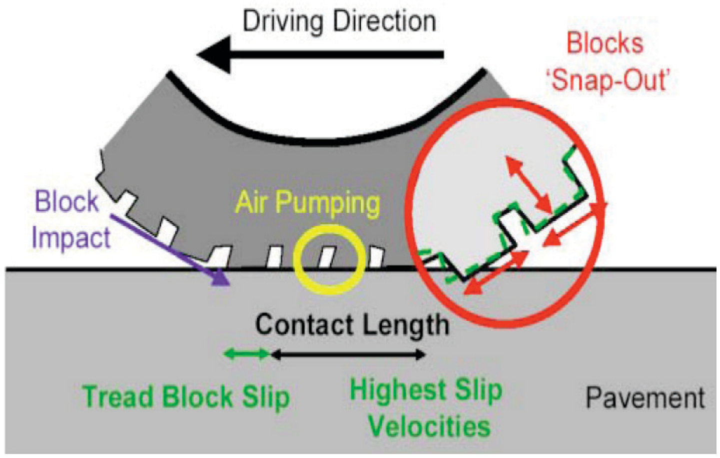


Figure 6-8. Noise-generation mechanisms on dry pavement (Olek, Weiss, and Garcia-Villarreal 2004).

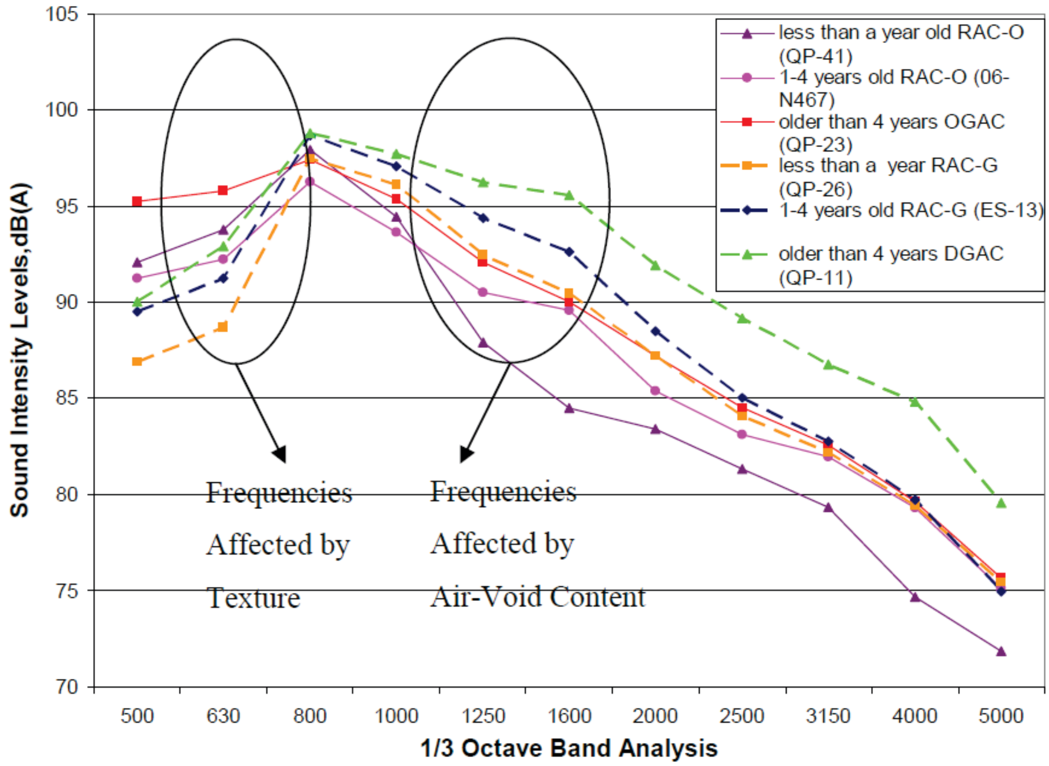


Figure 6-9. Example plot of one-third octave frequency content for several asphalt mixtures and influence of tire-pavement noise mechanisms (Ongel et al. 2008).

Asphalt pavements that have higher positive macrotexture include open-graded mixtures (especially those with larger maximum stone sizes), raveled dense-graded mixtures, and chip seals (again, particularly those with larger stones) (Rezaei, Harvey, and Lu 2012). The surface labeled "older than 4 years OGAC" in figure 6-9 is an open-graded asphalt concrete mixture that has raveling.

Pavement surfaces that can provide and maintain both negative macrotexture and air permeability are likely to reduce tire-pavement noise at the lower and higher frequencies, respectively (Bendtsen and Thomsen 2008; Lu and Harvey 2011; Ongel et al. 2008). Some asphalt surface examples include open-graded friction courses that have good raveling resistance (such as the rubberized open-graded asphalt concrete labeled "1-4 years old RAC-O" in figure 6-9) and some SMA mixtures (Donavan 2006). In addition to raveling resistance, open-graded asphalt surfaces also need to maintain surface air permeability to exhibit their high frequency noise reducing properties. Surface air permeability is more important than average air void content in noise-reducing asphalt mixtures (Reyes and Harvey 2011; Ongel et al. 2008). Surface permeability in the wheelpaths tends to diminish with time because of filling of the surface with mineral particles, oil, and tire rubber, as well as the additional compaction caused by trafficking.

The durability of noise benefits for asphalt surface mixtures will depend on their raveling and air permeability performance. As an example, the average life of noise benefits (defined as a 2 dBA or greater overall OBSI reduction compared to a standard, dense-graded asphalt) for rubberized open-graded asphalt concrete in California is about 10 years over a range of traffic levels and climate regions, which was found to be longer than for conventional open-graded mixes which raveled at a faster rate (Lu and Harvey 2011). The Arizona DOT has reported noise benefits for high-binder content rubberized open-graded mixtures lasting approximately 8 years on freeways in the Phoenix area (Scofield and Donovan 2003).

As previously described, new concrete pavements can be constructed with a number of different surface textures, including transverse tining, longitudinal tining, broom drag, burlap drag, and turf drag. Diamond grinding or diamond grooving can also be performed at the time of construction or as a later rehabilitation or preservation measure. Of these surfaces, diamond grinding and diamond grooving have been found to be the quietest, followed by longitudinal tining. Transverse tining is generally the noisiest type of texture, as shown in figure 6-10, although there can be a fairly wide tire-pavement noise distributions within each texture type (Rasmussen et al. 2012; Rezaei and Harvey 2012). Transverse tining can produce a "whine" (tonal spike) in the middle of the frequency spectrum, at about 1000 to 1500 Hz, with the frequency at which the spike occurs being a function of both the tine spacing and the speed at which the vehicle tires are passing over them (ACPA 2006).

Longitudinal tining of concrete pavement surfaces is being more commonly used by highway agencies. The noise levels of longitudinal tining and other texture types depends in part on the amount of positive texture that they produce, and the shape and depth of the negative texture that allows air to escape from under the tire. If there is loss of mortar around the coarse aggregates in the concrete pavement surface, it can create positive macrotexture similar to that caused by raveling of asphalt surfaces, with associated increases in noise.

In addition to surface texture, other factors can also make major contributions to tire-pavement noise. For asphalt pavements, weathering/raveling of the surface increases noise levels through the creation of positive macrotexture. For concrete pavements, wide, deep sawed joints (those with high cross-sectional area) increase noise levels due to a "flute" effect (Donavan 2009), while transverse joint faulting causes a thumping noise as the tire passes over the joint (Kohler and Harvey 2010). Transverse cracks due to low temperatures or shrinkage due to aging (sometimes showing as block cracking) cause similar thumping in asphalt pavements, especially when there is collapse of the edges of the crack, or when the edges of the crack are "tented" up. For both asphalt and concrete pavement, overbanding of sealant over joints or cracks produces positive texture that can increase noise.

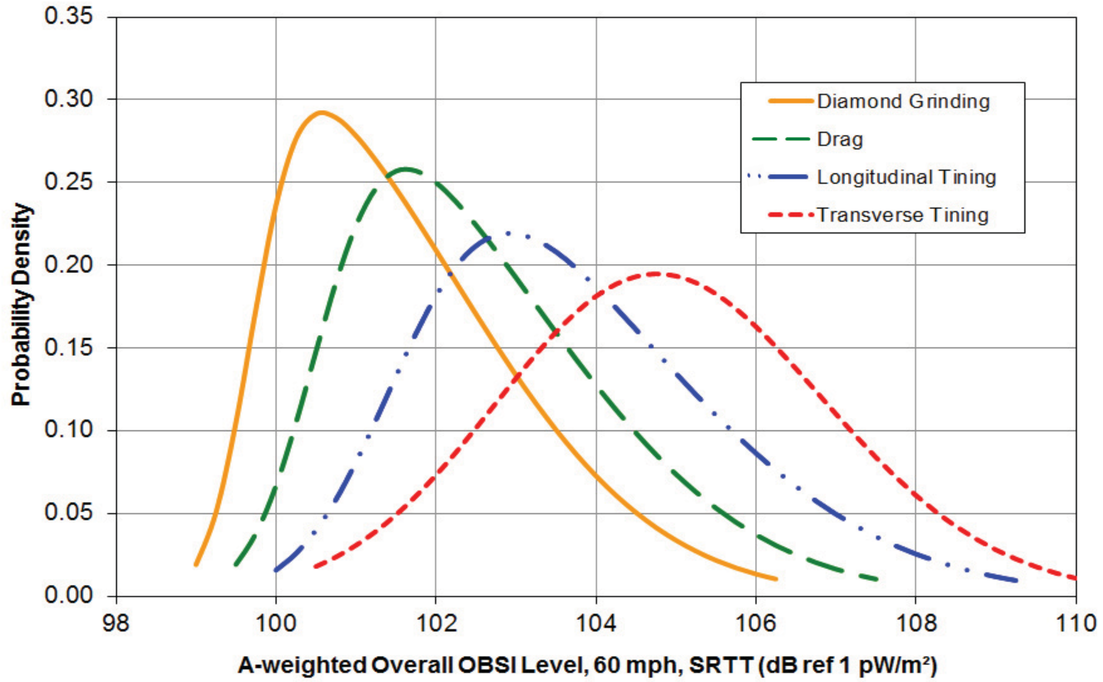


Figure 6-10. Normalized distributions of OBSI noise levels for conventional concrete pavement textures (Rasmussen et al. 2012).

The combined effects of faulting, sealing, and joint cross-sectional area can increase overall tire-pavement noise levels, and together are referred to as "joint slap" on concrete pavement (IGGA 2011). The magnitude of noise generated by joint slap can be estimated using a web tool (ACPA 2013) that considers joint geometry, existing pavement texture noise level, and vehicle speed using data from the Purdue University Tire Pavement Test Apparatus in the laboratory with some field validation at the MnROAD test track in Minnesota (ACPA 2007). Spalling of joints and cracks in all pavement types is also expected to increase noise levels.

Narrow joints and control of faulting in concrete pavement, good sealing practice (no overbanding), and good pavement preservation practices that minimize the extent and severity of cracking for both asphalt and concrete pavement will help maintain quieter pavements. Diamond grinding for concrete pavement and thin overlays (using durable polymer-modified or rubberized open-graded asphalt or SMA) for asphalt pavement are preservation treatments particularly suited to maintaining quiet pavements.

Innovative pavement surfaces are being developed based on studies indicating that negative macrotexture and paths that allow air to escape result in quieter pavements. For concrete pavement, laboratory investigations led to the development of the Next Generation Concrete Surface (NGCS), which features flush grinding (to minimize positive texture and remove faulting and old texture) and grooving (to provide passages for air and water) (Dare et al. 2009). These surfaces are under investigation in several states (Wilde and Izevbekhai 2010; Guada et al. 2013) and show some promise based on early performance, with noise levels below those of conventional diamond grinding. It has been observed that the NGCS is susceptible to accelerated wear under the action of studded tires/chains and therefore should not be used under such conditions (Anderson et al. 2014).

Figure 6-11a shows the frequency content of an example test section in three conditions: before treatment (designated as PreCDG [pre-conventional diamond grinding]), after treatment (designated as CDG [conventional diamond grinding]), and after flush grinding and grooving (designated as GnG (grinding and grooving, an NGCS texture). Figures 6-11b and 6-11c illustrate the surface textures corresponding to the CDG and NGCS treatments, respectively.

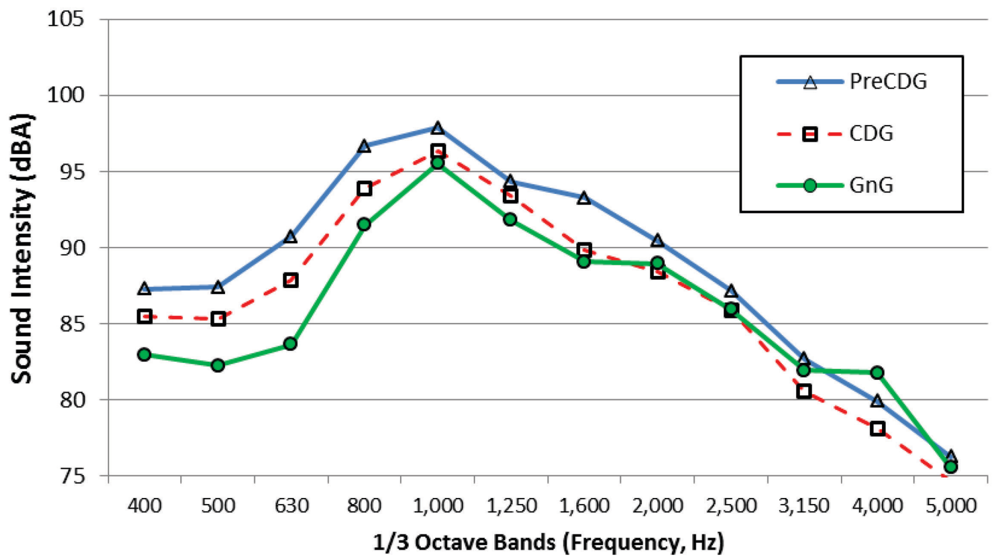


Figure 6-11 (a). Frequency content of OBSI measured at 60 mi/hr (97 km/hr) for pretreatment (PreCDG), conventional diamond grinding (CDG), and NGCS (GnG in the figure) for a California test section, Yolo 113– PM R0.5/R2.5 (Guada et al. 2013).

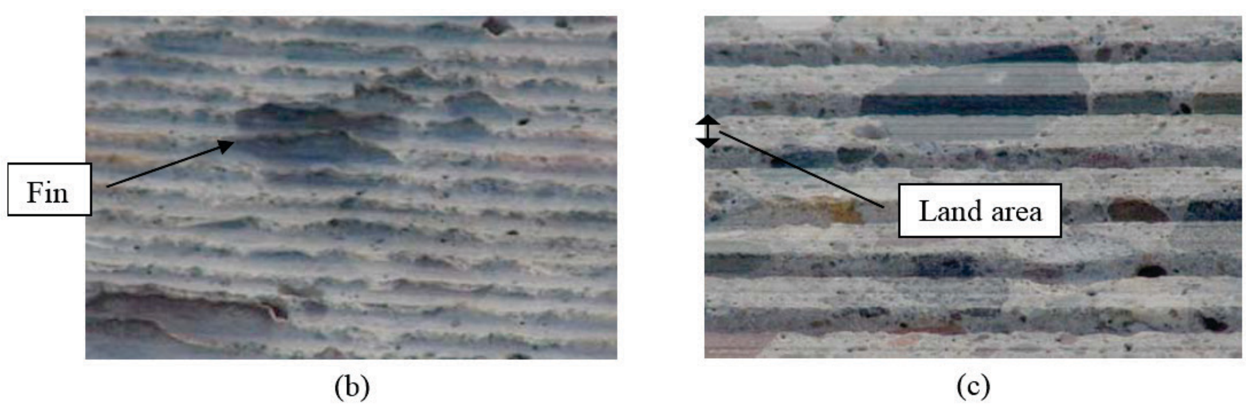


Figure 6.11 (b). Conventional diamond-ground surface showing "fins" that are eventually removed by traffic (Guada et al. 2013) (c). Conventional diamond-ground surface with the Next Generation Concrete Surface showing definition of "land area" between grooves (Guada et al. 2013).

Field measurements and laboratory work have led to the development of asphalt mixtures with smaller maximum aggregate sizes (passing # 4 [4.25 mm] sieve) and open gradations and air-void contents of 15 percent or more to provide air permeability. Although these have not been tested under high-speed traffic, preliminary laboratory testing (Lu and Harvey 2011; Wu et al. 2013) indicates improved raveling performance and high frequency tire-pavement noise performance compared with larger stone size mixtures (see figure 6-12a) and low-speed OBSI results on a test section indicate improved initial noise performance (see figure 6-12b).

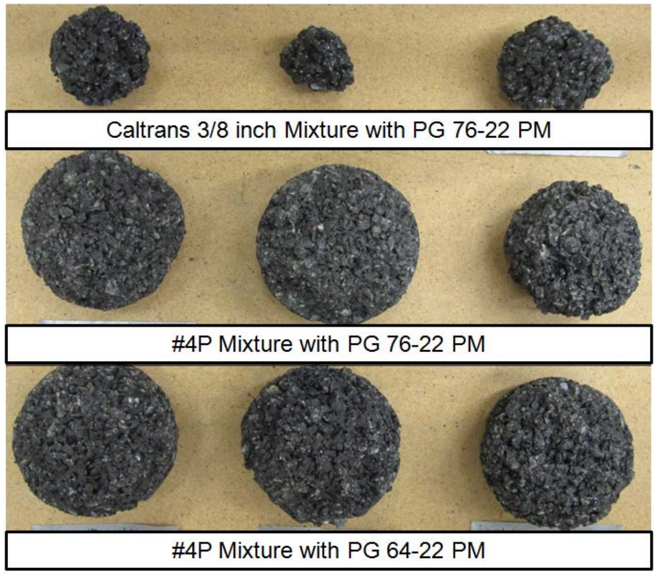


Figure 6-12 (a). Examples of residual specimens after Cantabro testing for raveling of the same OGFC mixtures (Wu et al. 2013). Each original specimen had a diameter of 4 inches (100 mm).

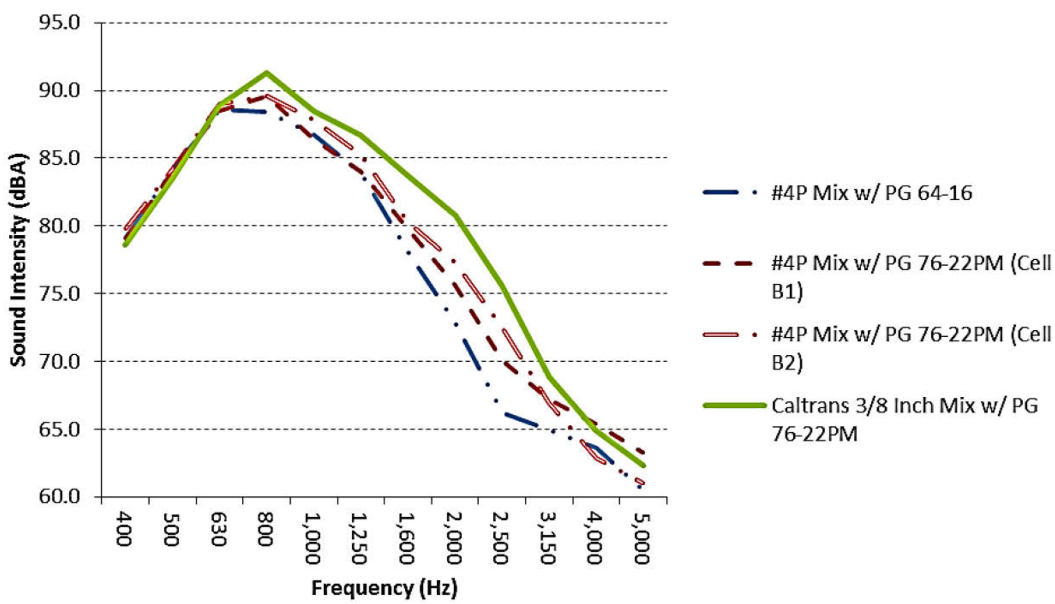


Figure 6-12 (b). Frequency content of OBSI measured at 35 mi/hr (56 km/hr) for Caltrans open-graded asphalt mixtures with typical 0.375 inch (9.5 mm) and #4 (4.75 mm) maximum aggregate sizes (Wu et al. 2013).

The Arizona DOT is currently involved in a Quiet Pavement Pilot Program (QPPP) in partnership with the FHWA. Several other states have Quieter Pavement Research (QPR) efforts underway that are producing research results such as those shown in this chapter, including California, Colorado, Florida, Texas, Virginia, and Washington (FHWA 2011c).

Strategies for Improving Sustainability

Practices that are available to pavement managers, designers, and specification developers that might be used to address tire-pavement noise are summarized in table 6-4.

Table 6-4. Summary of strategies for improving tire-pavement noise and potential trade-offs.

Tire-Pavement Noise Objective	Tire-Pavement Noise Improving Strategy	Economic Impact	Environmental Impact	Societal Impact
Reduce Noise on New and Existing Asphalt Pavements	Use durable open-graded or SMA mixtures	Open-graded mixtures generally have shorter lives than dense graded mixtures. SMA mixtures are more expensive than dense graded. Life-cycle cost analysis can be performed.	Quieter pavement benefit. Trade-offs depend on surface mixture impact and longevity. Can be calculated with LCA.	Quieter pavement improves the livability of neighborhoods near highways. Can potentially reduce stress on wildlife.
Reduce Noise on New Concrete Pavement	Eliminate transverse tining by using longitudinal textures; use quieter textures; use narrow (single-saw cut width) joints with recessed sealant if sealant is used.	Depends on alternative texture used. Generally very small cost compared to construction cost.	Quieter pavement benefit. Trade-offs depend on surface texture and longevity. Texturing generally low impact. Can be calculated with LCA.	Quieter pavement improves the livability of neighborhoods near highways. Can potentially reduce stress on wildlife. Must have adequate surface friction.
Reduce Noise on Existing Concrete Pavement	Retexture with conventional diamond grinding or NGCS	Relatively low cost treatment that also improves smoothness and removes faulting. Increased cost compared to Do Nothing.	Quieter pavement benefit. Trade-offs depend on surface texture and longevity. Texturing generally low impact. Can be calculated with LCA.	Quieter pavement improves the livability of neighborhoods near highways. Can potentially reduce stress on wildlife. Must have adequate surface friction.
Minimize Noise on Existing Pavement	Perform pavement preservation to minimize cracking, faulting and other surface imperfections that contribute to noise; use good practice for sealing to prevent overbanding	Can also reduce life-cycle cost	Quieter pavement benefit. Impact depends on traffic and interaction of smoothness and vehicle use. Can be calculated with LCA.	Quieter pavement improves the livability of neighborhoods near highways. Can potentially reduce stress on wildlife. Must have adequate surface friction.

Future Directions and Emerging Trends

The most important emerging trend in this area is the greater attention being paid to tire-pavement noise, and the increased consideration of pavement effects on highway noise in planning, traffic noise modeling, and pavement maintenance and rehabilitation design decisions.

Important future directions include the development of new materials and surface textures for concrete and asphalt that reduce noise while maintaining adequate surface friction, and the potential to set performance requirements for tire-pavement noise measured with OBSI for new construction and during long-term maintenance contracts.

Addressing Stormwater Runoff through Pavement Permeable Surfaces

Background

Major Issues:

- ✓ *Permeable surfaces may help economically handle stormwater quality and runoff rates.*
- ✓ *Currently best suited for low-speed, low-volume roadways and parking areas.*
- ✓ *Requires more frequent cleaning and maintenance.*
- ✓ *Due to runoff drained through permeable surfaces, groundwater sources may be contaminated.*

Conventional paved pavement surfaces are relatively impermeable, allowing precipitation to run off much faster than it does from vegetated or undeveloped surfaces. In addition, runoff from impermeable surfaces is often directed to stormwater collection systems and thus is not absorbed into the nearby soil. That runoff, because it does not benefit from being naturally filtered through the soil, can pollute and raise the temperature of the nearby surface waters and streams to which it is being diverted. Furthermore, the collection of runoff in this manner during high precipitation events can cause stormwater collection systems to overflow, potentially resulting in flooding and erosion because of the speed with which the runoff leaves the paved surface. In cases where the stormwater collection system is combined with the sanitary sewage system, the release of raw sewage may occur as the result of the system being overwhelmed during high precipitation events, causing significant environmental and economic impact for treatment and clean up. Finally, typical stormwater management solutions, including the reliance on retention ponds, are difficult to accommodate in areas with space constraints (such as built-up urban areas); consequently, innovative solutions to reducing road surface runoff are needed.

Research has shown that pavement materials themselves do not significantly contribute pollutants to stormwater runoff. Laboratory experiments on a range of concrete and asphalt pavements, including open- and dense-graded materials and different cement- and asphalt-binder sources (including asphalt rubber and aged specimens), showed that pollutant contributions to runoff were generally extremely low (Kayhanian et al. 2009; Kayhanian et al. 2010). From the laboratory study performed by Kayhanian et al. (2010) it was concluded that the major sources of pollutants measured from road surface runoff are mostly associated with vehicles and airborne deposition. One pollutant of concern in runoff is polyaromatic hydrocarbons (PAHs). These toxic compounds, which are primarily related to the combustion of transportation fuels and are deposited on the pavement surface through vehicle exhaust, are present at low concentrations in urban and highway runoff (Lau, Kayhanian, and Stenstrom 2005; Kang et al. 2009). It is important to note that large concentration of PAHs are reported in coal tar sealant and if these are used on a pavement then high PAH concentrations in the surface runoff would be expected (Van Metre and Mahler 2010; USGS 2011). However, the use of coal tar pitch or tar sealant are mostly isolated to residential driveways and parking lots in some regions of the U.S. and are rarely used on pavements for urban roads or highways.

Another pollutant of concern is metals. The laboratory study by Kayhanian et al. (2009; 2010) found amounts of toxic metal above the reporting limits in simulated runoff on a few of the concrete mixtures tested, which was attributed to the cement sources used. Additional information related to the type and concentration of different organic and inorganic pollutants observed from highway runoff can be obtained from a recent review article prepared by Kayhanian et al. (2012b).

Thin open-graded surfaces placed on otherwise impermeable pavements, such as thin open-graded asphalt surfacing, can help slow runoff and capture solids and pollutants, improving the quality of stormwater runoff (Pagotto, Legret, and Le Cloirec 2000; Barrett and Shaw 2007).

An innovative solution to actually reducing or eliminating runoff is through the use of fully permeable pavements, which were introduced in chapter 3. As described in chapter 3, permeable pavements can be constructed using pervious concrete, porous asphalt, or permeable interlocking pavers. Vegetated pavements have also been used effectively for low-volume traffic applications, most prominently as parking lots. All of these pavements types allow major portions of the stormwater runoff to pass through the surface and be absorbed into the underlying ground. This has the advantages of minimizing or eliminating the need for a stormwater collection system, recharging the groundwater table, filtering the runoff naturally through the soil, and reducing the direct discharge of runoff and any contaminants associated with them into nearby surface water. These applications can potentially be applied to the traveled way of the pavement, to the shoulders or strips of pavement outside the traveled way, or to parking areas.

Pervious concrete and porous asphalt pavements (see figure 6-13) are created by greatly reducing the fine aggregate fraction in a mixture, increasing the percentage of void space. In the case of interlocking permeable pavers (figure 6-14), void space is often created at the gaps between the pavers, and these voids are filled with permeable aggregate. For porous asphalt, the same mixtures used for thin surface open-graded layers can also be used for fully permeable pavements. With the increase in void space, rainwater can drain through the surface into a base/storage layer designed for hydraulic performance to retain the design rainfall, from where it seeps into the ground reducing the amount of runoff while recharging the groundwater. The natural filtering that occurs in the soil removes the majority of particle-bound inorganic and organic contaminates, but there may be an increased risk of groundwater contamination from regulated dissolved pollutants and thus it is not recommended to construct permeable pavements in locations near drinking groundwater supplies (EPA 1999).

Figure 6-13. Pervious concrete (left, courtesy John Kevern) and porous asphalt (right, courtesy National Asphalt Pavement Association).

Figure 6-14. Permeable interlocking concrete pavers (courtesy Interlocking Concrete Pavement Institute).

Another permeable pavement solution is the use of vegetated pavement. Vegetated pavements, an example of which is shown in figure 6-15, use a lattice of concrete, plastic, or metal to provide stability while vegetation is encouraged to grow between the lattices. The vegetation allows for a more natural infiltration of stormwater runoff and also can provide a more visually appealing surface compared to hard surfaces. Vegetated pavements can have comparable load-carrying capacity to conventional pavements, but are typically used in low-traffic conditions such as alleys, parking lots, residential streets, and trails in order to minimize damage to the vegetation. Also, they are best suited to climates with adequate summer moisture to keep the vegetation alive (EPA 2008).

Figure 6-15. Vegetated pavement (photo courtesy of Soil Retention Products, Inc.).

Water that passes through the pavement surface and is stored below the surface can also reduce pavement temperatures by means of evapotranspiration, where the heat that is stored in the pavement is released through the conversion of the stored water into water vapor. There is also significantly more surface area associated with the increased void space and thus the increased exposure to air increases the heat conductivity of the pavement. Consequently, permeable pavements (whether pervious concrete, porous asphalt, permeable interlocking pavers, or vegetated pavements) can be used in urban areas to help alleviate the need for other stormwater management devices such as retention ponds, sand filters, and swales (PCA 2011).

At the present time, the EPA (2010b) cites the use of pervious concrete and porous asphalt pavements as a Best Management Practice (BMP) for handling stormwater runoff on a local and regional basis. The majority of current pervious concrete and porous asphalt pavements are used as BMP in low-traffic, low-speed applications, such as shoulders or parking lots. When using these types of pavements, they need to be regularly maintained (typically using vacuum cleaning machines with no sweeping) in order to ensure continuous infiltration with no or minimum surface overflow. Surface infiltration can be measured through permeability measurements. In one recent study, the surface permeability of 20 pervious concrete and porous asphalt parking lots were measured in California and the results showed a large variability within each parking lot and among all parking lots, although localized impermeability did not affect the overall drainage of the facilities (Kayhanian et al. 2012a). The permeability value was directly related to the age of pavement as the older pavements had lower infiltration rates. The lower permeability in older permeable pavements was suspected to be impacted by particles from atmospheric deposition or from surrounding area soil erosion. Some densification under truck loads at hot temperatures may have contributed to reduced permeability in the porous asphalt materials in addition to clogging.

A similar study was performed on 40 permeable pavement sites in North Carolina, Maryland, Virginia, and Delaware (Bean et al. 2007). Again, localized low permeability was observed but often it did not hinder the overall performance of the facility as long as there was also localized areas with high permeability. In another study on open-graded asphalt under accelerated pavement testing, the addition of particles on the pavement surface was found to be partially responsible for surface void and permeability reductions; however, most of the void and permeability reduction was due to densification and rutting under loading (Coleri et al. 2013).

The use of permeable pavement for stormwater runoff management may not necessarily be limited to parking lots and other low-traffic or low-speed facilities. Preliminary research, although not yet validated by field sections or accelerated pavement testing, indicates that it may be possible to design and construct permeable pavements for the highway environment. For example, one innovative approach on a high-speed or high-volume roadway is to retrofit the shoulders of the impermeable pavement with a permeable pavement to capture the runoff from the impermeable mainline pavement. The technical feasibility of this design concept was recently simulated by researchers and the results of both structural and hydraulic performance simulations are reported by Li, Harvey, and Jones (2012) and by Chai et al. (2012), respectively. Extended periods of saturation of moisture-sensitive subgrade soils is a major concern for the design of permeable pavements to carry heavy loads. The simulation results indicated that thick layers of crushed permeable aggregate are needed to reduce shear stresses to acceptable levels at the surface of saturated clay subgrades.

One critical design consideration is that care must be taken to prevent water stored in the fully permeable shoulder from infiltrating back into the pavement layers and the subgrade of the adjacent impermeable pavement. Several example designs of permeable pavements for highway shoulder retrofits were proposed and simulated (and not yet validated by field or accelerated pavement testing sections) under heavy truck traffic at low to medium speeds and found to be technically feasible (Li, Harvey and Jones 2012). The study recommends that test sections be evaluated using APT or in actual field trials. The use of a full-depth permeable shoulder retrofit for highways was also recently investigated as part of an NCHRP project (Hein et al. 2013). As part of that study, several conceptual designs are proposed (not validated) and recommended for further investigation and verification under pilot and field conditions.

In addition to the benefit gained for stormwater management, other added benefits regarding the use of both porous asphalt surfaces and fully permeable asphalt, concrete, and paver pavements are improved surface friction and safety during rainstorms due to the open-graded surface. There may be noise benefits as well, although only open-graded asphalt materials have been evaluated for noise performance and the noise performance of pervious concrete and permeable interlocking pavers has not been evaluated. There are also reported water quality benefits from the use of various kinds of permeable pavements (Barrett, Kearfott, and Malina 2006; Bean, Hunt, and Bidelspach 2007; Brattebo and Booth 2003; Roseen et al. 2012; Sansalone, Kuang, and Ranieri 2008). In addition, Roseen et al. (2012) reported that lower salt application is required for the porous asphalt pavements investigated and no adverse freeze-thaw effects were observed in cold climates; for that reason, the life span of porous asphalt is expected to exceed that of typical pavement applications in cold climates. The concern about freeze-thaw resistance is also often raised for permeable concrete pavements, but testing and performance has shown mixtures with good freeze-thaw performance can be achieved through the proper fine aggregate grading, coarse aggregate absorptivity, and possible use of fibers (Kevern et al. 2008; Kevern et al. 2010). Freeze-thaw deterioration would generally not be expected to be a concern for permeable paver pavements unless the pavers themselves have high permeability.

There are a number of trade-offs to evaluate when considering the use of permeable pavements, including the potential for clogging, the additional cost of construction and cleaning, and potential moisture damage. The cost consideration is related to the underlying permeable aggregate layer used as the reservoir that causes the pavements to be more expensive than conventional pavement construction. This increased cost can often be overcome when considering the value of the land that would be needed for use as a retention basin (or other stormwater management requirements) (NAPA 2008). Another consideration is the maintenance of the permeable surface, which typically consists of vacuum sweeping and is essential to prevent dust and other particle matter from clogging the surface and rendering the pavement ineffective (Levine 2011). However, a preliminary analysis of life-cycle costs indicated that a full-depth permeable shoulder retrofit for highways is economically justifiable for stormwater management compared to conventional BMPs (Jones et al. 2010). In addition, a study performed by Houle et al. (2013) concluded that low impact development (LID) systems (including permeable pavements) generally have lower marginal maintenance burdens as measured by cost and personnel hours when compared to conventional treatment systems.

Care must be taken in the design of permeable pavements, particularly asphalt pavements, to minimize long-term saturation that would otherwise weaken the surface layers; however, water draining through these layers should not cause problems. Therefore, hydraulic design should aim to keep the water level in the pavement below the surface layers most of the time. The use of rubber-modified or polymer-modified binders and anti-stripping additives may help extend the life of open-graded asphalt mixtures. A study performed by Liu and Cao (2009) demonstrated that permeable pavement mixtures with typical neat asphalt were prone to be seriously damaged by water, whereas high-viscosity binders demonstrated better resistance to moisture damage, rutting, and raveling.

Strategies for Improving Sustainability

Practices available to pavement managers, designers, and specification developers that can be used to address stormwater runoff issues are provided in table 6-5.

Table 6-5. Summary of strategies to address stormwater runoff issues and potential trade-offs.

Stormwater Runoff Objective	Stormwater Runoff Improving Practices	Economic Impact	Environmental Impact	Societal Impact
Increase Structural Capacity for Application in High-Speed, High-Load Areas.	Pervious concrete. Porous asphalt.	Increased initial cost over comparable impermeable concrete and asphalt. Cost of handling and treating stormwater may be less than other BMP.	Improved stormwater quality. Impact on other impact categories has not been evaluated.	Uncertain.
	Permeable pavers.	Not applicable for high-speed applications.	Not applicable for high-speed applications.	Not applicable for high-speed applications.
	Vegetated pavement.	Not applicable for high-speed applications.	Not applicable for high-speed applications.	Not applicable for high-speed applications.
Create Lower Maintenance Permeable Pavement Surfaces.	Pervious concrete. Porous asphalt. Permeable pavers.	Research is still underway to develop improved durability without sacrificing hydraulic performance, and to develop better structural designs. Trade-offs between initial and life-cycle costs to be determined.	Longer life pavement designs should reduce environmental impact of materials production and construction.	Longer life pavement designs should improve societal impact of repeated construction.
	Vegetated pavement.	Improved designs for vegetation selection and management should reduce economic, environmental (water use) and societal impacts.	Improved designs for vegetation selection and management should reduce economic, environmental (water use) and societal impacts.	Improved designs for vegetation selection and management should reduce economic, environmental (water use) and societal impacts.
Understand the Potential for Ground-water Contamination.	All permeable pavement types.	Investment required in research to determine level of risk and mitigation approaches, although initial results positive.	Uncertain. Once the level of risk is fully assessed it can be weighed against alternatives, as needed.	Uncertain. Once the level of risk is fully assessed it can be weighed against alternatives, as needed.

Future Directions and Emerging Trends

One major initiative in the stormwater management area is integrating permeable pavements into urban designs, with benefits including reduced runoff, improved water quality, and the potential to reduce the localized urban heat island (UHI) effect through evaporative cooling. This is still under investigation. In addition, coupling permeable pavement surfaces with photocatalytic additives and/or coatings is also being studied, particularly with pervious concrete pavement and permeable interlocking concrete pavers. The presence of voids inherent in these surfaces increases the photocatalytic area exposed to the atmosphere, thus increasing the photocatalytic efficiency per unit of pavement surface area.

There is strong interest in using permeable pavement surfaces as part of mainline pavement construction. The initial effort thus far has been in parking areas and on mainline pavement shoulders, but work continues on evaluating designs that can perform well under heavier traffic loadings.

Scholz and Grabowiecki (2007), among others, have introduced the idea of developing a heating/cooling system that can be installed within the subbase of modern permeable pavement systems in urban areas. The energy gained from the below-ground pump can be used as a substitute for energy derived from fossil fuel and hence has the potential for reducing CO_2 emissions. The research suggests that the development of a combined geothermal heating and cooling, water treatment, and recycling pavement system is promising (Scholz and Grabowiecki 2007).

Pavement Thermal Performance and Contribution to Urban and Global Climate

Pavement Properties Affecting Thermal Performance

The thermal performance of a pavement is defined as the change in its temperature (most often surface temperature) over time as influenced by properties of the paving materials (e.g. albedo, thermal emittance, thermal conductivity, specific heat, and surface convection) and by the ambient environmental conditions (sunlight, wind, air temperature). It can also be influenced by evaporative cooling, which is related to ambient conditions, permeability, and the availability of near surface water (most often a factor if fully pervious pavement systems are used).

Albedo (or solar reflectance) is a measure of the ability of a surface to reflect solar radiation. Solar reflectance values range from 0 (no sunlight reflected) to 1 (all sunlight reflected). Light-colored materials generally have higher solar reflectance values than dark-colored materials, although color alone is not the only indicator of solar reflectance (NCPTC/NCAT 2013).

Emittance is the efficiency with which a surface emits radiant energy, and is defined as the ratio of energy radiated by the surface to the energy radiated by a black body (a perfect absorber and emitter) at the same temperature. Emittance ranges from 0 (no emission) to 1 (perfect emission). Thermal emittance is the emittance of a surface near 300 K (81 ºF or 27 ºC). Most nonmetallic surfaces have thermal emittances in the range of 0.80 to 0.95. The thermal emittances of dense-graded concrete and asphalt are similar, being in the range of 0.90 to 0.95.

Thermal conductivity is a measure of the ability of a material to conduct or transmit heat. It is the ratio of heat flux (power per unit area) to temperature gradient, and is expressed in units of W/m•K. A material with a high thermal conductivity will transfer heat at a higher rate than a material having a low thermal conductivity. The thermal conductivity of pavement materials varies widely in the reported literature from 0.8 W/m•K to 2.0 W/m•K or greater, with similar values reported for dense-graded asphalt and concrete.

Specific heat is the energy needed to raise a unit mass of a substance by one unit of temperature, typically expressed in units of J/kg•K. The specific heat of dense-graded asphalt and concrete are very similar, being about 900 J/kg•K.

Of these material properties, albedo is the most important with regards to how pavements interact thermally with the environment when exposed to sunlight. Thermal emittance, thermal conductivity, and specific heat capacity of the materials are second order factors (Li et al. 2013). However, as will be discussed, understanding the thermal characteristics of the pavement materials alone is insufficient to fully understand how pavements thermally interact with the urban and global environments.

The means by which solar radiation warms a pavement surface, the underlying layers, and the surrounding atmosphere during the day and then releases the absorbed energy as heat at night is illustrated in figure 6-16 (NCPTC/NCAT 2013). During the day, the pavement's surface will reflect some of the incident sunlight and absorb the rest. The absorbed solar energy is emitted as long-wave radiation from the pavement, convected to the air moving over the pavement, conducted into the pavement and ground below, and/or dissipated by evaporation of water. Some of the solar energy stored in the pavement during the day is released at night through emitted long-wave radiation and convection, and some is released laterally to cooler zones through conduction.

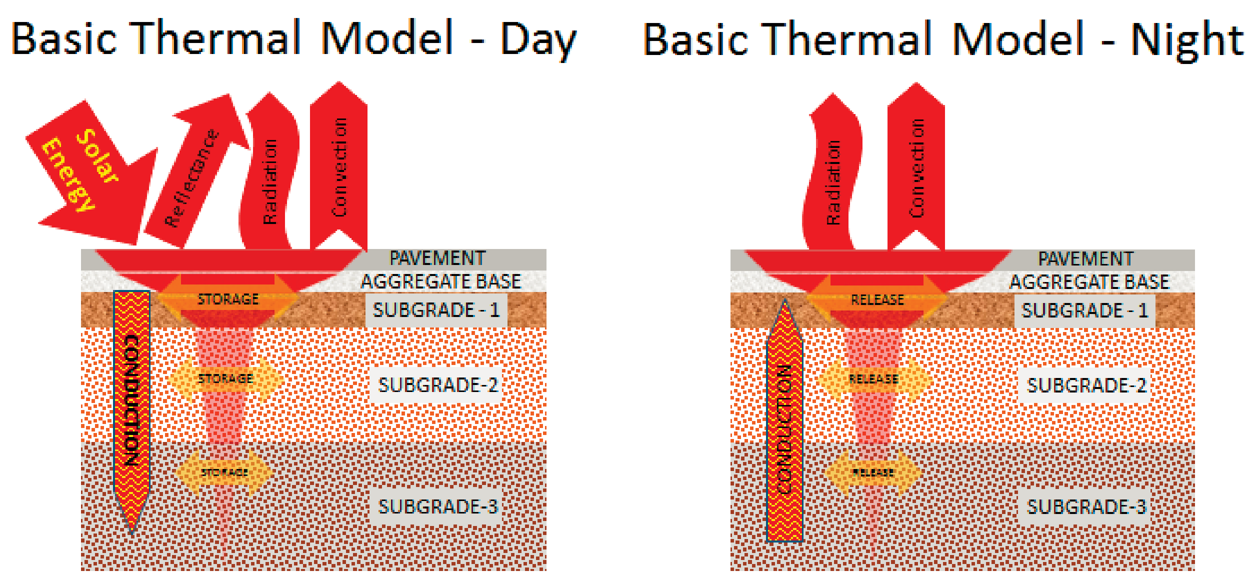


Figure 6-16. Heat flow and the basic thermal model for day and night (NCPTC/NCAT 2013).

The thermal emittance, thermal conductivity, and specific heat of common paving materials are influenced by their density (which is largely controlled by mixture porosity and aggregate type and gradation), the amount of binder (cement, asphalt or other materials) if they are present, and the moisture content (Li et al. 2013). As discussed, the thermal emittance, thermal conductivity, and specific heat of common dense-graded paving materials are similar and therefore differences in the thermal performance of pavements are largely the result of differences in albedo. It is noted that many additional factors contribute to how pavements interact thermally with their surroundings, which is the focus of the remaining discussion of this section.

Urban and Global Warming Effects

The Urban Heat Island Effect

On a summer afternoon, urban areas are generally warmer than surrounding rural locations (Jones et al. 1990), as illustrated in figure 6-17 (EPA 2003). This urban–rural air temperature difference, known as the urban heat island effect (UHIE), is driven by a variety of factors including the prevalence of dark, dry surfaces in cities and heavily urbanized locations.

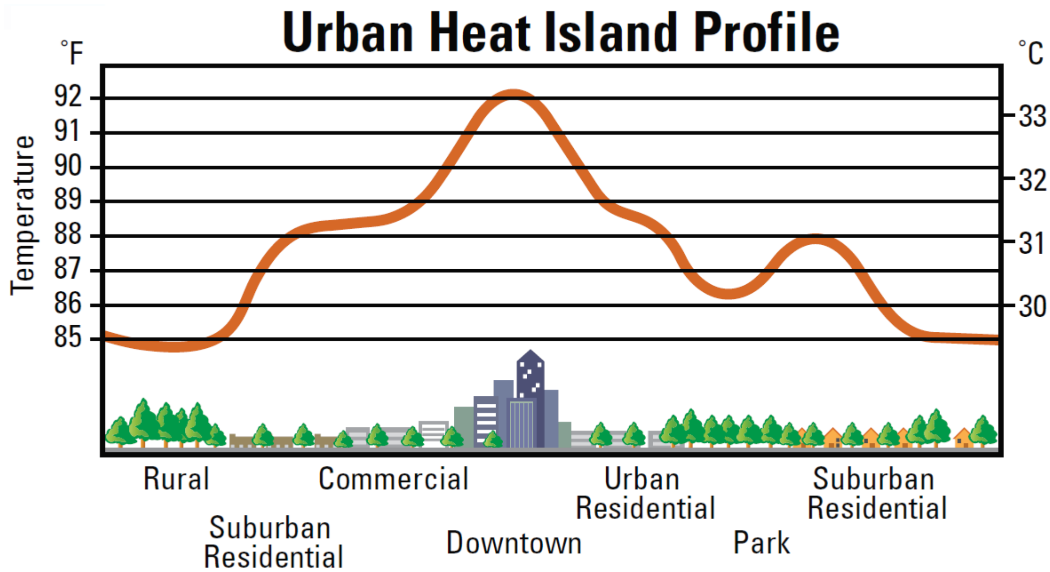


Figure 6-17. Heat islands for various areas of development (EPA 2003).

Although urban heat islands (UHIs) are most often thought of as existing in the atmosphere above the city, they actually exist at many different levels, including at the ground/pavement surface, in the air just above the surface (near-surface), and in the ambient air temperatures well above street level, as well as in the atmosphere above the city. In many cases, it is convenient to consider near-surface heat islands, which are characterized by increased ambient air temperature just above the ground/pavement surface, typically at 3 to 6 feet (1 to 2 m) where human outdoor activities occur (Li et al. 2013). Surface and near-surface heat islands can potentially affect human thermal comfort, air quality, and energy use of buildings and vehicles. Atmospheric heat islands can affect communities by increasing summertime peak energy demand, electrical grid reliability, air conditioning costs, air pollution and GHG emissions, heat-related illness and death, and water quality.

As illustrated in figure 6-17, the rise in the temperature of man-made urban areas is quite noticeable compared with the other land uses. Although heat islands may form on any rural or urban area, and at any spatial scale, cities are favored since their surfaces are dark and dry, which increases solar heat gain and reduces evaporative cooling.

The increased air temperatures associated with UHIs can contribute to greater energy demands (and the associated environmental impacts of increased electrical energy production) when and where increases in air temperatures result in greater use of air conditioning to cool buildings. In places that are already burdened with high temperatures, the UHIE can make cities warmer, more uncomfortable, and occasionally more life threatening (FEMA 2007). Furthermore, increases in temperature increase the probability of formation of ground-level ozone (commonly called smog), which exacerbates certain respiratory conditions such as asthma. Thus, it is believed that in most urban environments any potential benefits that might be derived from the UHIE (such as reduced winter heating requirements) are outweighed by their otherwise negative effects of extreme summer temperatures that can lead to increased air pollution, increased energy use for air conditioning, increased CO_2 emissions, and adverse health and economic impacts (Navigant Consulting 2010).

It is estimated that paved surfaces for travel, parking, and pedestrian use can account for around one-third of the land surface area in urban areas. Multiple studies have concluded, through simulation modeling, that low solar reflectance of paving materials can contribute to the formation of urban heat islands (Akbari, Rose, and Taha 1999; Taha, Konopacki, and Gabersek 1999; Rose, Akbari, and Taha 2003; Rosenzweig et al. 2006; Millstein 2013; Li et al. 2013; Santamouris 2013). Although research has demonstrated through the evaluation of satellite imagery the efficacy of using reflective roofs to lower urban temperatures in a city such as Chicago (Mackey, Lee, and Smith 2012), field data demonstrating the extent that pavement surface albedo contributes to the UHIE have not been found in the literature. This is partly because the relationships between the contribution of pavement surface albedo and the UHIE are complex and as of yet not fully defined due to urban areas having differing sizes, pavement densities, tree canopies, building patterns, latitudes, and climates (Navigant 2010). Furthermore, factors such as building ordering and heights create three-dimensional “urban canyons” that impact the flow of air through the urban environment and appear to have a significant effect on urban warming (Sobstyl 2013). And as pavements are for the most part at ground level, they are often shaded by buildings and trees in an urban environment.

To address these shortcomings, many simulation efforts have incorporated urban canopy models (UCMs) that accommodate the effects of urban canyons and complex urban morphology (Taha 2008a; Taha 2008b; Chen et al. 2011; Li and Bou-Zeid 2014; Li, Bou-Zeid, and Oppenheimer 2014). The most sophisticated models recognize the three-dimensional nature of urban surfaces, taking into account the impacts of vertical surfaces (walls) and horizontal surfaces (roofs and pavements) and considering shadowing, reflections, and radiation trapping in urban canyons (Chen et al. 2011). The exchange of energy between building interiors and the outside atmosphere can also be modeled to evaluate this important interaction. The model sophistication is such that calculations can be made on overall building energy consumption due to air conditioning and interior artificial lighting needs. These simulation efforts will continue to improve in complexity through better resolution and incorporation of even more sophisticated models, likely resulting in more definitive results focused exclusively on the impact of pavement albedo on the UHIE.

Published studies have evaluated the effect of changing both the albedo of roofs and pavements together, and as a result the impact of changing pavement albedo alone cannot be easily interpreted (Taha 2008a; Taha 2008b; Li et al. 2013). However, at least one study has been published that included the modeling of the urban canyon in which only the pavement albedo has been altered. In that study, Hamdi and Schayes (2008), when simulating the city of Basel, Switzerland, found that a mid-day summer temperature reduction of 1.1 °F (0.6 °C) could be obtained when the albedos of the road surfaces in the city were increased from 0.08 to 0.30. The effect of the urban canyon was investigated, showing that narrower streets with higher buildings resulted in a decrease in UHIE due to shadowing. Still, much more work is needed to determine to what degree pavement albedo alone has on the UHIE in typical North American cities. Efforts employing these sophisticated models to solely evaluate the effect of pavement albedo within a realistic range (0.05 to 0.50) are currently underway in California (CARB 2013).

With regards to the effects of pavements being shaded, pavement albedo is most relevant with regards to warming the pavement if the surface is exposed to direct solar radiation. Thus, not only is shading from buildings and trees relevant, but so is cloud cover and latitude. Figure 6-18 shows the average June flat plate solar radiation map of the U.S. illustrating that the southwestern U.S. has some of the highest annual levels of solar radiation nationally (as well as worldwide), whereas other areas of the country have far less (NREL 2012). June was chosen in this figure as it is the month where solar radiation is most direct, and is also a month where the UHIE becomes most relevant in many North American cities. Similar solar radiation trends exist monthly throughout the year.

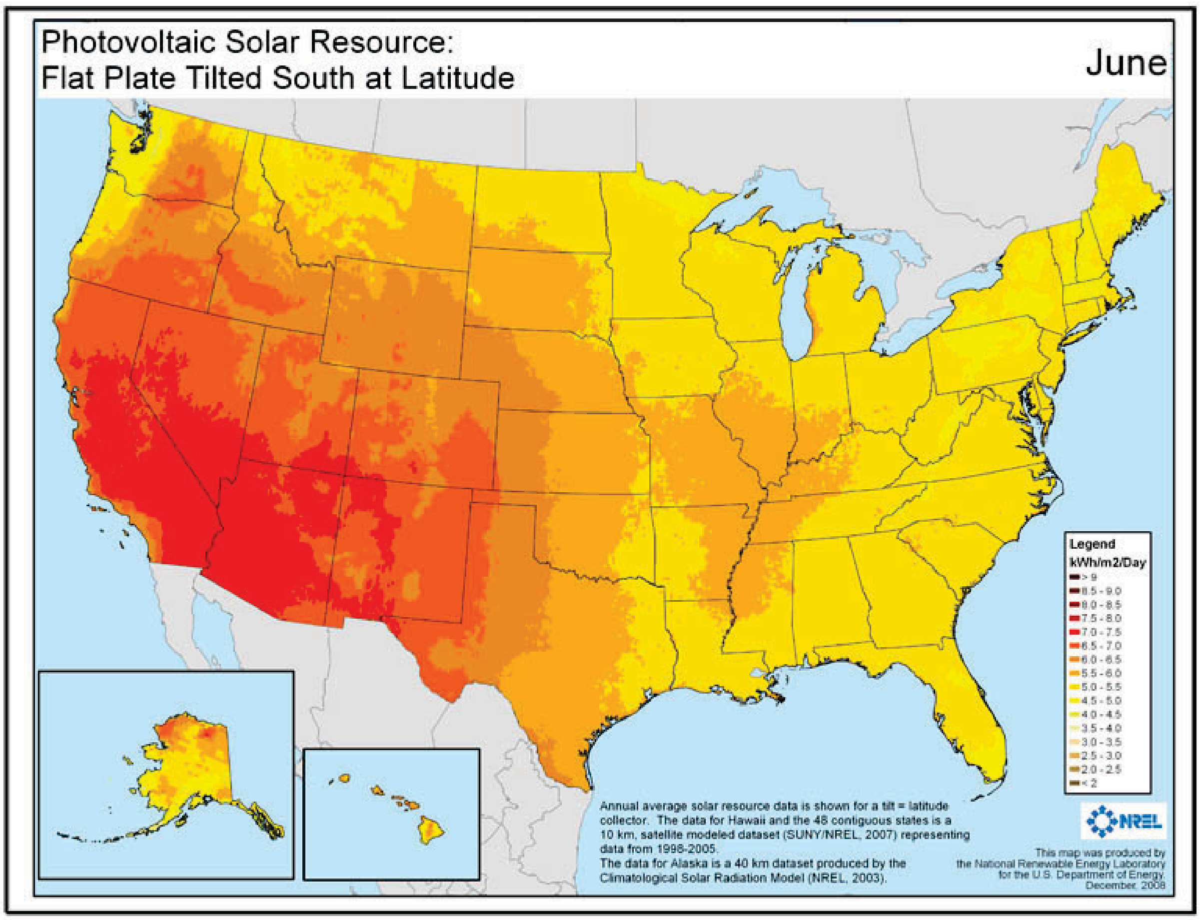


Figure 6-18. Average June horizontal flat plate solar radiation map of the U.S. (NREL 2012).

Figure 6-18 illustrates why the impacts of pavement albedo (with all other factors held constant) would be far greater in Phoenix compared to cities such as Chicago or New York. To some degree, this is reflected in the literature as a number of papers on the UHIE have been published focusing on Phoenix and on cities in California. On the other hand, there are also papers discussing the effectiveness of cool roof and pavements in Chicago (Mackey, Lee, and Smith

2012), New York City (Rosenzweig et al. 2006), and for many other regions in the U.S. (Taha, Konopacki, and Gabersek 1999), all of which demonstrated a reduction in their UHIE through the use of reflective surfaces. As another example, Li, Bou-Zeid, and Oppenheimer (2014) modeled a heat wave that occurred in the Washington-Baltimore metropolitan area in June 2008 showing that more reflective roofs and pavements could have helped mitigate some of the UHIE. This illustrates the importance of considering location and local climatic conditions, including singular events such as heat waves, when evaluating the impact of pavement albedo on the UHIE.

It is also apparent in the literature that simply reflecting more light off of paved surfaces in an urban environment may have unintended negative impacts. For example, a study modeling the impact of increasing the albedo of impermeable surfaces from 0.15 to 0.5 found that although this strategy was the most effective at reducing urban surface and near surface air temperatures, at periods of high sun (noon) it had a negative impact on modeled human comfort (Lynn et al. 2009). This is because although the pedestrian on a higher albedo surface experiences a reduction in thermal radiation due to the reduced pavement and near surface air temperatures of the high albedo surface, the increase in reflected solar flux is greater resulting in an increase in the effective temperature experienced.

In another example, a modeling study investigating reflective pavements (albedo of 0.5) found that although a small decrease in urban air temperature could be realized, high pavement reflectivity actually contributed to increased building energy use for summer cooling, especially for pre-1980 buildings constructed in Phoenix in areas having certain urban configurations (Yaghoobian and Kleissl 2012). In an associated press release, the authors state that the biggest increase in cooling energy use would be incurred in office park settings with older mid-rise office buildings that have large expanses of windows and do not have solar-control coatings (UCSD 2012). The press release also stated that this additional cooling energy could potentially be offset by utilizing the additional natural reflected lighting as one watt of daylight replaces up to two watts of fluorescent lighting, which could reducing electrical energy consumption and also cooling needs by reducing interior heating from the artificial lights. The authors concluded by stating further study is needed to quantify these potential savings (UCSD 2012).

Experimental results from Li (2012) conducted on a paved test site in Davis, California found that a more reflective surface reduced the paved surface temperature by 27 °F (15 °C) as compared to a less reflective surface on a hot summer day; however, it was also observed that the temperature of an adjacent painted wall (albedo around 0.3) was actually 5 °F (3 °C) warmer for the reflective versus the non-reflective pavement surface. The basis of these observations is found in the heat flow schematic presented in figure 6-16. Raising pavement albedo increases the short-wave flux incident on a nearby vertical surface, such as a wall or vehicle, but decreases the long-wave flux incident on the surface. The change in the surface's overall radiative heat gain will depend on the albedo and thermal emittance of the vertical surface.

In this context, some recent studies have questioned the overall regional and global climate impact of using highly reflective surfaces in urban areas, including roofs and pavements. Although these studies universally acknowledge that increasing the average urban albedo will reduce local air temperatures, the broader regional and global climate impacts are less clear. For example, Jacobson and Ten Hoeve (2011) used global climate simulations to conclude that white roofs would be expected to reduce local urban temperatures, but may result in a "net effect on globally-averaged temperatures that may be warming," although it is stated that a great amount of uncertainty still exists regarding this conclusion. The biggest effects were due to a decrease in cloud cover resulting from the stabilization of air masses over the city, which in turn reduced cloud cover and precipitation away from the urban areas. This had the net result of increasing the incidence of solar radiation in the affected regions and decreasing soil moisture.

In another paper, Millstein and Menon (2011) used a fully coupled regional climatic model and compared the results to previous work conducted at the Lawrence Berkeley National Laboratory (LBNL) that did not include coupling of the land-surface model to the atmospheric circulation scheme. The results found increased regional variability, characterized by a general cooling of the urban areas investigated but with some regional warming influences in rural areas that in some cases were significant. Even with the increased variability, the researchers concluded that the improved modeling showed greater normalized temperature reductions overall compared to past studies, although broader climatic effects were acknowledged. As climatic models continue to improve, the potential trade-offs between urban and surround rural areas, as well as broader regional and global effects, will be better understood and improved decisions can be made regarding the circumstances (e.g., climate, location, surface hydrology, emission profiles, chemistry transport) in which increasing the surface albedo of a city can have a net positive impact.

The majority of the analyses of the UHIE and the role of pavements has focused primarily on pavements with high albedo. To fully understand the impact of pavement strategies to address the UHIE, all pavement life-cycle phases must be considered, including material acquisition and pavement construction, while factoring in the longevity of the pavement treatments specifically directed at increasing albedo. A research project is currently underway, funded by the California Air Resources Board and the California Department of Transportation, to perform an LCA for implementation of high albedo pavement strategies in different cities and climate regions compared to normal practices (CARB 2013).

In summary, the degree to which pavement albedo contributes to the UHIE depends on a variety of local variables. All things equal, the surface of pavements with lower solar reflectivity (albedo) will become hotter when exposed to solar radiation. But the complexity of the urban fabric and local conditions make it difficult to ascertain what the overall impact of pavement albedo is on the development of the atmospheric UHIE. Further, the impact of reflective pavements on the overall energy balance of nearby buildings is yet to be resolved. Research strongly suggests that localized cooling can be achieved in certain urban areas by increasing average albedo of roofs and pavements, but the broader regional and global climatic impacts of uniformly increasing urban albedo are unclear. The variation in cooling potential will depend on local urban properties such as pavement area, shading, and building height, as well as on regional weather patterns.

As a result, cooling potential may be negated in locations where complex interactions exist between urban heating and cloud formation, which leads to decreased cloud formation as urban albedo increases. This effect could also result in some downwind rural areas experiencing low levels of surface warming due to increases in urban albedo. Climatic modeling efforts are being directed at developing a better understanding of the context in which the application of cool pavement strategies is justified for specific urban areas.

Radiative Forcing

In addition to UHIEs, there is a growing body of knowledge that relates planetary solar reflectance to global warming as a result of changes in radiative forcing. The concept of radiative forcing is fairly straightforward, but in practice it is a very complex phenomenon. A complex and complete definition of radiative forcing was presented by the Intergovernmental Panel on Climate Change (IPCC 1996), stating that radiative forcing is "the change in net (down minus up) irradiance (solar plus irradiance long-wave; in W•m^{-2}) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values." A common and more accessible definition is that radiative forcing is the difference between the radiant energy received by the earth and the energy radiated back into space (Wikipedia 2014).

Basically, solar energy is constantly flowing into the atmosphere on half of the Earth's surface. Some of this sunlight (about 30 percent) is reflected back to space and the rest is absorbed by the planet. Like any warm object in cold surroundings, some of the absorbed energy is radiated from the Earth back into space as long-wave (thermal infrared) radiation. A positive forcing (more incoming energy than outgoing) warms the system, while negative forcing (more outgoing energy than incoming) cools it. The factors contributing to radiative forcing are many, complex, and often interact with each other. They including the natural incoming solar irradiance (which changes with solar activity), atmospheric aerosols, GHGs, cloud microphysics, and changes to the land surface (Cubasch et al. 2013). The latter two categories (changes to the atmosphere and land surface) are influenced by both natural processes and human activities. The contribution of pavements to radiative forcing lies primarily in changes to the land surface by changing surface albedo, as illustrated in figure 6-19 (Cubasch et al. 2013).

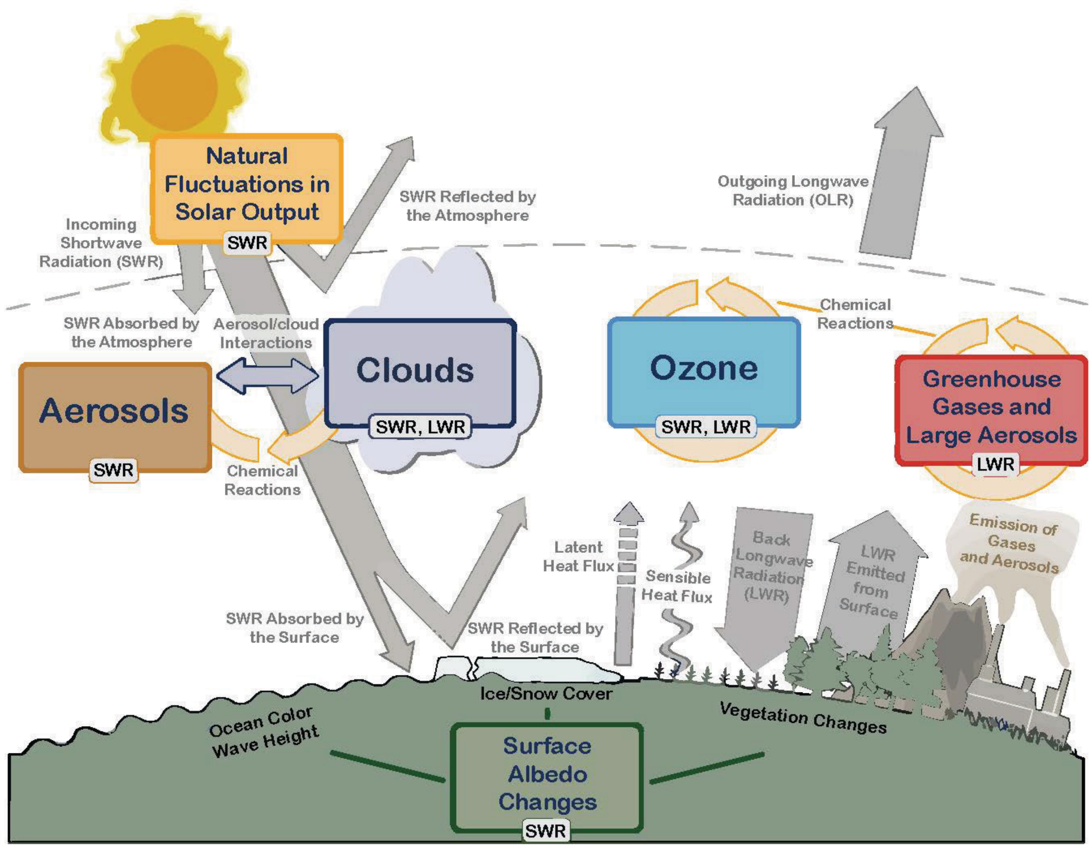


Figure 6-19. Illustration of the main drivers of climate change (Cubasch et al. 2013).

Although much of the work conducted on the contribution of pavements to radiative forcing has focused on urban areas (since those are most affected by human development), radiative forcing is considered in addition to the UHIE because it is a factor wherever the land surface albedo has been changed through human activity. Multiple studies have used modeling to demonstrate how increasing roof and pavement albedo (increasing reflection of sunlight to space) can reduce urban solar heat gain, lower urban surface temperatures, and thereby decrease both convection and thermal radiation of heat into the atmosphere (Akbari, Menon, and Rosenfeld 2009; Millstein and Menon 2011; Akbari and Matthews 2012). Related work concluded that the global warming mitigation effect of increasing the average albedo of urban environments worldwide by 0.1 could be on the order of 49 billion short tons (44 Gt) of CO_2 (Menon et al. 2010). Roughly 55 percent of this benefit (27 billion short tons [24 Gt]) would result from increasing the albedo of roofs by at least 0.25, whereas the remainder would derive from increasing the albedo of pavements by at least 0.15 for roadway and parking surfaces. These prospective savings equate to almost an entire year's estimated anthropogenic CO_2e emissions (roughly 50 billion short tons [45 Gt] CO_2e). Follow-up work, focusing on the continental U.S. and using a fully coupled regional climatic model joining the land-surface model to the atmospheric circulation scheme, found increased regional variability but concluded that overall even greater impacts could be achieved by increasing the average urban albedo of horizontal surfaces (Millstein and Menon 2011).

On the other hand, conclusions drawn in another paper found that an increase in average surface albedo will result in less local cloud cover, thus actually increasing local incident solar radiation and potentially contributing to global warming (Jacobson and Ten Hoeve 2011). Further, that study suggested that reflected short-wave solar radiation from higher albedos for white roofs (changes in pavement albedo were not considered) will result in additional heating of black and brown soot particles in the atmosphere resulting in increased localized atmospheric warming, although this effect was considered minimal and thus requires additional investigation to determine if it is of significance.

In closing, the use of high albedo pavements to provide global cooling through radiative forcing is uncertain. If there is no interaction with clouds, more reflective pavements could provide important global cooling benefits. However, once feedback to cloud formation is accounted for, the answer is not definitive and may depend on whether pavement albedo is universally increased in all locations, or whether high albedo pavements are constructed in select locations where effectiveness is demonstrated. The question of whether global changes in pavement albedo can provide global cooling benefits remains an active area of research.

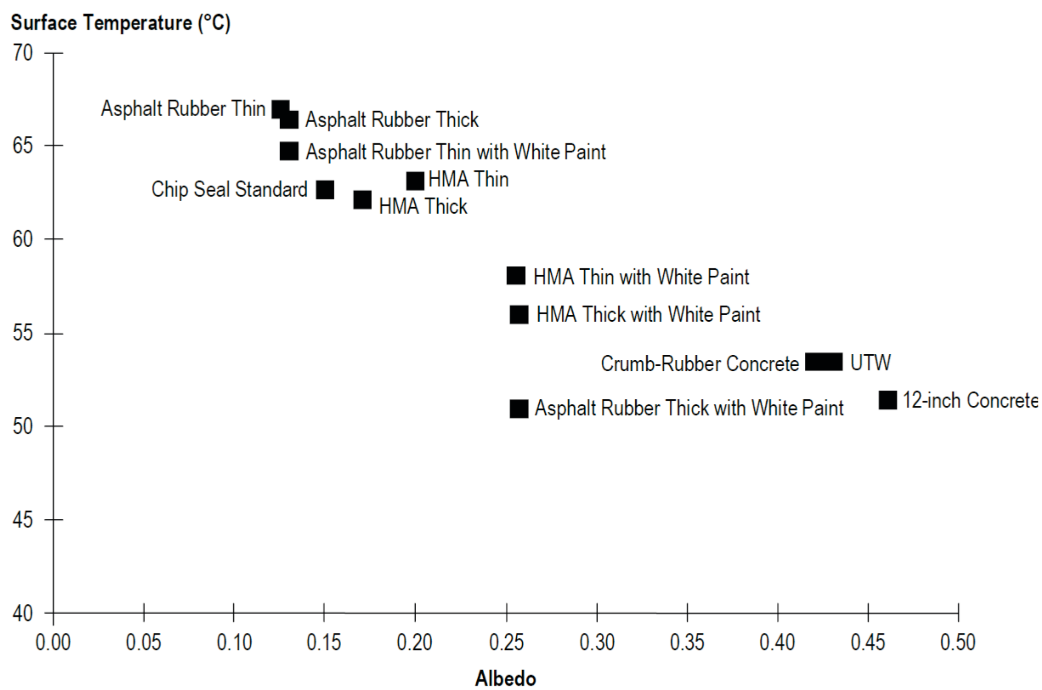
Stormwater Warming

Hotter, impermeable pavements also hold the potential to warm stormwater, which may affect sensitive biological communities (e.g., trout) in the receiving waters if their thermal regimes are altered by the stormwater runoff (NRDC 1999; OEC 2007; Jones and Hunt 2007). This is a particular issue in locations that receive significant rainfall during hot seasons and where heated stormwater is not cooled before entering the sensitive area, but should not be an issue in climate regions that have little or no summer rainfall. Fully permeable pavements (discussed earlier) can be used to mitigate stormwater heating if designed to retain water before releasing it into the environment.

Pavement Type and Thermal Performance

From the preceding discussion. it is clear that the solar reflectance of paved surfaces can be a strong contributor to pavement warming and that this warming has the potential to impact the UHIE in those built environments that experience hot weather and are large enough to generate a heat island. Furthermore, pavement reflectance may also contribute to overall global warming through radiative forcing although, as noted, additional research is needed to more clearly demonstrate that effect. In this section, studies specifically focused on various pavement types are reviewed.

Typical albedo values range from 0.04 to 0.16 for asphalt pavements and from 0.18 to 0.35 for concrete pavements (Pomerantz et al. 2003), although the albedo of new concrete can be as high as 0.69 (Marceau and VanGeem 2007). These albedo values are correlated to the color of the pavement whether it is asphalt (black) or concrete (grey or white), but the exposure of aggregates at the surface also plays a role in determining albedo. New asphalt pavements are quite black and have little exposed aggregate and thus have low albedos (less than 0.10). This will result in high pavement surface temperatures during hot, sunny periods when not shaded by trees or buildings (Li et al. 2013). With pavement albedo values around 0.10, extreme high pavement surface temperatures of 158 to 176 °F (70 to 80 °C) have been measured on hot summer days in mid-afternoon in Phoenix, Arizona, and up to 158 °F (70 °C) for similar pavements in Davis, California (Li et al. 2013). Figures 6-20 and 6-21 illustrate how pavement surface temperatures were greatly affected by pavement albedo both in Phoenix (Cambridge Systematics 2005) and in Davis (Li et al. 2013), respectively.



Source: Redrawn from data by Jay S. Golden and Kamil Kaloush, SMART Program, and Arizona State University, July 24, 2004.

Figure 6-20. Surface temperature and albedo for selected types of pavements in Phoenix, Arizona (note: UTW = ultra-thin whitetopping) (Cambridge Systematics 2005).

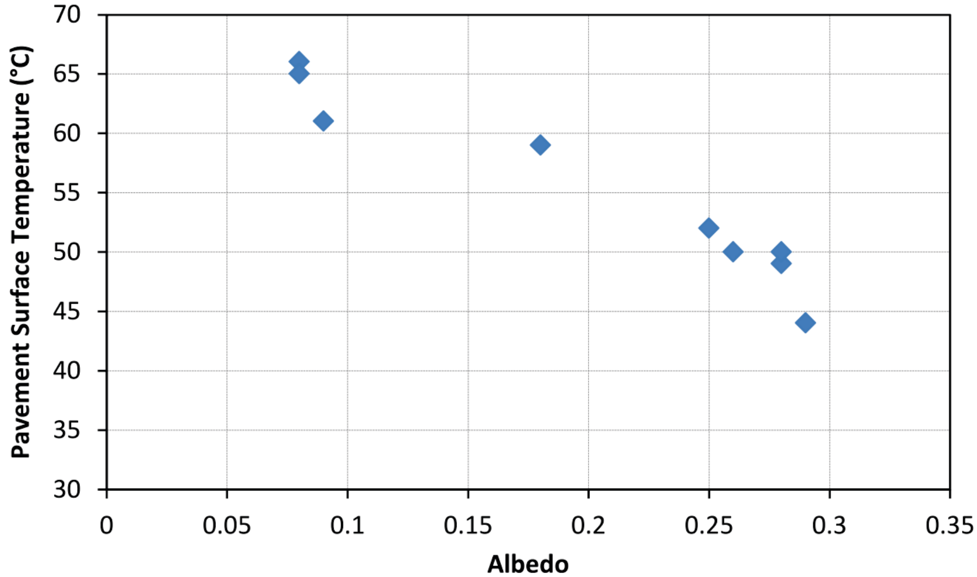


Figure 6-21. Effect of albedo on pavement surface temperature in Davis, California (16:00 9 July 2012) (Li et al. 2013).

New concrete pavements are typically light in color as long as no pigments are added. Even though over 90 percent of all paved surfaces in the U.S. are asphalt (NAPA 2013), in urban areas it is not uncommon to find a higher level of concrete in use as a paving material (14 to 20 percent of all paved surfaces including sidewalks [Levinson and Akbari 2001]). Work by Levinson and Akbari (2001) characterized the albedo of various concrete constituents (cement, sand, and coarse aggregate) and of the concrete produced from combinations of those constituents, and found that the albedo of unworn/unsoiled concrete was largely controlled by the albedo of the cement and sand, with cement albedo having a disproportionately strong influence on the albedo of concrete. Similar conclusions were made by Marceau and VanGeem (2007), who found that the solar reflectance of the cement has the largest single effect on concrete albedo compared to other constituent materials. Since the color of cement is largely affected by the iron content, cements being low in iron generally are lighter in color. For example, cement with a reported iron oxide content of 3.5 percent had a measured albedo of 0.32, whereas the albedo of a white cement with a reported iron oxide content of 0.2 percent had an albedo of 0.87 (Levinson and Akbari 2001).

The reflectance of concrete can be either enhanced or diminished depending on the type and color of SCMs or pigments added to the concrete. Marceau and VanGeem (2007) studied this in detail and found that fly ash can have an albedo either less than or greater than cement, and thus can darken or lighten the concrete. Slag cement on the other hand has a solar reflectance that is much higher than ordinary portland cement or fly ash and thus its use results in higher albedo concrete. The white cement included in the study had the highest albedo of any of the cementitious materials and thus could be used to create concrete with an albedo of 0.69. Further, it is not uncommon that pigments are added to concrete to change its color for aesthetic affect, almost always resulting in a decrease in albedo. For example, it is known that “lamp black” is routinely added to municipal concrete in areas of California to darken it (significantly reducing its albedo) so it will better match the color of existing concrete that may be several decades old.

Interlocking concrete pavers can also be manufactured to have high albedo. For example, the City of Chicago used highly reflective permeable concrete pavers featuring a photocatalytic surface to keep the pavers clean on the Cermak Road reconstruction project, a high-profile "green" pavement (CDOT 2013).

A recent study evaluated a number of different pavement types to investigate their thermal performance and how they interact with the surrounding environment (Li 2012; Li et al. 2013). A total of nine 13.1 ft (4 m) square instrumented asphalt, concrete, and interlocking concrete paver pavement sections were constructed and monitored for over a year. Climate and pavement temperature monitoring over the course of the year clearly showed that peak pavement temperature was strongly correlated to albedo, as shown previously in figure 6-21. Furthermore, the near-surface air temperature measured 2 inches (50 mm) above the surface was higher for the dark asphalt pavement compared to the conventional concrete pavement and conventional concrete pavers. As stated by Li et al. (2013), this increase in near-surface air temperature is thought to decrease the comfort level of human beings (especially the young) and contribute to the formation of ground-level ozone. Typical near-surface air temperatures for the four seasons in Davis, California are shown in figure 6-22.

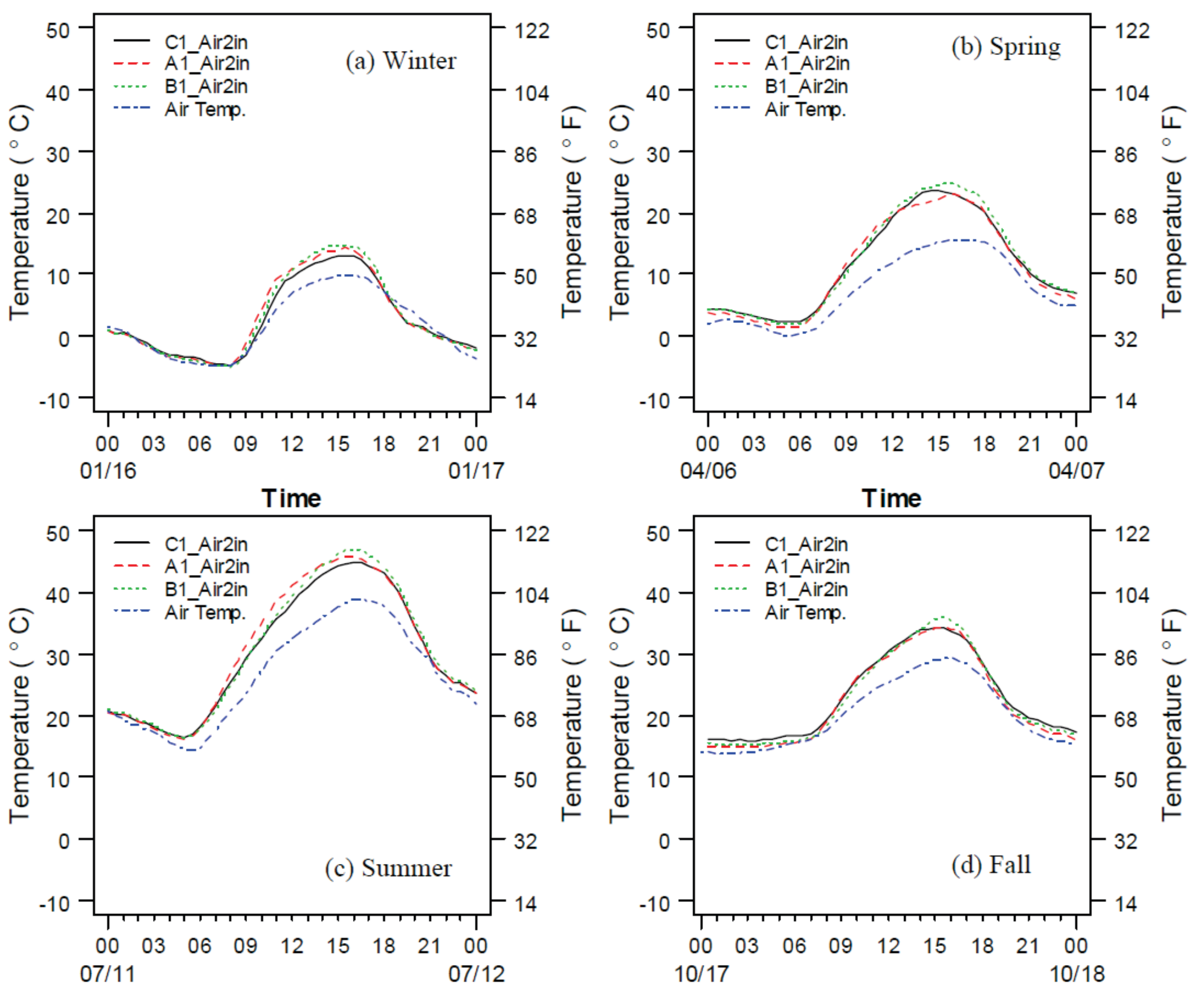


Figure 6-22. Near-surface air temperatures of different pavements measured 2 inches (50 mm) above the surface (Li 2012).

These results clearly demonstrate the effect of convection, in which heat from the pavement surface warms the air at the boundary. Based on this alone, it is understood why the use of highly reflective pavements exposed to sunlight will reduce pavement temperatures and lessen the temperature of the air immediately above them compared to lower albedo pavements.

Nevertheless, as discussed previously, the effect of albedo on the urban environment is more complex. This is partly explained by figure 6-23, where q_ref is reflected short-wave solar radiation; q_em is emitted long-wave radiation; q_radio is radiosity which is equal to q_ref + q_em; and q_conv is convective heat.

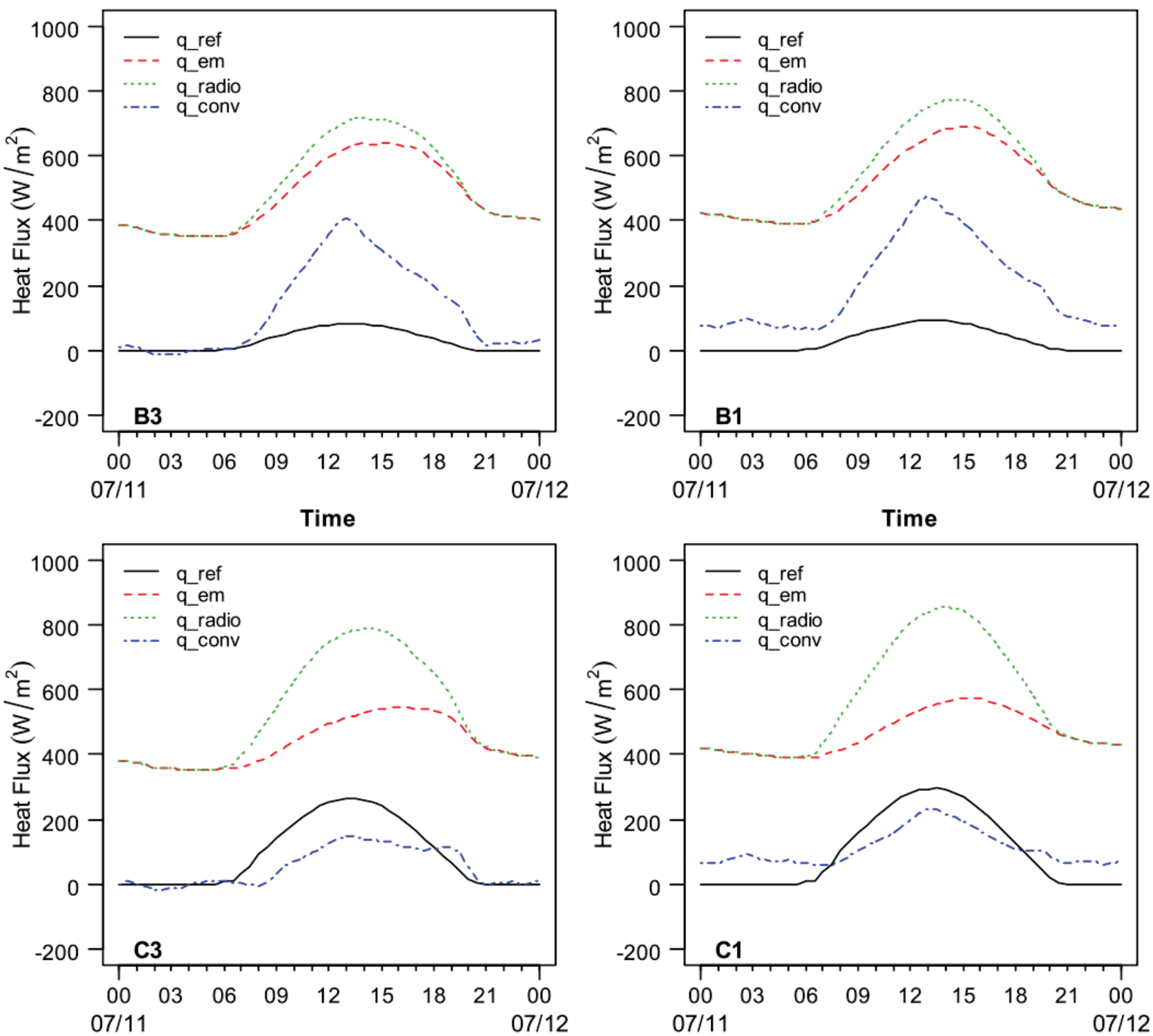


Figure 6-23. Heat flux from pavement surfaces for 1 full day during July 2012 (Li et al. 2013).

As shown in figure 6-23, the convective heat and emitted long-wave radiation is highest for pavements with the lowest albedo (B1, B3). Pavements with high albedo (C1, C3) will absorb the least solar radiation and thus have the highest reflected short-wave solar radiation. This results in higher pavement and near-surface air temperatures in the low albedo pavements, but in some cases the total radiosity is higher with the high albedo pavements. This is reflected in figure 6-23 where the conventional concrete (C1) has the highest radiosity of the four sections. Reflected short-wave solar radiation transmitted into space contributes to negative radiative forcing. However, if it is absorbed by nearby buildings or cars it can result in increased cooling energy needs or if by humans it can increase discomfort, modeling of which has not been validated. Research is currently underway modeling the effects of light and energy reflected from pavements on the energy use for interior lighting of nearby buildings, in addition to energy use for cooling and heating.

But the broader impacts of this are far less clear. For instance, 33 feet (10 m) of air will absorb only 1.6 percent of reflected short wavelength sunlight, but will absorb 22 percent of emitted long wavelength thermal radiation. Thus, at a path length of 0.6 miles (1 km), absorption is 9 percent and 61 percent, respectively. Hence, emitted long wavelength thermal radiation heats the air much more effectively than reflected short wavelength radiation. Further, the albedo of the surface of a wall, vehicle, or even the clothing worn by a person has a large impact on the radiative heat gain from reflected light. Radiosity is thus not equivalent to radiative heat gain, and thus all these factors have to be accounted for when considering increased cooling needs for buildings or human comfort. Consequently, the overall influence of reflected solar radiation is uncertain and needs further evaluation.

Permeable surfaces (porous asphalt, pervious concrete, and permeable pavers) show trends similar to impermeable surfaces regarding the impact of albedo on pavement surface temperature and near-surface air temperature when the pavement is dry. The addition of surface voids in permeable surfaces decreases albedo as well as thermal conductivity and specific heat capacity, and thus it is common for the peak surface temperature of pervious pavement alternatives to be higher than those of comparable impervious pavements if the pavement is dry (Li, Harvey, and Jones 2013). Independent of albedo, the effects of the lower thermal conductivity and lower specific heat are to trap heat nearer the surface and resulting in more rapid heating. For the same reasons, once solar radiation diminishes at the end of the day, permeable surfaces also cool more rapidly and have less heat energy to emit than impermeable surfaces (Li, Harvey, and Jones 2013).

If there is a source of near surface water, permeable pavements will undergo evaporative cooling that has been found to significantly reduce peak surface temperatures. Under these conditions, even though comparable permeable surfaces would have a lower albedo, the peak surface pavement temperature and near-surface air temperature is lower than the conventional impermeable pavement counterparts (Li, Harvey, and Jones 2013).

An additional complicating factor is that the solar reflectance of both asphalt and concrete pavements changes over time. For example, at the time of initial construction, a dense-graded asphalt pavement will have a very low albedo (typically below 0.05), but over time that asphalt surface oxidizes and becomes lighter, increasing the albedo. In addition, the asphalt film on the surface of the pavement wears away under traffic, exposing the underlying coarse aggregate and potentially increasing the solar reflectance, particularly if a light-colored aggregate was used in the mixture.

Similarly, as concrete is abraded under the action of traffic, the albedo of the coarse aggregate becomes more important; if the aggregate is light in color, the albedo may not be negatively impacted and may even increase, but if a dark coarse aggregate is used, the surface will become less reflective. Additionally, even the lightest colored concrete pavement will become soiled over time from road grime, oil, and tire rubber, reducing the albedo. Figure 6-24 illustrates this concept, qualitatively showing the change in solar reflectance (albedo expressed as a percentage) of typical concrete and asphalt pavements over time. This figure shows that the reflectance of the two surfaces gradually begin to approach one another. There is a study underway to better characterize changes in pavement albedo over time (NCPTC/NCAT 2013).

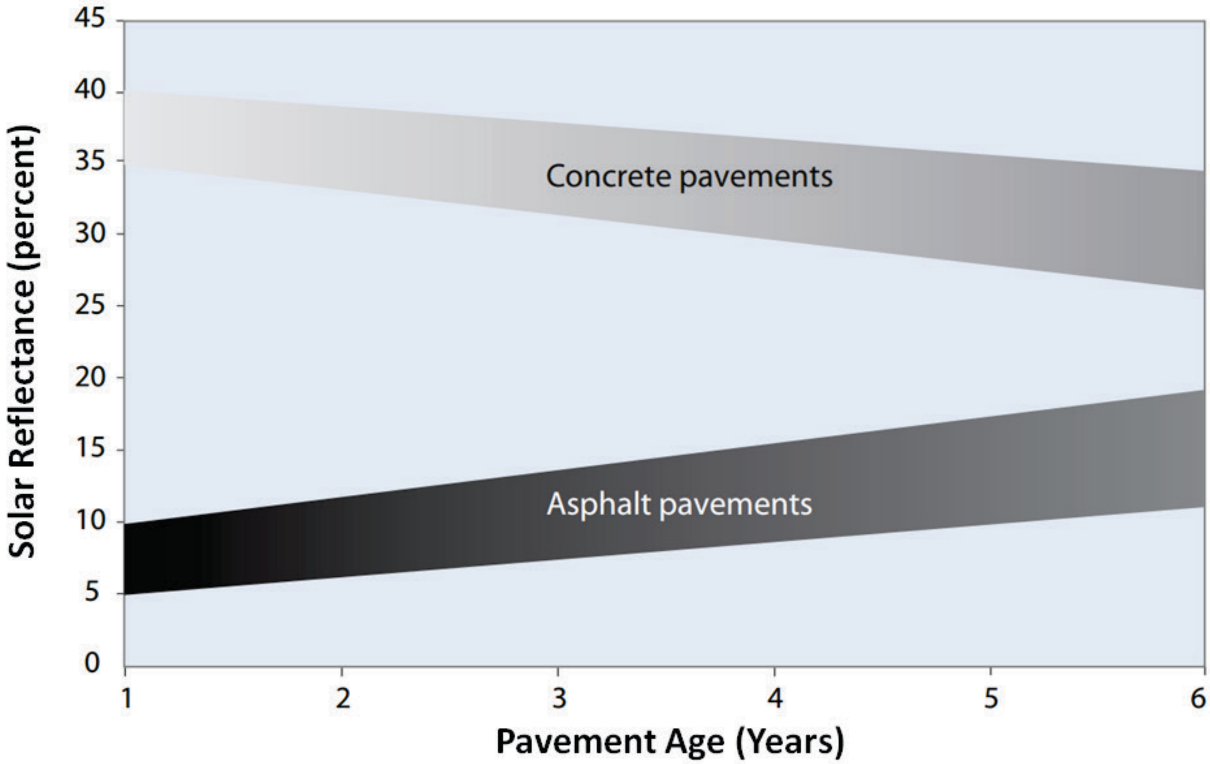


Figure 6-24. Typical pavement solar reflectance of conventional asphalt and concrete pavements over time (EPA 2008).

Another factor to consider regarding albedo is the application of pavement maintenance and rehabilitation treatments. In general, any treatment that changes the color of the pavement surface will impact the albedo. With regards to asphalt pavements, surface treatments can either decrease or increase the albedo, depending on the nature of the treatment. Those that leave a lot of asphalt binder exposed, such as conventional fog seals, slurry seals, sand seals, and microsurfacing, will have a tendency to darken the surface and reduce the solar reflectance. These treatments are a common application to "weathered" asphalt surfaces, the very surface that has increased solar reflectance due to oxidation. It is the tendency of many maintenance engineers to "restore" a weathered asphalt surface through these treatments that yields a "like new" surface that may adversely affect solar reflectance if the project is located in an area where UHIEs are a concern.

Decreasing the reflectivity of existing asphalt pavements with maintenance treatments such as fog seals can potentially increase the risk of rutting because of increased pavement temperatures, particularly in those locations with hot climates and heavy, slow-moving truck traffic. Reducing the near surface temperatures in asphalt pavements through the use of higher albedo surface materials—such as chip seals with more reflective aggregate or highly reflective surface coatings—can potentially reduce the risk of rutting by lowering peak pavement temperatures.

Such reflective coating may also help reduce aging in the asphalt binder, which in turn can reduce the probability of top-down cracking and thermal cracking in the winter months (Pomerantz, Akbari, and Harvey 2000). It is noted that the stiffening of an asphalt binder that occurs as it ages helps resist rutting, so a balance between reducing the risk of rutting and increased risk of cracking needs to be struck.

Where solar reflectance is important, treatments that can lighten the surface, such as chip seals using light-colored aggregate or pigmented/colored surface seals, should be favored (Nichols Consulting Engineers 2012). Regarding the latter, pigmented/colored surface seals continue to evolve with a number of proprietary materials becoming available for coating pavement surfaces that are designed specifically to reduce the pavement surface temperature not only through using a lighter color, but actually preferentially reflecting infrared radiation through the use of infrared reflective pigments (Wan et al. 2009; Synnefa et al. 2011; Santamouris et al. 2012). The long-term durability of pavement coatings and the environmental impacts of their manufacture have not yet been fully documented and are currently being evaluated.

The albedo of concrete pavement can be changed by diamond grinding, which removes a thin layer of the surface to restore ride quality, while also removing tire rubber, oil drippings, and other deposited materials that may have darkened the pavement surface. Figure 6-25 shows a typical diamond ground surface in which the coarse aggregates have been exposed. If the coarse aggregate is light colored, diamond grinding will likely increase the solar reflectance. On the other hand, grinding a concrete pavement made with dark coarse aggregates may reduce albedo.

For both asphalt and concrete pavements, rehabilitation featuring the use of overlays will have obvious impacts on the solar reflectance of the resulting surfaces. All the same considerations exist for asphalt and concrete overlays as exists for newly constructed asphalt and concrete pavements.

Figure 6-25. Diamond ground concrete pavement surface.

Other Strategies to Reduce Pavement Temperatures

In addition to solar reflectance, there are other pavement factors that contribute to reducing the temperature of pavement surfaces. A few of these are highlighted below:

- Permeable pavements (discussed previously), in addition to their capability of providing a mechanism for stormwater management, are known to contribute positively to a reduction of the peak pavement temperature if near surface water is available for evapotranspiration (Tran et al. 2009). This is well documented in a recent study showing that permeable pavements (including concrete, asphalt, and concrete pavers) under wet conditions have reduced surface temperatures compared to impermeable pavements of similar solar reflectance (Li et al. 2013). This was largely the result of evaporative cooling, which is dependent on the availability of near surface water and a high rate of evaporation. The benefit disappears once the pavement dries out. Combining high reflectance with a permeable surface was found to be especially effective.
- There are coatings that can be applied to a pavement surface that do not actually change the visible color of the pavement, but instead only increase the reflectance of the near infrared spectrum (Kinouchi et al. 2004; Wan et al. 2009). These can create a dark pavement with a relatively high albedo, thus reducing the pavement surface temperature. These are still experimental in nature and their effectiveness and durability have not been fully established.
- Strategies that use shade to minimize exposing pavements to direct sunlight, particularly through vegetation, is a well-practiced strategy employed in many urban environments to mitigate the UHIE (McPherson 1994; Akabari, Pomerantz, and Taha 2001; EPA 2003; Nichols Consulting Engineers 2012). Solar panels have also been used to provide shade to pavements (particularly in parking lots) while also providing a renewable source of electrical energy.
- As described earlier, the use of vegetated permeable pavers in parking and low-volume traffic areas is an innovative approach to addressing both stormwater management and the UHI effect (EPA 2008; Nichols Consulting Engineers 2012). These pavers are made of plastic, metal, or concrete lattices that provide support to traffic while allowing grass or other vegetation to grow in the substantial voids space.

Strategies for Improving Sustainability

Practices available to pavement managers, designers, and specification developers that can be used to reduce peak pavement temperatures and might be used to address UHI issues are provided in table 6-6.

Future Directions and Emerging Trends

A number of pavement technologies continue to emerge that have the potential to address or reduce the UHIE, as listed below:

- Photocatalytic cements and coatings. Certain forms of titanium dioxide are known to be photocatalysts, using solar energy to accelerate chemical reactions without being consumed in the process. In the presence of sunlight, organic materials such as dirt components (soot, grime, oil, and particulates), biological organisms (mold, algae, bacteria, and allergens), airborne pollutants (VOCs, NOx and SOx), and chemicals that cause odors are all decomposed by the photocatalytic effect (Burton 2011). Not only does titanium dioxide help to reduce air pollution, but it can help maintain a high albedo for pavements by removing surface contaminants that typically darken the concrete surface (PCA 2013). This technology is in the earliest phases of implementation, being employed both in white cements and in concrete pavers, as well as in coatings for asphalt pavements. Its long-term effectiveness and the environmental footprint of producing these materials are still being investigated.

- Alternative binders. Resin-based binders (such as clear tree resins) are being used in place of the typical black petroleum-derived asphalt binder, which allows the pavement to have the natural appearance of the aggregates used in the mixture. Resin-based binders have been used to construct pavements for hiking and biking trials, but have not been used for highway applications. Aside from resin-based binder, a variety of colorless and reflective synthetic polymer binders are available that have been used with light-colored aggregates, typically for surface courses for sports and leisure areas (Tran et al. 2009).
- Reflective chip seals. The development of exposed aggregate surfaces for asphalt pavements with light-colored aggregates that are more suitable to urban environments than current chip seal technologies hold promise and should be further investigated.
- Coatings and pigments. There are a number of coatings that increase the solar reflectance of an asphalt surface, either by changing the color of the surface through the addition of a thin layer and/or by preferentially increasing the reflectivity of the surface in the near infrared spectrum (Kinouchi et al. 2004; Wan et al. 2009). The long-term effectiveness of such coatings on high-traffic facilities has not been demonstrated. Similarly, there have been studies investigating the use of pigments to lighten the asphalt binder and thus increasing solar reflectance, but these have only been used on a limited basis and their long-term effectiveness has not been established.

Table 6-6. Summary of considerations to address UHIE issues and potential trade-offs.

UHIE Objective	Sustainable Approach and Trade-offs	Economic Impact	Environmental Impact	Societal Impact
Improve Understanding of Pavement Solar Reflectance and the UHIE	Systematically collect data on the solar reflectance of various pavement types at various ages	Initial cost for conducting data collection and research effort	Better information will support better decision making improving the environmental and societal impacts	Improve understanding of pavement solar reflectance and the UHIE
	Improved modeling of pavement solar reflectance and the impact on the surface, near surface, and atmospheric UHIE	Initial cost for conducting research and modeling effort	Better modeling capabilities will support better decision making improving the environmental and societal impacts	Wise use of available funding for global warming solutions requires informed decisions
Utilize a Robust, Repeatable Methodology to Assess Pavement Solar Reflectance	Requires a concerted effort by the pavement community to establish standards for specifying and assessing pavement solar reflectance	Initially high, but over time low once procedures are established	Improved as a standard approach for assessing solar reflectance will increase implementation	Improved as a standard approach for assessing solar reflectance will increase implementation
Increase the Albedo of New Pavement Surfaces (where it is determined to be beneficial)	For concrete pavement, use light colored cement	White cement is more costly than typical grey portland cement	Can be negative if using white cement as it has a higher production environmental footprint	Improved human comfort
	For concrete pavement, use light colored SCMs	Generally less expensive or cost neutral	Improved as reduced need to landfill industrial waste	Improved as a potential waste is beneficially used
	For asphalt pavement, apply high albedo coatings, such as exposed light colored aggregate treatments such as chip seals or specialized coatings	Initial and long-term costs dependent on cost of material and frequency of applications required	Specialized coatings may have high environmental footprint	Improved through reduced UHIE
	Employ permeable pavement technologies where applicable (water must be available during critical UHIE periods)	Permeable pavement technologies can be cost neutral to slightly increased cost	Reduced environmental footprint and improved social benefit through reduced UHIE and improved stormwater management	Reduced environmental footprint and improved social benefit through reduced UHIE and improved stormwater management
	Use high albedo interlocking concrete pavers where applicable	Typically more costly than conventional pavement alternatives	Reduced environmental footprint and improved social benefit through reduced UHIE	Reduced environmental footprint and improved social benefit through reduced UHIE
	Use vegetated pavers in low-volume traffic and parking areas	Less expensive than conventional pavement alternatives	Reduced environmental footprint and improved social benefit through reduced UHIE and improved stormwater management	Reduced environmental footprint and improved social benefit through reduced UHIE and improved stormwater management

Table 6-6. Summary of considerations to address UHIE issues and potential trade-offs (continued).

UHIE Objective	Sustainable Approach and Trade-offs	Economic Impact	Environmental and Societal Impact
Maintain High Albedo Over Time (where it is determined to be beneficial)	Use light colored aggregates in concrete and asphalt mixtures	Cost neutral to increased cost depending on local availability	Lower UHIE over time but may have increased environmental and societal impact if aggregate not locally available
	Use high albedo surfaces, including reflective coatings, thin overlays and light colored chip seals, to maintain asphalt pavements	Cost neutral to significantly increased cost depending on local availability of reflective aggregates and proprietary nature of coating	Lower UHIE over time but may have increased environmental and societal impact if aggregate not locally available or if proprietary coatings contain environmentally damaging constituents
	Use diamond grinding to expose light colored aggregates if present for concrete pavements	High initial cost if not done to also improve ride quality	Lower UHIE, while also improving ride quality and reducing tire-pavement noise provides environmental and societal benefits
	Use photocatalytic surface on concrete pavement to reduce soiling	High initial cost	Lower UHIE over time but may have increased environmental and societal impact if the photocatalyst has large environmental footprint
	Use cleaning program to maintain high solar reflectance of high albedo surfaces	Increased maintenance cost	Trade-off between improved UHIE and energy and water use for cleaning Lower societal impacts through reduced UHIE
	Concrete overlays on concrete and asphalt pavements	High initial cost, but potentially reduced long-term expenses depending on design and application, and also depends on cost of cleaning to maintain albedo	Lower UHIE and improved structural capacity over time but may have increased environmental and societal impact due to materials production and construction environmental impacts, traffic delays and materials cost.
Employ System-wide Strategies to Reduce Pavement Temperatures Where it is Determined to be Beneficial	Use vegetation, trees and solar panels to shade pavements as appropriate	Slightly higher initial cost	Lower UHIE plus the multiple environmental and social impacts of increasing plant density or low impact energy production in an urban environment

- Enhanced data and thermal modeling. A number of efforts are underway to better characterize the contribution of pavements to the UHIE, as well as the broader issue of radiative forcing (e.g., NCPTC/NCAT 2013 and initiatives undertaken by the Heat Island Group at Lawrence Berkeley National Laboratory and by the Global Institute of Sustainability at Arizona State University).

The UHIE has emerged as a statewide issue in California with the passage of Assembly Bill No. 296 in the 2011-2012 session (see http://leginfo.legislature.ca.gov/faces/billSearchClient.xhtml).

Among other things, that legislation requires the California DOT to develop a standard specification for sustainable pavements that can be used to reduce or minimize the UHIE. The research currently underway to support implementation of that legislation includes modeling of the effects of changing pavement albedo in cities in California using a statewide WRF climate model similar to that used by Chen et al. (2011), and initial life cycle assessment modeling of the net effects on GHG, energy use, and emissions affecting air pollution of changing pavement albedo on material production, construction, and the use phases (building energy use for cooling, heating, and lighting).

Artificial Lighting

Background

> ***Major Issues:***
>
> - ✓ *High energy demand of current lighting has high economic and environmental impact.*
> - ✓ *Providing appropriate amount of artificial lighting for driver safety*
> - ✓ *Reducing amount of light pollution*
> - ✓ *Understanding impact of pavement reflectivity/luminosity on nighttime and daytime safety.*

Roadway lighting is an often overlooked component in roadway and pavement design, even though it can have a large impact on safety, energy consumption, and generation of emissions. As a means of perspective, it was estimated that 131 million luminaires were used in the U.S. in 2007 for street and area lighting, consuming 178.3 terawatt hours (TWh) of electricity each year (Navigant Consulting 2008). This lighting was predominately provided by high pressure sodium lamps (39 percent), with metal halide (27 percent), mercury vapor (13 percent), fluorescent (6 percent), halogen quartz (8 percent), and incandescent (2 percent) lamps also being used.

Solid-state lighting, using light-emitting diode (LED) technology, is an energy efficient option in roadway lighting. LEDs produce light by moving electrons through a semiconductor compared to traditional light bulbs that use a filament that heats up and ultimately burns out. LED lighting can reduce energy consumption by up to 75 percent compared to the mercury lamps that are in common use today for street lighting (Wu et al. 2008). On top of comparative energy savings, LED lighting can be better positioned to direct most of the light directly on to the roadway where it is needed. This requires less light or energy to sufficiently and safely light the roadway and also reduces light pollution, which affects both people and wildlife, especially migrating birds (Rich and Longcore 2005). Furthermore, the characteristics of the light provided by an LED (color rendering, lighting distribution, and enhanced nighttime lighting conditions) may permit a reduction in total lumen output from an LED light source relative to the most common high-pressure sodium light source, resulting in further savings (Cook, Shackelford, and Pang 2008).

Solid-state LED lighting technology is fully embraced by the U.S. Department of Energy (DOE).[3] It is estimated that a 100 percent market penetration by more efficient solid-state LED technologies could save 44.7 TWh/yr, which is equivalent to the electrical consumption of 3.7 million residential households (Navigant Consulting 2008). The U.S. DOE has participated in the GATEWAY Demonstrations[4] in which the effectiveness of high-performance LED lighting products have been demonstrated on real world projects in multiple cities and also established

[3] http://www1.eere.energy.gov/buildings/ssl/index.html

[4] http://www1.eere.energy.gov/buildings/ssl/gatewaydemos.html

the Municipal Solid-State Street Lighting Consortium[5] to further promote that technology (U.S. DOE 2013). The City of Boston, for example, began installing LED street lighting in 2010 and has seen up to a 60 percent decrease in energy use and carbon emissions (City of Boston 2013). The City expects the LED lamps to last up to three times longer than conventional lamps and, although the initial cost is higher, it is expected that the payback period is 2 to 3 years.

In addition to energy conservation, light pollution from roadway lighting, which results in "skyglow," "light trespass," and "glare," has become a major social concern in many urban areas (AASHTO 2008). Sky glow is a brightening of the night sky caused by natural and human-made factors, while glare is an objectionable brightness or reflection of light and a driving hazard especially bothersome to older drivers. Light trespass is the actual light that falls off the right-of-way and can be measured and quantified. Although safety is of paramount concern, there are ways to reduce the amount of light pollution while still providing a completely safe amount of light. Positioning the light to be directed at the roadway surface and reducing the amount that is projected elsewhere is important regardless of the light sources. Also, reducing the amount of light that is being used (i.e., maintaining safe levels without overdesign) is another part of the solution. Finally, as previously mentioned, using more efficient solid-state LED lighting with high light quality can provide the same level of safety at lower lumens, thus contributing less light pollution.

From a pavement perspective, the color and texture of the pavement can also aid in reducing the amount of lighting needed (Gajda and VanGeem 2001; Adrian and Jobanputra 2005; MnDOT 2010; FHWA 2012). Lighter, more reflective pavement surfaces, or those with less texture, can provide the same level of luminance (the intensity of light emitted from the surface) at reduced illuminance (the amount of luminous flux per unit area) values. This can result in energy savings either by increasing the spacing between luminaries or by reducing the required lumens per luminary to achieve similar illumination. This is illustrated in figure 6-26, which shows that for the same illuminance values (e.g. lighting energy) across the two lanes, the lane on the right has twice the luminance value due to reflective differences in the pavement surfaces due to color and texture (FHWA 2012).

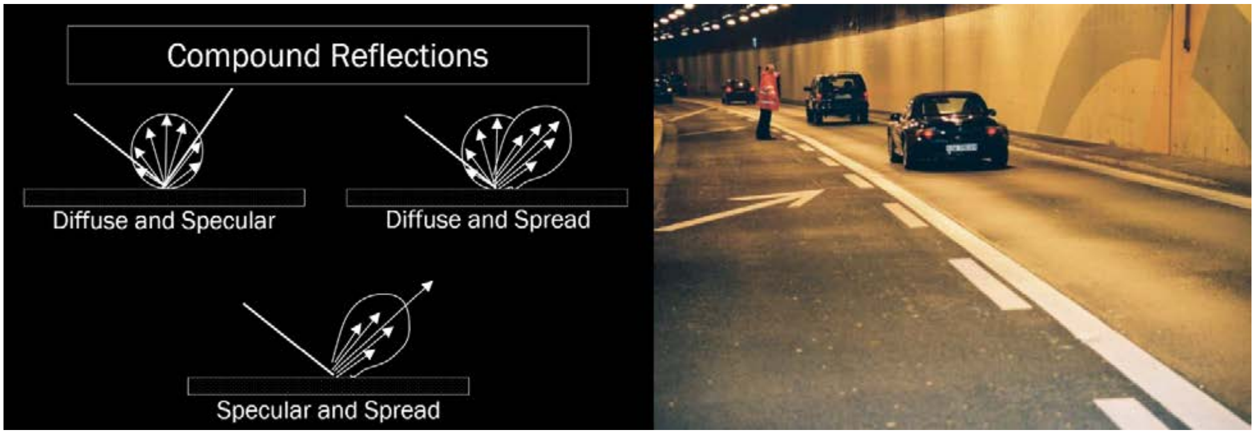


Figure 6-26. Pavement reflective differences (FHWA 2012).

[5] http://www1.eere.energy.gov/buildings/ssl/consortium.html

This concept of illumination is standardized in the pavement reflectivity classification numbers (R-numbers) used in IESNA RP-8 (IESNA 2000) to compute the required pavement illumination based on pavement surface luminance and roadway classification. A higher pavement luminance (e.g., R1) requires less illumination than pavements having less luminance (e.g., R3). This standard is used in the Minnesota DOT roadway lighting manual that prescribes more illumination for darker and more textured pavement surfaces (R2 and R3 which are asphalt/gravel and asphalt/rough texture) than for lighter, smoother textured pavement surfaces (R1 which is cement/concrete, and to a lesser degree R4 which is smooth textured asphalt); this standard is applied for all paved surfaces (including sidewalks) other than interstates (MnDOT 2010).

Many state DOTs (for example, California, Florida, and Texas) do not differentiate between surface types, partially because it is unknown what the long-term color and texture of the pavement will be. Thus, they are designed for a reduced luminance condition even though the newly constructed pavement may have a high luminance value, which results initially in overdesign. Although it is recognized that reductions in illumination can be warranted due to initial pavement surface luminance, reducing energy costs, and environmental impacts, it is difficult to design long-term lighting systems with the assumption that the pavement surface will always retain a given reflectance. The use of adaptive lighting, in which occupancy sensors, ambient light sensors, and adjustable lighting are employed, could address this limitation as the lighting level (and thus energy consumption) can be automatically adjusted as pavement luminance changes over time (FHWA 2014).

In addition to stationary roadway lighting, there are questions regarding the impact of pavement luminance on the effectiveness of vehicle headlights. Although lighter pavements may increase the efficiency of vehicle headlights, little documentation is available in terms of how they affect safety, and what was found reveals that this issue is unresolved. The problem is more complex than it may at first appear, as the contrast between an obstacle and the background is extremely important, as is the glare generated by oncoming traffic (Mace et al. 2001). Thus, in some scenarios, darker pavements may provide enhanced nighttime obstacle recognition for light colored obstacles, but further work needs to be done to better understand this issue (Dumont et al. 2009).

Future Directions and Emerging Trends

The impact of roadway lighting practices on the surrounding environment is of increasing concern to the public and highway agencies out of concern for impacts on wildlife and on energy efficiency and costs (AASHTO 2008). Overall, there is a general trend to reduce light pollution and unneeded lighting and its associated cost and environmental impact. As of about 2005, cities and states have responded with lighting ordinances and requirements regarding certain types of fixtures, minimum and maximum lighting levels, lumen/acre limits, and lighting elimination in some cases. Legislation has been adopted in Arizona, California, Connecticut, Colorado, Maine, New Mexico, Texas, Georgia, and New Jersey and has also been introduced in other states (AASHTO 2008).

Strategies for Improving Sustainability

Practices available to pavement managers, designers, and specification developers that might be used to address lighting issues are provided in table 6-7.

Table 6-7. Summary of strategies to address lighting issues and potential trade-offs.

Lighting Objective	Sustainable Approach and Trade-offs	Economic Impact	Environmental Impact	Societal Impact
Increase Energy Savings	Use of LED technology coupled with adaptive lighting.	High initial costs but with high energy savings, payback period is around 3 years.	Significant reduction in energy consumption and reduced emissions. Downward directionality helps migrating birds.	Provides clear, consistent, and more natural light and less lighting when not needed.
Provide Appropriate Amount of Artificial Lighting	Better design that accounts for the long-term pavement reflectivity. Adaptive lighting to only provide illumination when needed.	Lower economic costs for lighting	Reduced environmental impact due to reduce lighting.	Less light pollution.
Reduce Light Pollution	Better design of luminaries, consideration of lighting needs, and implementation of new technologies	Increase in cost due to investment in new luminaries and lighting technologies	Reduction in light pollution	Reduction in light pollution
Provide Better Understanding of the Impact of Pavement Reflectivity/Luminosity on Safety	Conduct research to determine what effect, if any, pavement reflectivity/ luminosity have on night and daytime safety	Investment is required to conduct research to determine significance	Unknown	Positive if safety can be enhanced

As an example of addressing the effects of light pollution on wildlife, the Florida Department of Transportation (FDOT) performed lighting research primarily because the state's beaches serve as important nesting habitat for several species of threatened and endangered sea turtles. Artificial light on or near nesting beaches can negatively affect the nesting process by interfering with normal nocturnal behaviors and spatial orientation of sea turtles, a problem to which streetlights contribute. Consequently, FDOT contributed to the development of the Florida Power and Light Company's Coastal Roadway Lighting Manual (AASHTO 2008; Ecological Associates 1998; Salmon, Wyneken, and Foote 2003).

The need to reduce electrical energy consumption has stimulated significant research and product development in the field of roadway lighting, the most relevant being the coupling of LED lights with adaptive lighting technology. Research is underway considering lighting types, directionality, placement, and warrants for placing lighting and adaptive lighting controls. Adaptive lighting controls allow lighting levels to be reduced during off-peak periods and to adjust to ambient lighting conditions (FHWA 2012). Simply put, a significant amount of power can be saved by varying the levels of lighting between peak and off-peak periods and as lighting needs change due to changes in ambient light conditions and pavement luminance over time.

Adaptive lighting can be even more responsive to demand using tools such as occupancy sensors and multilevel lighting (FHWA 2014). For example, a new project on the campus of the University of California–Davis wirelessly connects more than 1,400 energy efficient lights along pathways and roadways to a main control area, so that lights that once operated in solitude are now "talking" to each other as part of a seamless web. The lighting can be scheduled and adjusted for increased or decreased levels of activity, such as during sporting events, or to guide pedestrians along preferred routes. The system senses occupants, whether on foot, bicycle or automobile, predicts their direction of travel, and lights the path ahead. The smart network also senses when areas are vacant, then dims lights enough to save energy and reduce light pollution, without compromising safety. This system has an approximate 10-year payback period ($950,000 investment and $100,000 per year in energy savings). These types of controls are currently being piloted on a city street (CLTC 2012). Similar systems will likely become more widely available for street and highway lighting, and can be tuned to consider pavement luminance (FHWA 2014).

Safety

Safety is a key part of a sustainable transportation system. Figure 6-27 shows the trends in fatalities and fatality rates from 2002 to 2011 in the U.S., where it is observed that the number of fatalities has decreased by almost 25 percent since 2002 and the fatality rate per 100 million vmt (161 million vkt) has declined from 1.51 to 1.10 (NHTSA 2013). This is the result of the continuous improvements in transportation safety. One of the goals of the Federal Surface Transportation Policy and Planning Act of 2009 is to reduce the motor-vehicle related fatalities by 50 percent by 2030.

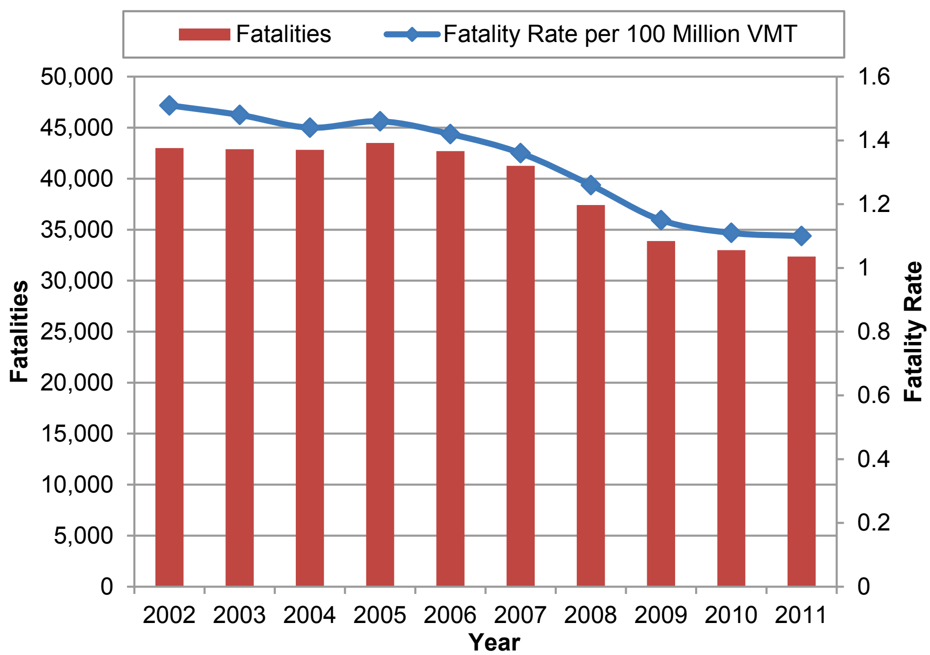


Figure 6-27. Fatality and fatality rates, 2002 – 2011 (NHTSA 2013).

A study conducted by Miller and Zaloshnja (2009) found that the roadway condition is a key contributing factor in vehicle crashes and that roadway-condition related crash costs are over $215 billion dollars annually (see figure 6-28). In order to have a sustainable and safe transportation system, keeping roadways in good condition is one of the most important factors. The MAP-21 Act signed into law in July 2013 supports FHWA's aggressive transportation safety goals. The Highway Safety Improvement Program (HSIP) is highlighted as one of the key programs in the MAP-21 act. The HSIP emphasizes a data-driven approach with each state required to identify key safety problems, establish a relative severity, and then adopt performance-based objectives to maximize transportation safety.

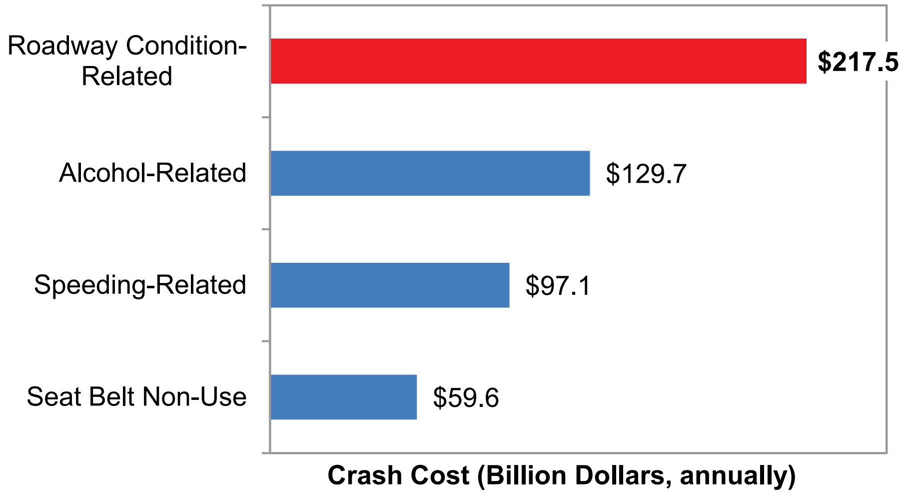


Figure 6-28. Crash costs by crash factor (Miller and Zaloshnja 2009).

From a pavement perspective, there are a number of major pavement-related factors that can influence safety, including the following:

- Traffic work zones. It is well documented that the number of crashes increases in work zones (Walls and Smith 1998). The utilization of pavement systems that minimize the number and duration of work zones over the life cycle reduce exposure to the increased crashes that occur in work zones.
- Surface friction. Adequate surface friction is critical to provide safe stopping distances. Friction levels should be based on friction demand, i.e., higher levels of friction required where there is a distinct need, such as on curves, ramps, and signalized intersections (Larson et al. 2008).
- Pavement macrotexture. Longitudinally grooved or tined concrete surfaces can add directional stability, reduce splash and spray, and provide drainage channels for surface water to reduce hydroplaning. Open-graded friction courses are effective at minimizing splash and spray from adjacent vehicles, which increases visibility while also reducing hydroplaning. Porous pavements also remove water from the surface, although they are generally not used on high-speed routes.
- Cross slopes. The pavement must have an adequate cross slope (typically a minimum of 2 percent) to promote surface drainage and help prevent hydroplaning. This includes maintenance of a continuous slope to the outside edge of the shoulder by avoiding wheelpath ruts and other transverse profile changes that can allow water to pond on the pavement surface.
- Rumble strips. These undulations that are paved, cast, or retrofitted into pavements emit a loud and abrupt noise when traversed, and have proven effective in shoulders (preventing roadway departure accidents by alerting wayward drivers to return to the roadway), at approaches to intersections and stop lights (preparing the driver to slow down or stop), and along the centerlines of two-lane roadways (helping to prevent head-on collisions).

- Pavement smoothness. Smoother pavements are comfortable and help reduce driver fatigue and minimize the potential for the driver to make unsafe maneuvers.

Obviously, there are a number of other roadway factors that also affect safety (e.g., geometrics, pavement markings, signage, shoulder condition/dropoff, ditch and roadway side slopes, right-of-way and clear zones, etc.), but these are not considered as part of the pavement decision.

Concluding Remarks

This chapter reviews important sustainability impacts of pavements in the use phase, including key factors related to rolling resistance and fuel consumption, tire-pavement noise, stormwater runoff, pavement thermal performance, lighting, and safety. For each of these factors, information is provided on their importance, quantification of their impact where available, current limitations, and trade-offs that must be considered. Only those use-phase effects that are influenced by pavement decisions are included.

The major highlights with regard to pavement characteristics and vehicle fuel use (and associated environmental benefits) are the following:

- Significant environmental benefits from reduced fuel consumption can be achieved by keeping high traffic pavements in smooth condition. There are trade-offs between negative effects of materials production and construction that occur when maintaining pavements in good condition versus benefits that may be realized in the use phase. Therefore, little or no environmental benefits from fuel economy improvements may be achieved from maintaining low-traffic pavements in smooth condition even though there are other reasons for doing so. Considering social aspects, roads should be kept in a functional condition to maintain access to the transportation system for efficient movement of people and goods by protecting pavement structures with appropriate preservation treatments.
- A high level of pavement smoothness should be sought whenever a pavement is built, rehabilitated, or maintained, particularly on high-volume routes. This can be accomplished by instituting rigorous smoothness specifications for new construction and rehabilitation, and by requiring that high-volume pavements are maintained at a high level of smoothness throughout their life.
- Structural responsiveness and its effect on vehicle fuel economy is the subject of several models that have been developed, and a number of field studies have been performed measuring vehicle fuel economy on different pavement structures under different conditions. These provide indications that under various conditions the structural responsiveness of different pavements to vehicle loading can have a measureable effect. However, unlike roughness, this effect is highly dependent on pavement temperatures and is much more sensitive to vehicle type and speed than roughness. The calibration of models that will allow definitive conclusions to be drawn based on general application of the models to a wide range of pavements under a broad range of traffic and climatic conditions in various locations has not yet been completed.
- The smoothness of pavements in locations where there are utilities should be preserved by avoiding utility cuts where possible, and by obtaining the best possible repairs to cuts where they must be performed.

The major conclusions with regard to pavement characteristics and tire-pavement noise are the following:

- Noise can have adverse effects on humans and wildlife. Although other factors are typically more important than the pavement in determining noise levels, noise attributable to the pavement surface characteristics should be controlled if it is determined to be detrimental to surrounding communities and habitat.
- Methods are available to measure tire-pavement noise. Research performed to date offers information regarding the noise benefits of different pavement surface types and textures, and initial indications of their long-term performance. For example, thin rubberized asphalt overlays have been found to be effective at mitigating pavement-generated noise in some locations such as Phoenix, Arizona. Diamond grinding is another strategy that has noticeably reduced noise emissions from some concrete pavement surfaces. The longevity of these noise mitigation strategies is still under investigation.
- New materials for asphalt surfaces and new textures for concrete surfaces have been developed to reduce noise and are being evaluated.

The major conclusions regarding the use of permeable pavements and stormwater management are:

- There are many options to construct permeable pavements including porous asphalt, pervious concrete, and permeable paver systems. Regardless of the pavement type, permeable pavements are currently better suited for low-speed, low-volume roadways and parking areas. Ongoing research is being done to investigate the applicability of permeable pavements to more heavily loaded facilities.
- Permeable pavement systems require more frequent cleaning and maintenance than do conventional pavements in order to maintain adequate permeability. This often requires the need to purchase specialized cleaning equipment and to schedule more frequent cleanings.
- Although rare, the runoff drained through permeable pavement surfaces may contain pollutants that could potentially contaminate groundwater sources. This must be evaluated for each specific application.

The major conclusions of the discussion on the thermal performance of pavements and their potential contribution to the UHIE are as follows:

- Methods are available to measure solar reflectance, but quality assurance and control procedures need to be more fully developed (NCPTC/NCAT 2013). Typically, concrete pavements have higher reflectivity than asphalt pavements but it is recognized that age and weathering generally result in asphalt pavements becoming more reflective over time (increasing albedo) whereas concrete pavements become less reflective over time (decreasing albedo). Application of preservation and rehabilitation treatments can alter the reflectivity of the pavement surface. These changes in pavement solar reflectance over time are not well understood and research is underway to better quantify them (NCPTC/NCAT 2013).
- In general, in locations where it is deemed important, high solar reflectance should be maintained over time, which may become a consideration for maintenance and

rehabilitation activities. For example, the frequent use of some asphalt surface treatments (e.g., slurry seals, microsurfacing) has a tendency to keep albedo low. Diamond grinding of concrete may also change the surface reflectivity, either increasing it or decreasing it depending on the color of the aggregate.

- Some materials used to create the most highly reflective surfaces, particularly highly reflective photocatalytic materials and some proprietary coatings, may have a high environmental footprint during manufacturing compared to conventional materials. Their use in pavements should be considered on a case-by-case basis. An LCA study can help to evaluate the net environmental effects of implementing more reflective surfaces for different applications.
- Pavement strategies that reduce pavement surface temperatures consist of more than just using pavements with high solar reflectance, and instead require a systems approach. The use of pervious pavements and shading should also be considered.
- At this time, it is unclear to what degree pavement solar reflectance impacts the development of the UHIE for different urban architectures, climate regions, and other variables. Research is underway to provide a more comprehensive understanding of the UHI phenomenon. Similarly, the overall impact of reflective surfaces and regional and global climate is a subject of current research, which is needed to provide a more complete understanding of the potential positive and negative impacts of increased pavement reflectivity.

Some of the major conclusions surrounding roadway lighting and pavement are as follows:

- The high energy demand of current lighting systems has a significant economic and environmental footprint. Thus, the goal is to provide an appropriate amount of artificial lighting for driver safety that is not excessive or wasteful. This will not only result in economic and environmental savings, but will also help reduce the amount of light pollution produced.
- Pavement surface luminance is known to influence the amount of artificial lighting required, but practical application of this knowledge is currently unclear as surface luminance changes with time. Adaptive lighting technologies featuring the use of LEDs offers an opportunity to account for pavement luminance by adjusting illuminance in response to changing ambient conditions.
- Understanding of the impact of pavement luminance on nighttime and daytime safety is still unclear, as trade-offs exist with respect to the improved lane demarcation that can exist between light-colored line markings and a dark pavement surface, with light colored pavement and dark backgrounds beyond the pavement edge, and with the increased efficiency of artificial lighting (such as headlights) on pavement surfaces with higher luminance.
- Development and implementation of new adaptive lighting systems, which provide lighting only when it is needed, is currently underway and has the strong potential to significantly lower economic, environmental, and societal costs associated with artificial lighting.

Finally, regarding safety, it is emphasized that adequate surface friction should be made available on all pavement facilities to ensure that safe stopping distances are achievable. Friction levels should be based on the demands of the facility or location, in that higher levels should be targeted where there is a distinct need, such as at curves, ramps, and intersections. Smoothness levels of pavements should also be maintained as it contributes to safer traveling conditions. Open-graded friction courses or porous pavements are effective at minimizing splash and spray from adjacent vehicles, which increases visibility. Similarly, grooved concrete surfaces can add directional stability, reduce splash and spray, and provide drainage channels for surface water to reduce hydroplaning.

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