# Heat Transfer from Vehicular Catalyst to Pavement

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A study was undertaken to assess the effect of vehicle heat on bituminous pavement by comparing it with the effect of solar radiation. The catalytic converter (or catalyst) was chosen to represent a vehicle exhaust system. Catalysts transfer heat to pavements primarily by radiation, which can be calculated on the basis of existing theories. Two methods were used to calculate radiation from catalyst to pavement: view factor and solid angle. A simplified experiment showed that view factor calculation was closer to measured heat transfer. Data from catalysts of three vehicles were taken. Solar radiation absorbed by the pavement can be estimated from existing models and meteorological data. Results indicate that for one vehicle, pavement directly under the catalyst with an area the same as or smaller than the catalyst absorbed more radiation from it than from the sun. Size and temperature of the catalyst, distance between catalyst and pavement, and oxidation level of the catalyst material were all important factors. Because of the very small sample of vehicles studied, no general conclusions were drawn about whether vehicles on highways increase pavement surface temperature and cause rutting damage.

Rutting of bituminous pavements has been a subject of national attention in recent years. New York State had a few critical rutting failures before the New York State Department of Transportation (NYSDOT) Materials Bureau developed new heavy-duty flexible pavement mixes, specified from 1991 for all new construction. Combinations of weak foundations, poor-quality aggregates, improper mix designs, inadequate compaction, heavy truckloads, and high temperatures all contribute to rutting.

Properties of bituminous concrete make it highly susceptible to temperature. In 1988, a rutting failure had occurred on the Cross-Bronx Expressway in an abnormally hot summer. Heat emitted from vehicle exhaust systems is another possible source contributing to high temperatures. It was suspected that vehicles may worsen the rutting problem by causing further increase in pavement surface temperatures, particularly at intersections or on highly congested roadways where vehicles must stand with idling motors or move very slowly, if at all, for long periods. Recently, some minor rutting was also noted in Albany on the Route 5 approaches to the busy intersection of Routes 5 and 155. Route 5 had been reconstructed less than 3 years earlier, and no rutting had occurred in other areas.

The possible effect of heat transferred to pavements from standing or slow-moving vehicles does not appear to have been explored elsewhere, and, consequently, was selected for a short-term study by the Engineering Research and Development Bureau. The objectives were to determine the total heat transferred to the pavement surface from a catalytic converter, commonly called a catalyst, and whether its effect on pavement is significant compared with the effect of solar radiation. Although various parts of exhaust systems all contribute to this effect, it was decided to study only the catalyst because it produces particularly high temperatures, its area is easy to define, and it is unobstructed from the pavement surface, thus fitting this study's requirements: to produce results with limited resources and time.

In this paper, heat-transfer phenomena—especially radiation—are briefly reviewed. Then radiation from a catalyst to a pavement is calculated, using appropriate theories and data from three vehicles. The calculated radiation heat transfer was verified by a simplified test. Results are compared with those from calculated solar radiation that a pavement receives to determine whether catalysts have any significant effect on pavement temperatures.

## HEAT TRANSFER

Heat transfer is a science that involves the prediction of energy transfer between bodies as a result of a temperature differential (*1*). This prediction tries to explain how and at what rate energy is exchanged. The transfer of heat energy may take any of three forms: conduction, convection, or radiation.

1. Conduction occurs when a temperature gradient exists within a single body or two bodies in contact. It cannot take place without a material medium.
2. Convection is the process in which a gas or liquid with a given velocity carries heat away from a hot body. Its two types are (a) forced and (b) free or natural. Forced convection occurs when velocity of the fluid is driven by an external force such as a fan. Free convection occurs without external force; velocity is induced by the temperature gradient near the hot body. Convection also requires a material medium for it to occur.
3. Radiation, unlike convection and conduction, does not need a medium and is transmitted by electromagnetic waves. Thermal radiation is propagated by temperature differences. "Black-body" radiation consists of electromagnetic waves emitted from an object radiating according to the $T^4$ law. In this form, it is directly proportional to the area of the radiating object. Black-body radiation is calculated as follows:

$$q = \sigma_b A T^4 \tag{1}$$

where

$q$ = black-body radiation (W),
$\sigma_b$ = Stefan-Boltzmann constant ($5.67 \times 10^{-8}$ W/m$^2 \cdot$ K$^4$),
$A$ = area of radiating object (m$^2$), and
$T$ = absolute temperature of radiating object (°K).

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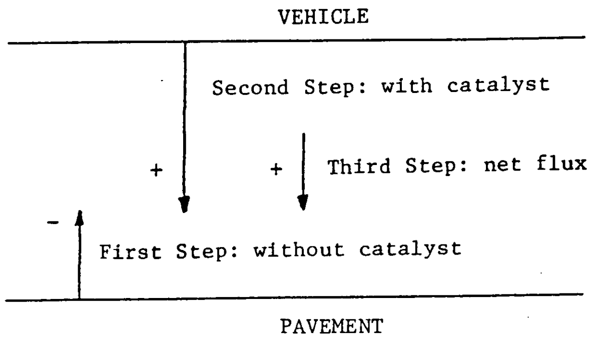


**FIGURE 1** **Net radiation between vehicle and pavement.**

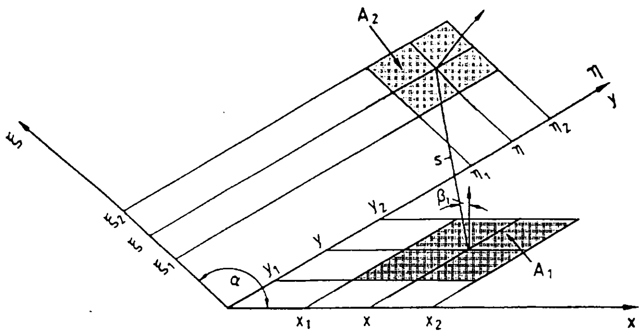


**FIGURE 3** **Two areas on two arbitrary planes.**

If two objects face one another, and one has a higher temperature but the same area, thermal radiation transmitted to the cooler object is equal to

$$q = \sigma_b A(T_H^4 - T_C^4) \tag{2}$$

where

$q$ = radiation heat transfer (W),
$T_H$ = absolute temperature of hotter object (°K), and
$T_C$ = absolute temperature of cooler object (°K).

Equations 1 and 2 are valid if the objects are "black," a term referring to their ability to radiate or absorb energy according to the $T^4$ law.

## RADIATION FROM A CATALYST

### Theory

Thermal radiation is the main form of heat transfer between catalyst and pavement. Convection heat transfer between vehicle and pavement may be neglected because the hotter body is above the cooler body so that gravity reduces heat flow. Because catalyst and pavement are not in contact, heat transfer does not occur as conduction.

A "gray" body, such as a catalytic converter, radiates proportionately to the $T^4$ law, with the proportionality constant called "emissivity" ($\epsilon$). Its value depends on the material's composition, type of finish, level of oxidation, and surface temperature. The darker the surface, the higher is its emissivity, and vice versa. "Black" bodies have an emissivity of 1.

Net heat exchange in the form of radiation from catalyst to pavement can be calculated in a three-step process. The first is to calculate radiation transfer to the pavement from a vehicle without a catalyst. The second step is to calculate the additional radiation contribution from adding a catalyst to the vehicle. In the third step, these results should then be added to obtain total heat transfer; this process is shown in Figure 1. Throughout this study, the conventions of radiation leaving the pavement upward and leaving the vehicle downward were assumed to be negative and positive, respectively.

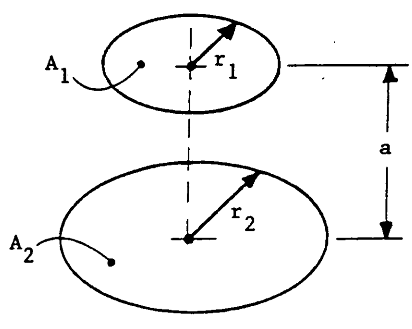


**FIGURE 2** **Two parallel concentric disks.**

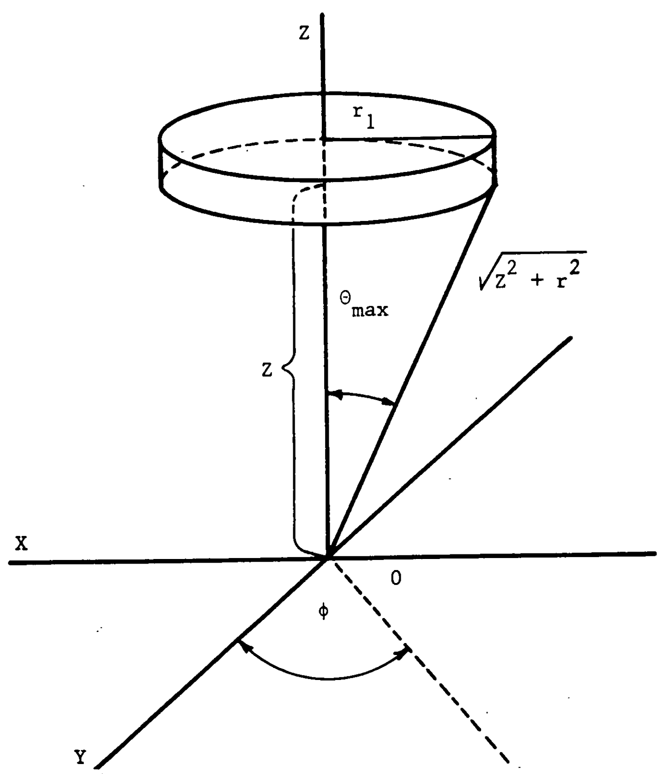


**FIGURE 4** **Solid-angle approach.**

Step 1 is calculated as follows:

$$q_1 = -\sigma_b A_p (T_p^4 - T_v^4) \tag{3}$$

where

$q_1$ = radiation (W) between pavement and vehicle without a catalyst,
$A_p$ = pavement area of interest ($m^2$),
$T_p$ = pavement temperature (°K), and
$T_v$ = temperature of underside of vehicle (°K).

Step 2 involves using a view factor (explained later in detail) and an emissivity for catalyst radiation. Step 1 does not require a view factor because the vehicle acts as an infinite plane compared with the pavement section that is of interest. No emissivity is used because pavement surface and vehicle underside are both assumed to radiate as black bodies because of their dark colors. The additional radiation contributed by the catalyst is calculated as follows:

$$q_2 = \epsilon_c F_{1-2} \sigma_b A_c (T_C^4 - T_v^4) \tag{4}$$

where

$q_2$ = additional radiation (W) from catalyst,
$\epsilon_c$ = emissivity of catalyst,
$F_{1-2}$ = view factor,
$A_c$ = area of catalyst facing pavement ($m^2$), and
$T_c$ = temperature of catalyst surface (°K).

Step 3 is the summation of Equations 3 and 4, yielding the net radiation between a catalyst and an area of pavement beneath it:

$$q_t = q_1 + q_2 \tag{5}$$

or

$$q_t = \sigma_b[\epsilon_c F_{1-2} A_c (T_c^4 - T_v^4) - A_p (T_p^4 - T_v^4)] \tag{6}$$

where $q_t$ is total radiation flux (W) between a vehicle catalyst and a pavement area.

The view factor ($F_{1-2}$) is the portion of total radiation from the catalyst that reaches the pavement area of interest ($A_p$). The view factor is a function of the geometry of the catalyst and pavement area in question (*2*). The most common geometry of two parallel concentric disks of varying radii was used in this study, as shown in Figure 2. $F_{1-2}$ for this arrangement is calculated as follows:

$$F_{1-2} = \frac{1}{2}\left\{X - \left[X^2 - 4\left(\frac{R_2}{R_1}\right)^2\right]^{\frac{1}{2}}\right\} \tag{7}$$

where

$$X = 1 + \frac{(1 + R_2^2)}{R_1^2} \tag{8}$$

and

$R_1 = \dfrac{r_1}{a}$,

$R_2 = \dfrac{r_2}{a}$,

$r_1$ = radius of catalyst (m),
$r_2$ = radius of pavement area of interest (m), and
$a$ = distance between catalyst and pavement (m).

Because most catalysts are not circular, $r_1$ is the equivalent radius and is calculated as follows:

$$r_1 = \sqrt{\frac{A_c}{\pi}} \tag{9}$$

Gross et al. (*3*) have explained that if surfaces of the radiating bodies are not parallel but inclined with respect to each other, the view factor is calculated as follows (with all variables defined as in Figure 3):

$$A_c F_{1-2} = \int_{\xi_1}^{\xi_2}\int_{\eta_1}^{\eta_2}\int_{y_1}^{y_2}\int_{x_1}^{x_2} \frac{x\xi}{[x^2 - 2x\xi\cos\alpha + \xi^2 + (y-\eta)^2]^2}\, dx\, dy\, d\eta\, d\xi \tag{10}$$

where

$A_n$ = areas of radiating bodies,
$x, y, \eta, \xi$ = coordinates,
$\beta$ = direction angle relative to normal surface,
$\alpha$ = angle of inclination between two planes, and
$s$ = distance between two planes.

A second possible method to calculate radiation from catalyst to pavement is to use the solid angle concept instead of the view factor, as shown in Figure 4 and described as follows:

$$I_{q_2} = \epsilon_c\, \sigma_b\, \frac{\text{solid} \angle}{2\pi} (T_c^4 - T_v^4) \tag{11}$$

where $I_{q_2}$ is the radiation intensity of $q_2$ directly below the center of the catalyst at a distance $Z$, and solid $\angle$ is the solid-angle catalyst carved out to a point $Z$ distance below the center.

Equation 11 gives the radiation intensity directly below the center of the radiating body. This intensity drops off for locations away from the $Z$ axis. $I_{q_2}$ reduces to half when the radial distance is about 0.76 $Z$ from the $Z$ axis. It also decreases as $Z$ increases, and vice versa.

The solid angle is calculated by

$$\text{solid} \angle = \int_0^{2\pi}\int_0^{\theta_{max}} \sin(\theta)\, d\theta\, d\phi \tag{12}$$

Integration yields

$$\begin{aligned}\text{solid} \angle &= -\cos(\theta)\Big|_0^{\theta_{max}} \cdot 2\pi \\ &= 2\pi\,[1 - \cos(\theta_{max})]\end{aligned} \tag{13}$$

From Figure 4

$$\cos(\theta_{max}) = \frac{Z}{\sqrt{Z^2 + r^2}} \tag{14}$$

where $r$ is the radius of catalyst (Equation 9), and $Z$ is the distance between catalyst and pavement.

Substituting Equation 14 into Equation 13 and then into Equation 11 will give the intensity. Total radiation absorbed by the pavement is obtained using the three-step process described earlier by adding $q_1$ and $q_2$. $q_2$ is the intensity ($I_{q_2}$) multiplied by the pavement area ($A_p$). That produces the following calculation:

$$q_t = \epsilon_c \sigma_b A_p \left[1 - \frac{Z}{\sqrt{Z^2 + R^2}}\right] (T_c^4 - T_v^4) + q_1 \qquad (15)$$

### Data and Calculations

From these theories, radiation heat transfer from catalyst to pavement can be calculated by knowing pavement temperature, catalyst temperature, vehicle underside temperature, catalyst geometry, and emissivity of the catalyst.

Pavement surface temperatures were computed using the NYTEMP computer model developed by Chen (*4*). Pavement surface temperatures on midsummer afternoons were calculated to range from 40.5°C to 54°C, and a pavement surface temperature of 49°C (322°K) was used throughout the calculations.

Three vehicles (a van, a pickup truck, and a station wagon) were available for testing in this study. Temperatures of their catalysts were measured with copper constantan thermocouples attached by pipe clamps, using thermally conductive grease to ensure good contact. A multichannel data collector recorded the thermocouple readings, which were taken inside a garage at 19.5°C air temperature. It is suspected that measured catalyst temperatures might have been higher if the surrounding air temperature had been warmer, as in summer. Other vital measurements included distance from catalyst to the ground and catalyst width, length, and inclination angle. These data are summarized in Table 1.

Average temperatures of the vehicle undersides were not directly measured but should range from 30°C to 45°C. A vehicle underside temperature of 38°C (311°K) was assumed for all three vehicles. Exhaust systems were all stainless steel. Its emissivity may range from 0.17 to 0.7, depending on oxidation level and temperature. Without a scale to estimate emissivity of the three catalysts, an $\epsilon$ of 0.7 was used in this study, assuming that critical conditions existed.

Using this method, view factors had to be estimated before calculating radiation. Equation 7 was used to compute view factors for the van and pickup. Equation 10 had to be used for the station wagon, whose catalyst inclined 20 degrees with respect to

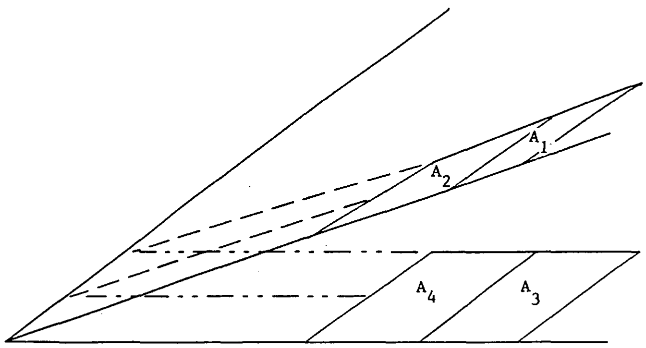


**FIGURE 5 Radiation calculation for station wagon catalyst.**

the ground. Integration of Equation 10 was performed by a specialized software using numerical methods. The wagon's catalyst also had additional shielding covering its lower half, resulting in two different catalyst surface temperatures and requiring additional calculation of view factors. As shown in Figure 5, pavement beneath the catalyst was also derived into two areas. Four view factors ($F_{1-3}$, $F_{1-4}$, $F_{2-3}$, and $F_{2-4}$) were calculated using Equation 10. For the first half of the pavement ($A_3$), second half of the pavement ($A_4$), and whole pavement area, the radiation absorbed is simply the sum of both halves of the catalyst:

$$q_{A_3} = q_{A_1-A_3} + q_{A_2-A_3} \qquad (16)$$

$$q_{A_4} = q_{A_1-A_4} + q_{A_2-A_4} \qquad (17)$$

$$\text{Whole area: } q = q_{A_3} + q_{A_4} \qquad (18)$$

Radiation heat transfer can be calculated using the three-step process described earlier. Three different pavement areas ($A_p$) in Equation 3 were used: half, the same, and twice the area of the catalyst ($A_c$). ($A_p$ twice the area of $A_c$ was not used for the wagon because calculation of view factors was too time consuming.) Results are given in Table 2.

The solid-angle approach was used for the van and pickup, but not for the station wagon, because this method assumes two parallel disks with uniform radiation, which the wagon did not have. Radiation was calculated with the assumption that the intensity calculated by Equation 11 decreased linearly with the increase in radial distance. Results of the solid-angle approach are given in Table 3.

**TABLE 1 Catalyst Data**

| Vehicle | Angle of Incline | Length, m | Width, m | Area, m$^2$ | Distance to Pavement, m | Highest Measured Temp, K |
|---|---|---|---|---|---|---|
| Van (8 cyl) | 0 | 0.46 | 0.30 | 0.1380 | 0.28 | 427.44 |
| Pickup (8 cyl) | 0 | 0.33 | 0.23 | 0.0759 | 0.29 | 369.11 |
| Wagon (4 cyl) | | | | | | |
| 1st Half | 20 | 0.15 | 0.23 | 0.0345 | 0.19 | 459.11 |
| 2nd Half | 20 | 0.15 | 0.23 | 0.0345 | 0.14 | 386.89 |

**TABLE 2 Catalyst Radiation by View-Factor Method**

| Vehicle | Catalyst Area, $m^2$ | Pavement Area, $m^2$ | View Factor | Radiation Absorbed by Pavement, W |
|---|---|---|---|---|
| Van | 0.138 | 0.069 | 0.160 | 15.6 |
| | | 0.138 | 0.286 | 26.7 |
| | | 0.276 | 0.463 | 39.1 |
| Pickup | 0.076 | 0.038 | 0.103 | -0.15 |
| | | 0.076 | 0.076 | -0.76 |
| | | 0.152 | 0.325 | -3.01 |
| Wagon | 0.069 | | | |
| 1st Half | | 0.0345 | $F_{1-3} = 0.005$<br>$F_{2-3} = 0.004$ | 6.26 |
| 2nd Half | | 0.0345 | $F_{1-4} = 0.003$<br>$F_{2-4} = 0.007$ | 5.01 |
| Whole Area | | 0.0690 | -- | 11.28 |

The view factor for parallel concentric disks (Equation 7) and the solid angle (Equations 13 and 14) are similar mathematical functions. Both converge to 1 when the distance between catalyst and pavement ($a$ or $Z$) approaches 0, and both approach 0 when distance approaches infinity. They differ somewhat in that the view factor takes into account the areas of both radiating bodies, whereas the solid angle directly considers only the hotter body area. Figure 6 compares the two functions using the van's catalyst data. This figure shows that the solid-angle factor (i.e., solid angle divided by $2\pi$) is less than the view factor when pavement area exceeds or equals catalyst area, or both. When pavement area is half the catalyst area, the solid-angle factor is greater than the view factor. At this point, the authors do not know why these two approaches for the same problem yield quite different results, as shown in Tables 2 and 3.

### Tests

To verify the foregoing theories and calculations, a simple experiment was conducted. Knowing that the enthalpy of air-saturated water is about 4.18 J/(g · °C) heat absorbed by water can be calculated. A known volume of water with the same surface area as the pickup truck catalyst was placed beneath it for a measured duration, and temperature change was recorded. About 3000 ml of distilled water with a surface area (facing the catalyst) of 0.0759 $m^2$ and depth of 39.5 mm was enclosed in plastic, covered with black paper, and placed 114.3 mm beneath the pickup catalyst for 51 min. Water temperature increased by 2.5°C. The calculated heat absorbed by the water was 10.24 W. Performing the radiation calculation using the view-factor method yielded a net flux of 8.5 W. The solid-angle method yielded an intensity of 69.6 W/$m^2$, corresponding to a net flux of 5.3 W.

This test indicates that the view-factor radiation calculation procedure is fairly accurate. The difference between calculated and measured heat transfer can be attributed to omission of convection heat transfer in the calculation because a considerable amount of heat could be transferred through convection during the 51-min period. The test also suggests that the solid-angle calculation is less accurate than the view-factor method.

## SOLAR RADIATION

Radiation delivered to the pavement can be calculated by knowing the extraterrestrial radiation and percent of possible sunlight on a given day, using the following equation:

$$H = (a + b \cdot S) \cdot H_0 \tag{19}$$

**TABLE 3 Catalyst Radiation by Solid-Angle Method**

| Vehicle | Solid Angle/$2\pi$ | Pavement Area, $m^2$ | Average Intensity $I_{q_2}$, W/$m^2$ | Radiation Absorbed By Pavement, W |
|---|---|---|---|---|
| Van | 0.1994 | 0.069 | 156.1 | 5.31 |
| | | 0.138 | 142.5 | 8.76 |
| | | 0.276 | 123.3 | 12.20 |
| Pickup | 0.1186 | 0.038 | 37.9 | -1.56 |
| | | 0.076 | 35.7 | -3.29 |
| | | 0.152 | 32.5 | -7.08 |

where

$H$ = solar radiation delivered to pavement (W/m$^2$),
$a$, $b$ = constants,
$S$ = percent of possible sunlight, and
$H_0$ = extraterrestrial radiation (W/m$^2$).

$H_0$ is obtained by using the NYETRI computer program developed by Chen (*4*) and is about 1100 to 1200 W/m$^2$ at 1:00 p.m. on a typical day in July or August. $S$ on clear days is normally 90 percent or more. For Albany it was estimated that $a$ = 0.15 and $b$ = 0.556. Using these parameters, with good weather conditions solar radiation reaching the pavement may be as high as 800 W/m$^2$, with an average of 600 W/m$^2$ at 1:00 p.m. in July. Table 4 lists calculated solar radiation on hottest day and monthly averages for July and August of 1990 through 1992, using actual weather data from the Albany County Airport. From these data, 800 W/m$^2$ was used for solar radiation reaching the pavement.

Before calculating the amount of radiation that the pavement absorbs from the sun, one must subtract the portion that is reradiated and returned upward after reaching the pavement surface. This "black-body" radiation was calculated using Equation 1. Using the previous assumption that the pavement surface temperature was 322 K, the pavement radiated at 610 W/m$^2$. This resulted in a net absorption (by the pavement from the sun) of 190 W/m$^2$. This intensity was used in the comparisons of catalyst radiation.

**TABLE 4 Solar Radiation Reaching Pavement at 1:00 p.m.**

| Month | Year | Average, W/m$^2$ | High, W/m$^2$ | Date of High |
|---|---|---|---|---|
| July | 1990 | 596.3 | 701.3 | 4 |
| | 1991 | 650.0 | 830.8 | 1 |
| | 1992 | 509.2 | 707.4 | 6 |
| August | 1990 | 512.7 | 750.9 | 31 |
| | 1991 | 601.3 | 777.8 | 5 |
| | 1992 | 481.0 | 553.2 | 12 |

## RESULTS AND DISCUSSION

Calculated radiation (using the view-factor method) that pavements absorbed from catalysts of the three tested vehicles and the sun is listed in Table 5. The pavement absorbed less radiation than it emitted to the environment, primarily because of the pickup catalyst's relatively low temperature and high position. The van catalyst radiated slightly more heat to the pavement directly beneath it than did the sun to that same pavement area. For the wagon, catalyst radiation was slightly less than solar radiation for the pavement area beneath the catalyst. For pavement areas twice as large as the catalysts, solar radiation far exceeded catalyst radiation.

These results indicate that (compared to the sun) some catalysts may significantly affect pavement temperature, but this is limited only to areas directly beneath the catalysts. Some combination of vehicles in a traffic stream having hot, old, low, and large catalysts located at various lateral positions across their widths might increase pavement temperature and contribute to rutting damage at intersections or along congested roadway sections.

The fact that the wagon had a shield over the lower half of its catalyst and that all three vehicles had shielding between the catalysts and passenger compartments indicates that vehicle designers are concerned about protecting the pavement and surrounding objects from excessive heat generated by catalysts and other high-temperature engine parts. Catalysts of vehicles of average age (3 to 5 years) have midrange emissivity. Vehicles with low centers of gravity, such as sports cars, may significantly affect the pavement because the catalyst is so near its surface. On the other hand, trucks are likely to have less effect because the exhaust system is farther from the pavement. Because so few vehicles were included in this study, the real effect of vehicle catalysts remains unknown.

The relation between vehicle heat and pavement temperature is highly complex. Not only vehicle configuration, but also vehicle movement and the effect of small-area heating on pavement temperature must be considered. Any specific area of pavement at intersections or along congested roadways is subjected to con-

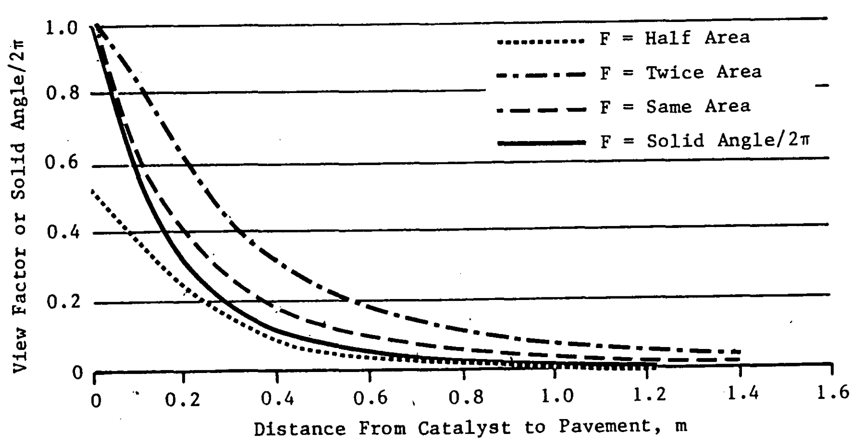


**FIGURE 6 Comparison between view factor and solid angle.**

**TABLE 5 Comparison of Catalyst and Solar Radiation**

| Vehicle | Catalyst Area, $m^2$ | Pavement Area, $m^2$ | Radiation Absorbed From Catalyst, W | Radiation Absorbed From Sun, W |
|---|---|---|---|---|
| Van | 0.138 | 0.069 | 15.6 | 12.8 |
| | | 0.138 | 26.7 | 26.2 |
| | | 0.276 | 39.1 | 52.4 |
| Pickup | 0.076 | 0.038 | -0.15 | 7.2 |
| | | 0.076 | -0.76 | 14.4 |
| | | 0.152 | -3.01 | 28.9 |
| Wagon | 0.069 | | | |
| 1st Half | | 0.0345 | 6.26 | 6.55 |
| 2nd Half | | 0.0345 | 5.01 | 6.55 |
| Whole | | 0.0690 | 11.28 | 13.10 |

stantly changing radiation as a result of vehicle movement and varying catalyst characteristics (temperature, location, size). The mechanism of temperature rise in pavement caused by small-area heating by catalysts and its relation to rutting are yet to be investigated.

Including the convection effect in this problem increases the calculated heat transfer because some heat can be transferred through the air between vehicle and pavement, even against gravity if enough time elapses. Vehicle movement to some extent disturbs this process and reduces its effects.

## CONCLUSIONS

Heat transfer by radiation from catalyst to pavement is a function of catalyst temperature, pavement temperature, temperature of the vehicle underside, catalyst emissivity (in turn affected by its level of oxidation, color, and finish), distance from catalyst to pavement, catalyst size, and the pavement area being considered. According to the calculations, catalysts of some vehicles can radiate more heat than the sun to the small pavement areas beneath them. Because of the very small vehicle sample in this study and the problem's complexity, no general conclusion can be drawn about whether vehicles cause additional temperature increase and thus rutting damage to bituminous pavements.

## RECOMMENDATIONS

This relationship between vehicle heat and bituminous pavement does not appear to have been studied in the past, and many unanswered questions remain. From this investigation, the following future research is suggested:

1. Pavement temperature measurement

–Simple: Measure pavement temperatures at about 1:00 p.m. on hot summer days, with and without vehicles parking over thermocouples, to determine whether running engines emit more radiation to the pavement than does the sun.

–Detailed: Place thermocouples in approach and nonapproach sections at a busy intersection (such as Routes 5 and 155), to determine whether the combined effect of several vehicles and their movement causes any increase in pavement temperature. The same measurement plan can also be tried on highly congested and less-traveled sections of a roadway.

2. Convection study. Investigate how properly to include convection into heat-transfer theory and calculation for this problem.
3. Simulation study.

–Comprehensive vehicle sampling: Obtain necessary data (catalyst location, size, and temperature, and vehicle underside temperature) for a sample of vehicles reasonably representing those on the road.

–Simulation: Compute expected radiation distribution for intersections and congested pavement areas, using data from sampling and simulation techniques. This can assess effects of mixed vehicles and their movement and may help clarify the results from Study 1.

4. Temperature and modulus model. Establish temperature distribution across a pavement lane width under the influence of prevailing vehicle heat. From this temperature model, compute the corresponding in situ modulus distribution within the bituminous pavement.
5. Finite element analysis and rut prediction. Mechanistic responses of the pavement can be computed by the finite element method, using the modulus obtained in Study 4. Then rutting may be predicted on the basis of these responses with existing rut models or new ones to be developed.

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## REFERENCES


1. Holman, J. P. *Heat Transfer*, 7th ed. McGraw-Hill, Inc., New York, 1990.
2. Howell, J. R. *A Catalog of Radiation Configuration Shape Factors*. McGraw-Hill, Inc., New York, 1982.
3. Gross, U., K. Spindler, and E. Hahne. Shapefactor-Equations for Radiation Heat Transfer Between Plane Rectangular Surfaces of Arbitrary Position and Size with Parallel Boundaries. *Letters in Heat and Mass Transfer*, Vol. 8, 1981, pp. 219–227.
4. Chen, H. J. *NYTEMP User's Manual: A Pavement Temperature Model*. Special Report 111. Engineering Research and Development Bureau, New York State Department of Transportation, Albany, July 1993.


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