CO_2 emissions reduction by solar reflective coating for automobiles

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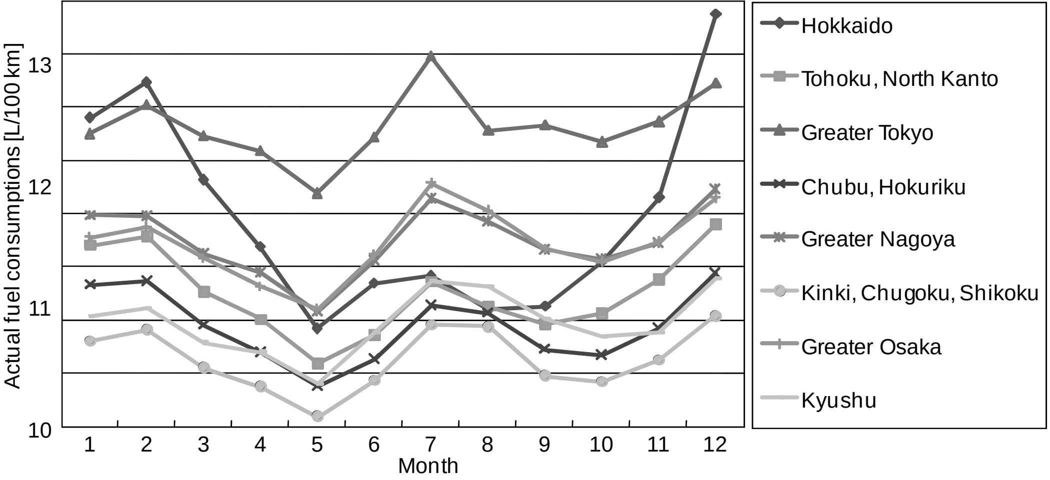
ABSTRACT

As one measure to reduce CO_2 emissions from the transportation sector, the application of solar reflective paint (SRP) to automobile bodies is being considered. In order to quantify the CO_2 effects by SRP, we performed driving measurement experiments and numerical heat load simulations. Our results suggest that the following policy would be effective. SRP has larger effects in hotter areas, cars with little insulation, and cars which are driven at low speeds. From the viewpoint of global warming mitigation, it is preferable that policy makers promote the application of SRP to such cars first.

Introduction

In order to reduce CO_2 emissions from the transportation sector, the application of solar reflective paint (SRP) to automobile bodies is being considered. Actual fuel consumption has seasonal changes and those changes seem to depend on the use of mobile air conditioners (MAC). Figure 1 shows seasonal changes in actual fuel consumption (in L/100 km) as exhibited by area in Japan. In every area, the actual fuel consumption was minimized in May. In all areas except Hokkaido, the northernmost region in Japan, actual fuel consumption becomes worse in the summer. One possible reason is the use of MAC. Therefore, improvement of the cabin's thermal environment by SRP should lead to reduction in actual fuel consumption.

Figure 1. Seasonal Changes in Actual Fuel Consumption in Japan



Source: Kudoh, el al. 2004.

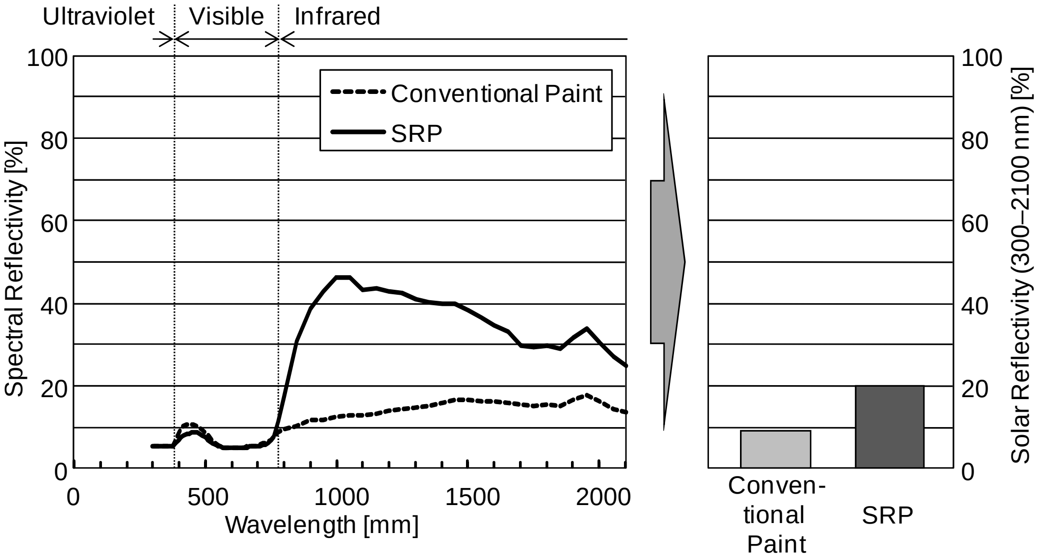
Our past research (e.g., Ihara 2006a; Ihara 2006b) resulted in several findings. Firstly, improvement of actual fuel efficiency by SRP is small: +0.9% in private use and +0.2% in commercial use when an automobile body's solar reflectivity is increased from 8.0% to 50.4%. Secondly, the cost is a lot lower than other CO_2 mitigating technologies in automobiles. In addition, SRP is easy to apply. The low cost makes SRP easy to apply even on a mass basis. When SRP is applied to all passenger cars in Japan, the CO_2 reduction is counted to be 210,000 tons per year. This figure is not small.

However, our past research has been based on results of parking measurement and simulation. Because automobile shape and MAC controls are complicated, it is difficult to evaluate realistic effects on the basis of parking measurement only. In addition, few simulation conditions were used when we evaluated the potential of CO_2 emissions. In this study, we aim to evaluate more realistic CO_2 mitigating effects by SRP through driving measurement and simulation under various conditions.

Measurement Experiment

To evaluate cabin thermal mitigating effects while driving, we performed parking and driving measurements. Two cars were prepared for the measurement. Both cars were colored with dark blue mica metallic, but one was coated with SRP and the other was conventionally coated. Both reflectivities are shown as Figure 2. However, SRP of Figure 2 has solar reflective pigments in only its finish base coating and middle coating. It does not have in its electrocoating because we recoated the existing car with it. The solar reflectivity is increased by 10.9%, from 9.3% to 20.1% by replacement of normal pigments with solar reflective pigments in its middle and finish base coatings.

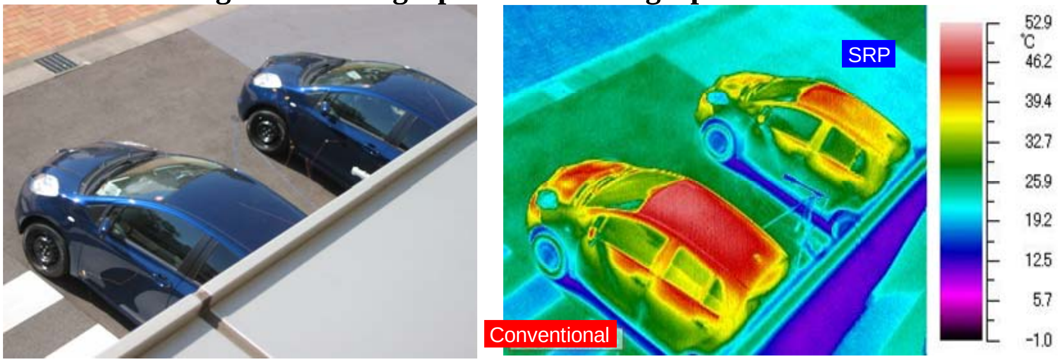
Figure 2. Solar Reflectivity of SRP (Dark blue mica metallic)



Source: Nippon Paint Co., Ltd.

Figure 3 shows one of our experiment's results. This photograph was taken on Jan. 29th, 2006. Both cars in Figure 3 are the exact same color, however, the car on the left is conventionally coated and the car on the right is coated with SRP. Simultaneously, a thermograph was also taken. From the thermograph, we find that the automobile body's surface temperature was reduced. When compared to conventional paint, SRP was able to reduce a car's surface temperature by 5–10 °C.

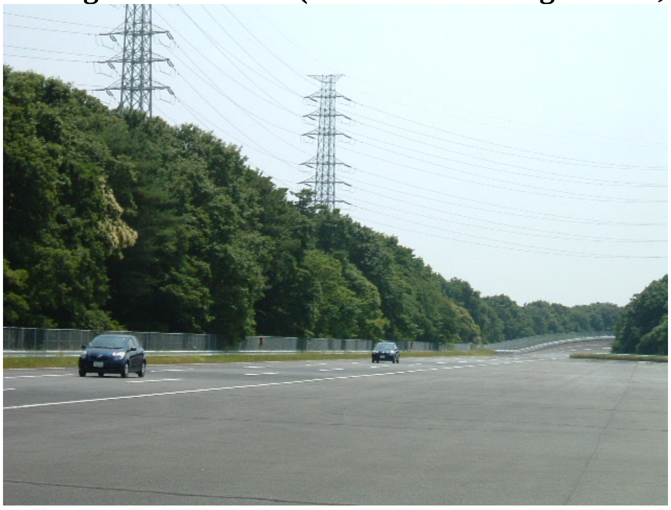
Figure 3. Photograph and Thermograph of the Cars



Driving Measurement

We drove the two cars on the National Institute of Advanced Industrial Science and Technology (AIST)'s test driving course in Tsukuba under controlled conditions during six days in August of 2008 (see Figure 4).

Figure 4. Driving Measurement (AIST Test Driving Course, Tsukuba)



When driving, we also measured the cars' surface and cabin temperatures, weather conditions, and automobile fuel conditions. The measuring items and measurement equipments are listed in Table 1. All items were measured every 1 second. Figure 5 shows the points that were measured with the thermocouples. Table 2 is the controlled conditions.

Table 1. Measuring Items and Measurement Equipments

Measured item	Measuring system		
Solar radiation	Pyranometer: Campbell Scientific LI200X-Lx	→	Data logger: OMRON ZR-RX40
Outdoor air temperature (3 points)	Thermocouples: Yamari DT20TT		
Cabin air temperatures (6 points)			
Inside/outside surface temperatures (10 points)			

Figure 5. Measured Points with Thermocouples

Ch.	Point	Ch.	Point	Ch.	Point
0	(Solar radiation)	4	A/C reference cabin temp.	10	Outdoor air temp. 10mm above the outside surface of the roof
1	Outdoor air temp. 1	5	Cabin temp. at the head of the passenger's seat	11	Temp. at the outside surface of the roof
2	Outdoor air temp. 2 (A/C reference outdoor air temp.)	6	Cabin temp. at the head part of the anterior compartment	12	Temp. at the inside surface of the roof
3	Temp. at the outside surface of the dash panel	7	Cabin temp. at the lumber part of the anterior compartment	13	Cabin temp. 10mm below the inside surface of the roof
		8	Cabin temp. at the head part of the posterior compartment	14	Temp. at the outside surface of the driver's door
		9	Cabin temp. at the lumber part of the posterior compartment	15	Temp. at the inside surface of the driver's door
				16	Temp. at the outside surface of the passenger's door
				17	Temp. at the inside surface of the passenger's door
				18	Temp. at the outside surface of the rear door
				19	Temp. at the inside surface of the rear door

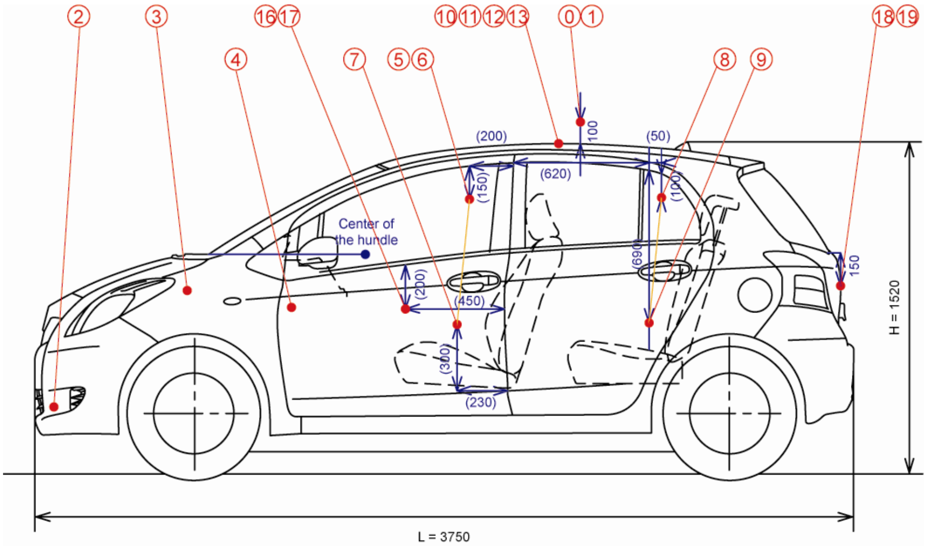


Table 2. Measurement Conditions

Parameter	Value	
Driving	(5)	Driving at constant speeds: 20, 30, 40, 50, and 100 km/h *The measurement was mainly performed under 20, 50, or 100 km/h.
Air conditioning	(2)	25 °C without stopping when idling, no air conditioning
Ventilation	(1)	No natural ventilation with the all car windows closed
Driver	(8)	A, B, C, D, E, F, G, and H
Period	-	Aug. 12th, 14th, 18th, 19th, 20th, and 22th Every 20 minute of 10:00–11:40/13:00–16:00 (*e.g.*, 14:20–14:40)

In addition, some meteorological elements are being observed at Japan Meteorological Agency's observation stations close to the driving course. For our analysis, outdoor air temperature data at Shimotsuma station (7.0 km away from the driving course) and solar radiation data at Tateno station (16.3 km) were used because they have higher reliability than our observed data.

Parking Measurement

We also performed parking measurement when driving measurement was not performed. In parking measurement, the same items were measured.

Results

We removed error data from the measured data and averaged them every 5 minute. The result showed that the top plate surface temperature was reduced even when driving but cabin temperatures were not reduced. This is because the effect of a 10.3 % rise in solar reflectivity is small and each measurement was performed under different conditions (see Table. 2). In order to remove effects by the measurement conditions other than the effect of solar reflective paint, we analyzed the results with the following multi regression model at every vehicle speed.

$$\Delta T_c = T_{c,\mathrm{srp}} - T_{c,\mathrm{cvt}}$$

$$T_c = a_{\mathrm{srp/cvt}} I + b H_i + T_o$$

Here,

ΔT_c : Temperature difference between the conventionally coated car (cvt) and the car with coated with SRP (srp) [°C]

$T_{c,\mathrm{srp/cvt}}$: The cabin temperature [°C]

I : Solar radiation [W/m^2]

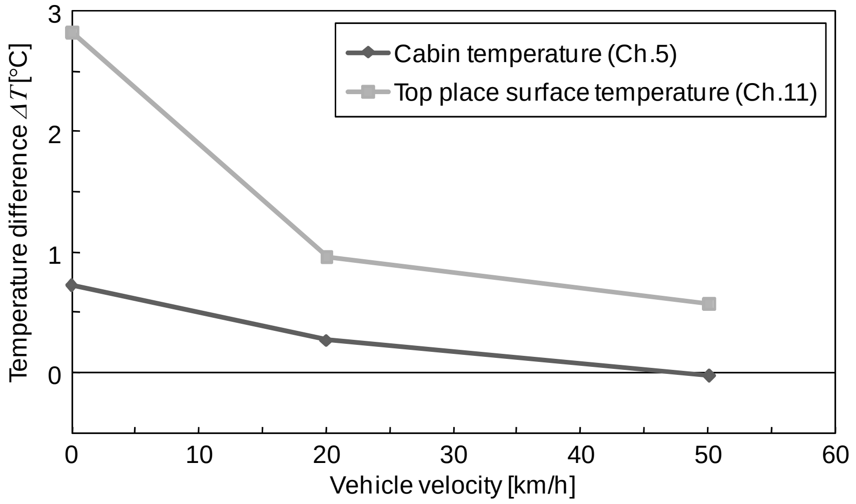
H_i : Sensible heat from a driver [W] (i : driver, i = 1~8)

T_o : Outdoor air temperature [°C]

$a_{\mathrm{srp/cvt}}$, b Coefficients.

Among the above parameters, H_i, $a_{\mathrm{srp/csv}}$ and ΔT_c are unknown parameters. The least-squares method was applied to the above regression model. The analyzed results are shown in Figure 5. Figure 5 shows the results when driving at 20 km/h and 50 km/h and parking (0 km/h). The cabin temperature was reduced even when driving but the cabin thermal mitigating effect was reduced when driving at high vehicle speed.

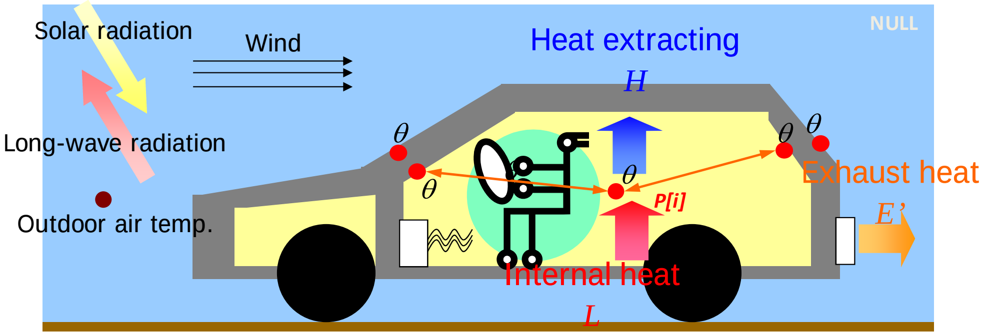
Figure 5. Relationship between Temperature Reductions and Vehicle Speed



Simulation under Various Conditions

The CO_2 reduction effect by SRP is varied by not only vehicle speed but also meteorological conditions and car insulation conditions. We developed a simple heat load simulation program (Ihara, et al 2006a; Ihara, et al 2006b) based on the building heat load simulation program (Ihara, et al 2002; Ihara, et al 2003) to evaluate the effect under various conditions (see Figure 6). From the simulation we found that highly insulated cars reduce SRP effects. We also found that SRP is more effective in hotter areas.

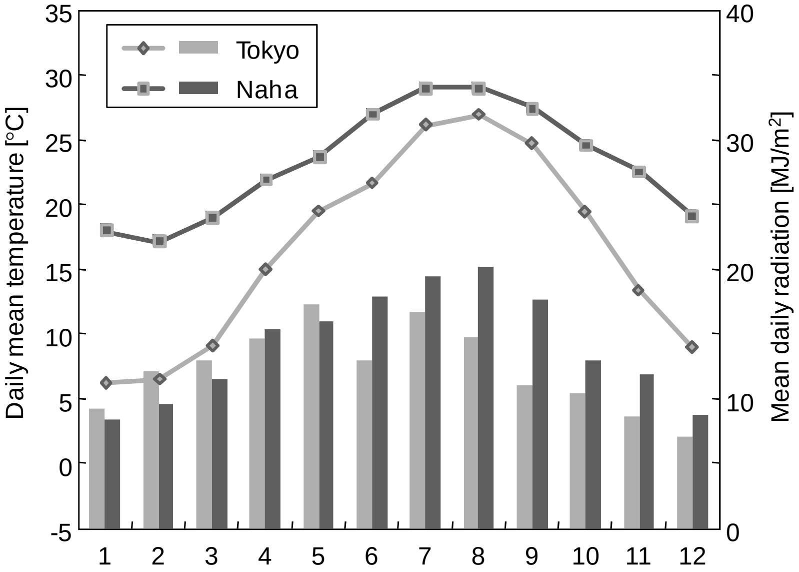
Figure 6. Heat Load Simulation Model



Relationship between Meteorological Conditions and SRP Effects

The SRP effect is considered to change by meteorological conditions. We took up two cars which are a conventionally car and a car coated with SRP and evaluated the effect under Tokyo and Naha. Naha is the southernmost and hottest city among the major cities in Japan. Figure 7 shows annual change in outdoor air temperature and solar radiation there. A typical year in Figure 7 is composed of meteorologically typical 12 months from 1981 to 2000. In the typical year, mean daily solar radiation throughout the year in Tokyo is 12.3 MJ/m^2 and that in Naha is 14.2 MJ/m^2. The difference is not large. However, yearly mean outdoor air temperature in Tokyo is 16.6 °C and that in Naha is 23.3 °C. The difference in outdoor air temperature reaches 6.7 °C.

Figure 7. Annual Change in Outdoor Air temperature and Solar Radiation in Tokyo and Naha in Typical Year



Compiled from Expanded AMeDAS Weather Data (AIJ, 2005)

The simulation conditions are following. The solar reflectivities of the cars are listed in Table 3. The scenario without SRP in electrocoating means the experiment condition (see Figure 2). Another scenario is a scenario assuming real application of SRP. Weather conditions have been shown in Figure 7. Table 4 is the driving conditions.

Table 3. Solar Reflectivity of Automobile Body

Body color & how to apply SRP	Conventional coating		SRP coating	*ΔR*
Dark blue mica metallic (without application of SRP to electrocoating)	9.8%	→	20.1%	+10.3%
Dark blue mica metallic (with application of SRP to electrocoating)	8.0%	→	50.4%	+42.4%

Source: Nippon Paint Co., Ltd.

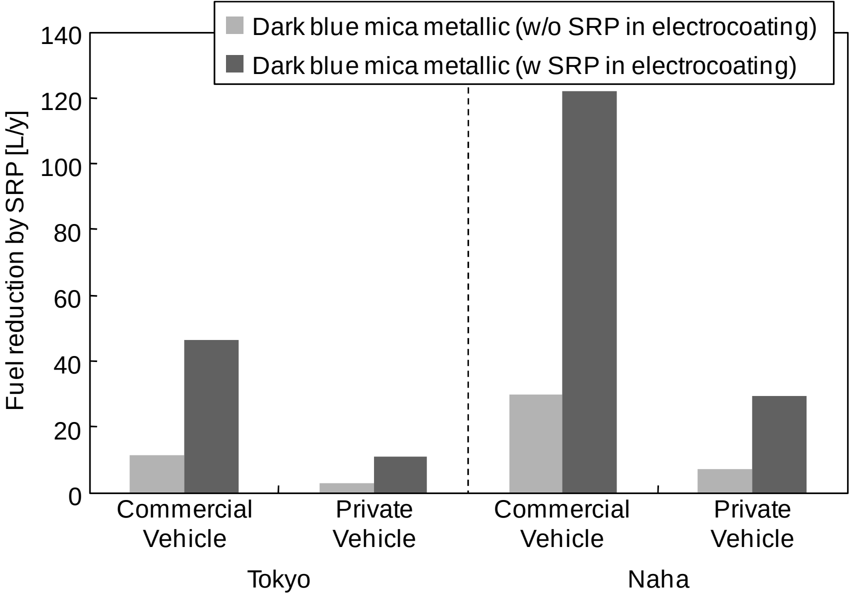
Table 4. Driving Conditions

Driving conditions	Private vehicle	Commercial vehicle	References
Yearly mileage [km/y]	10,575	63,113	Average yearly mileage
Daily mileage [km/d]	43.5	216.9	Average vehicle velocity: 18.8 km/h (Tokyo Met., Special wards)
Driving time	Mon.~Fri., 1.82 h/d	Mon.~Sat., 9.07 h/d	Default schedule (SCHEDULE)
	Getting to work 7:30~7:45	Working 8:45~17:45	
	Shopping 11:30~12:00		
	Shopping 15:00~15:45		
	Getting back from work 19:15~19:30		
Setting air temp. of MAC [°C]	20 (Lower) ~ 25 (Upper)		

Mileage: MLIT(2005), Vehicle velocity in Tokyo: MLIT(2006), and Schedule: SHASE(2000)

Figure 8 is one of our simulation results. Naha is hotter than Tokyo. Taken up the case with SRP in electrocoating, the car coated with SRP reduced annual fuel consumptions by 46.2 L for commercial use and 11.1 L for private use in Tokyo. However, those reached 122.0 L for commercial use and 29.4 L for private use in Naha. The result shows that SRP reduces fuel consumption in Naha almost three times than that in Tokyo.

Figure 8. Reduction in Annual Fuel Consumption in Tokyo and Naha



Policy Proposition Regarding Installation of SRP to Automobiles

The fuel reduction effect by SRP is not large. However, through our measurement experiment, SRP has effect even if driving. In addition, its installation cost is small.

SRP is considered to reduce fuel consumption of any car. Therefore, it is possible that the fuel efficiency of eco cars is improved by the application of SRP. However, most of the eco cars have already been insulated well. SRP has larger effects in hotter areas, cars with little insulation, and cars that are driven at low speeds. From the viewpoint of global warming mitigation, it is preferable that policy makers promote the application of SRP to such cars first.

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