Program Record (Vehicle Technologies Office)	
Record #:	**Date:** June 19, 2024
Title: Greenhouse Gas Emissions for Annual Construction and Maintenance of U.S. Roadways	
Originators: Rakesh Iyer, Jarod Kelly, Kang Shen, and Michael Wang	
Independent Reviewers: Kara Podkaminer, Branden Leonhardt, Diana Galperin	
Approved by: Austin Brown, Sarah Ollila, Patrick Walsh, Raphael Isaac	**Date:** August 14, 2024

Item

In addition to the production and use of fuels and vehicles, roadway infrastructure construction and maintenance contributes to the transportation sector's greenhouse gas (GHG) emissions. This record documents a life cycle GHG analysis of public roadway infrastructure construction and maintenance in the United States (U.S.) using a largely bottom-up approach that considers specific materials and usage quantities in U.S. road infrastructure. The results include embodied emissions from roadway construction and maintenance materials, usually the largest emission sources for roadways. The annual consumption of materials reported here characterizes the construction of new roads and bridges and the maintenance of existing roads and bridges. In addition, the GHG results also consider the emissions of construction and maintenance equipment operations based on results from existing literature. These GHG emissions results are normalized by a consistent functional unit, the total U.S. annual vehicle miles traveled, to derive an average GHG footprint for public roadway infrastructure on the cradle-to-grave life cycle emissions of vehicles. Finally, the sensitivity of significant assumptions made on results is considered.

Background

Roadways are a crucial element of road transportation, particularly in assessing the transportation system. However, existing studies on the life cycle GHG analysis of roadway infrastructure are mainly based on outdated data and utilize either the Economic Input-Output life cycle analysis (EIO-LCA) or Hybrid methods that combine EIO-LCA and process-based LCA [1]. Both EIO-LCA and hybrid methods are known to overestimate emissions relative to bottom-up/process-level methods [2,3], which can lead to an inconsistent assessment of the most important drivers of LCA burdens. Further, the definition of *infrastructure* in existing assessments of transportation [1] includes not only roadway construction and maintenance[1] but also other activities such as roadway de-icing, salting, and the construction of individual and mass parking spaces. Usually, these additional activities are not included in the definition of "roadway infrastructure," and data for these activities is less easily accessible. Hence, to address this research gap and focus only on roadway infrastructure instead of other auxiliary activities, the life cycle GHG emissions of roadway infrastructure were calculated considering a clearly defined system boundary encompassing the construction and maintenance of U.S. roads and bridges. GHG emissions were computed using the embodied emissions of key materials in Argonne National Laboratory's Research and Development Greenhouse gas, Regulated Emissions, and Energy use in Technologies (R&D GREET®) 2023 model

[1] Maintenance refers to the built maintenance, i.e., any maintenance that involves re-surfacing and re-constructing a road and/or bringing the road to its near-original or original state (when it was first built/constructed), since the focus is on infrastructure-related emissions.

[4,5]. Additionally, GHG contributions from roadway construction and maintenance processes were calculated using assumptions based on literature [6,7] and are included in this analysis.

Assumptions for Analysis

Concrete (plain and steel-reinforced) and asphalt mixtures are the primary materials used to construct and maintain U.S. roads and bridges. Several assumptions were considered for these materials in this analysis. Table 1 lists these assumptions in detail, along with the appropriate references.

Table 1. Key assumptions/values for materials in this study

Material or Parameter	Details		Assumed value
Plain/Reinforced concrete	Composition of concrete	Cement	9 wt.% (15 vol.%) [4,5]
		Aggregates (incl. sand and water)	91 wt.% (85 vol.%) [4,5]
	Steel reinforcement	% of concrete roads reinforced with steel	20% (this ranges over 10-30% per literature [8])
		% of steel in reinforced concrete	0.6 wt.% [9]
		% of recycled steel content	72% [10]
Asphalt mixture	Composition of asphalt mixture	Asphalt binder	5 wt.% [4,5]
		Aggregates	95 wt.% [4,5]
	% of recycled content	Asphalt binder	20% [8]
		Aggregates	23% [8]
	GHG footprint of recycled content	Asphalt binder and aggregates	0 kg $CO_{2\text{-eq}}$/metric ton of binder or aggregate
	Usage of other constituents	Lime^	7.7 kg/metric ton of asphalt mixture [11]
		Polymer*	1.8 kg/metric ton of asphalt mixture [11]

^Lime is added in the form of hydrated lime is added as a constituent in asphalt mixture. Hydrated lime (calcium hydroxide or ($Ca(OH)_2$)) is produced by mixing quicklime (lime, i.e., calcium oxide or CaO) in water (H_2O). This analysis assumes that water has zero GHG footprint. Thus, for GHG calculations, lime use represents the actual use of hydrated lime in asphalt mixture, after accounting for lime's contribution to the weight of hydrated lime (lime constitutes 76 wt.% of hydrated lime per chemical stoichiometry). Per [11], 10.1 kg of hydrated lime is used per metric ton (MT) of asphalt mixture, which translates to 7.7 kg of lime use per MT of asphalt mixture.

*Per [11], the polymer used is styrene-butadiene-styrene (SBS). Since the R&D GREET model [4,5] does not contain the GHG footprint of SBS, we use acrylonitrile-butadiene-styrene (ABS) resin as a substitute for ABS in calculating the GHG contributions of polymer to roadway infrastructure impacts. Also, [11] provides the use of 1.8 kg/metric ton of asphalt mixture.

Furthermore, this analysis makes assumptions regarding two parameters, the share of public roadway infrastructure in the U.S. asphalt market, and the share of GHGs from operation and maintenance equipment in the life cycle GHG emissions of roadway infrastructure (for this parameter, values in the literature show a large range of 10-30% [8]). Sensitivity (scenario) analyses were conducted to evaluate the effect of the variation of these parameters on the total GHG emissions of roadway infrastructure. Table 2 provides these parameters, along with their values for both the baseline scenario and alternative scenarios considered in the sensitivity analyses.

The first parameter is the share (%) of public roadway infrastructure in the total U.S. asphalt market. The baseline scenario assumes that all asphalt in the U.S. is used to construct and maintain public roadways. For sensitivity analysis, the value of this parameter is taken as 65%, as this represents the share of publicly funded highway programs in the U.S. asphalt market [12]. Note that while a substantial portion of U.S. roads are constructed using funds from these highway programs, there are U.S. roads that are constructed using funds from other sources (such as rural roads and county roads). These roads, as well as other infrastructure (e.g., individual and mass parking spaces), comprise the remaining 35% share of the U.S. asphalt market. The sensitivity analysis scenario assumes that only roads built using highway programs constitute public roadway infrastructure.

The second parameter is the share of GHG emissions of the operation of construction and maintenance equipment (e.g. onsite generators, rollers, graders, semi-trucks, loaders, etc.….) in the total life cycle GHG emissions of roadway infrastructure. Per literature [6,7], this share ranges between 5% and 30% across different nations and types of roads. In the baseline scenario, the value of this parameter is assumed to be 20%, while the sensitivity analysis scenarios use values of 10% and 30% for this parameter.

Table 2. Parameters and scenarios for sensitivity analyses

Parameter	**Values**	
	Baseline scenario	**Sensitivity analyses scenarios**
Share (%) of public roadway infrastructure in the total U.S. asphalt market	100% (assumed)	65% [12]
Share (%) of GHGs from operations of construction and maintenance equipment in total life cycle GHG impacts of roadway infrastructure	20%	10% and 30% (based on [6,7])

Material Inventory

Based on the assumptions for different materials and parameters in this analysis (Tables 1 and 2), Table 3 summarizes the annual usage of concrete, steel (in reinforced concrete), and asphalt mixture for all U.S. roads and bridges. Here, U.S. roads include all federal, state, and local roads across urban and rural landscapes.

According to the Portland Cement Association (PCA), 12 million metric tons (MMT) of cement is used annually to build and maintain roads [13], with an additional 9 MMT of cement used annually to construct bridges [14]. Concrete is produced using a mix of cement, sand, aggregates, and water. Based on the U.S. national average material shares for different constituents in concrete (provided in Table 1) [4,5], the annual concrete use for U.S. roads and bridges is obtained as 233.3 MMT. Further, based on our assumptions that only 20% of concrete roads are reinforced with steel [8] and that steel constitutes 0.6 wt.% of reinforced concrete [9], an additional 0.3 MMT of steel is used annually for U.S. roads and bridges in reinforced concrete. Lastly, the National Asphalt Pavement Association (NAPA) [12] presents the annual asphalt mixture production at 391.9 MMT. Assuming it is all used for U.S. roads in the baseline scenario (Table 2), this translates to 19.6 MMT of asphalt binder and 372.3 MMT of aggregates used for public U.S. roads and bridges (for more details on asphalt mixture composition, see Table 1).

Table 3. Annual Quantity of Materials Used for U.S. Roadway Construction and Maintenance

<table>
<tr><th colspan="3">Materials (wt.%)</th><th colspan="2">Annual quantity of use (MMT/year)</th></tr>
<tr><th>Material Category</th><th>Constituents</th><th>Sub-constituents</th><th>Sub-total (Sub-constituents)</th><th>Total (Constituents)</th></tr>
<tr><td rowspan="2">Concrete</td><td>Cement</td><td></td><td>21</td><td rowspan="2">233.3</td></tr>
<tr><td>Aggregates</td><td></td><td>212.3</td></tr>
<tr><td rowspan="2">Steel (for reinforced concrete)</td><td>Virgin (28%)</td><td></td><td>0.1</td><td rowspan="2">0.3</td></tr>
<tr><td>Recycled (72%)</td><td></td><td>0.2</td></tr>
<tr><td rowspan="8">Asphalt mixture</td><td rowspan="3">Asphalt binder</td><td>Virgin</td><td>15.7</td><td rowspan="6">391.9</td></tr>
<tr><td>Recycled</td><td>3.9</td></tr>
<tr><td>Total</td><td>19.6</td></tr>
<tr><td rowspan="3">Aggregates</td><td>Virgin</td><td>286.7</td></tr>
<tr><td>Recycled</td><td>85.6</td></tr>
<tr><td>Total</td><td>372.3</td></tr>
<tr><td>Lime</td><td></td><td></td><td>3.0</td></tr>
<tr><td>Polymer</td><td></td><td></td><td>0.7</td></tr>
</table>

GHG Impact Analysis

The R&D GREET model provides the GHG intensities of all the constituent material inputs for roadway construction and maintenance [4]. Each material's intensity is multiplied by its corresponding mass (provided in Table 3) to calculate the GHG contributions of all the input materials toward roadway infrastructure. Table 4 summarizes the material mass, GHG footprint (per metric ton), and the resultant contribution of each input material to the total GHG emissions of U.S. roadway infrastructure. The same table also provides the total life cycle GHG impacts of U.S. roadway infrastructure, assuming that construction and maintenance processes comprise 20% of these impacts (see Table 2). Additionally, Figure 1 shows the total life cycle GHG footprint of U.S. roadway infrastructure, with a breakdown by contributions from different materials and construction processes.

Based on these life cycle GHG impacts, Table 5 provides the average GHG footprint of U.S. roadways on a per vehicle-miles-traveled (VMT) basis, based on the total VMTs for the year 2022 [15]. Note that in Table 4, the aggregates for concrete are broken down by contributions from water (assumed to have zero GHG footprint) and other aggregates (primarily sand and gravel). Further, existing literature shows that an increase in roadway construction activities could result in an increase in the amount of vehicle driving [16], and thereby, on the VMTs involved. However, this analysis does not consider such induced or rebound effects.

Table 4. Total Life Cycle GHG Impacts of U.S. Roadway Construction and Maintenance

Contributing Factors	Sub-factor	Annual use (MMT/yr.)	GHG footprint [4,5] (kg $CO_{2\text{-eq}}$/metric ton)	Total GHG emissions (MMT $CO_{2\text{-eq}}$)
Materials	Concrete: Cement	21	951	20.0
	Concrete: Aggregates (without water)	196	6	1.2
	Concrete: Water	16.3	0	0
	Concrete: Production	217.0	6	1.2
	Steel: Virgin	0.1	3,032	0.24
	Steel: Recycled	0.2	702	0.14
	Asphalt binder: Virgin	15.7	1,552	24.3
	Asphalt binder: Recycled	3.9	0	0
	Aggregates: Virgin	286.7	6	1.7
	Aggregates: Recycled	85.6	0	0
	Lime	3.0	1,282	3.9
	Polymer	0.7	3,351	2.3
Construction and maintenance	Operation of equipment			13.8
Total life cycle GHG emissions of U.S. roadways infrastructure				**68.8**

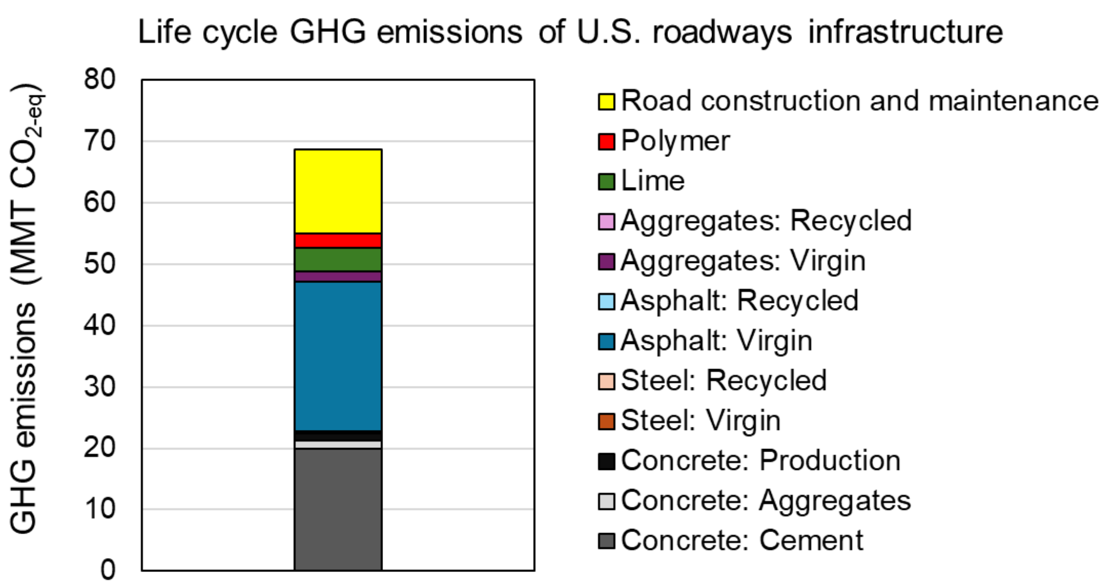

Figure 1: Total life cycle GHG footprint of U.S. roadways infrastructure by constituents and processes

Table 5. Average GHG Footprint of U.S. Roadway Construction and Maintenance

Parameters	Values	Units
Life cycle GHG impacts of U.S. roadways infrastructure	68.8	MMT $CO_{2\text{-eq}}$
Annual vehicle miles traveled	3,196,095 [15]	Million vehicle miles
Average GHG footprint	21.5	g $CO_{2\text{-eq}}$/VMT

Overall, the cement used in concrete, virgin asphalt binder, and road construction and maintenance processes, together dominate the life cycle GHG impacts of U.S. roadway infrastructure. For cement, major GHG contributions stem from high process carbon emissions generated due to the chemical decomposition of limestone and the combustion of fossil fuels during cement making in kiln [4,5]. Virgin asphalt binder production contributes to the GHG footprint of U.S. roadway infrastructure on account of substantial GHG emissions associated with refining processes and the combustion of refinery still gas for them [4,5]. Finally, the share of roadway construction and maintenance processes in the life cycle impacts of U.S. roadway infrastructure is based on their assumed share of 20%, as mentioned in Table 1. Additional contributions are from lime (due to process carbon emissions during its production from limestone) and polymer (due to its production from crude oil resources) [4,5].

The total annual GHG footprint of U.S. roadway infrastructure (construction and maintenance) is estimated at ~68.8 MMT $CO_{2\text{-eq}}$. According to the U.S. Department of Transportation (DOT) [15], the annual VMT for all vehicles on the road in the U.S. is ~ 3.2 trillion vehicle miles. This translates to an average life cycle GHG burden of U.S. roadway infrastructure of 21.5 g $CO_{2\text{-eq}}$/mile (Table 5).

Sensitivity (Scenario) Analyses

Figure 2 shows the variation in the average GHG footprint of U.S. roadway infrastructure (construction and maintenance) with changes in the parameters considered for scenario analyses in Table 2. The x-axis values in Figure 2 refer to the market shares of public road infrastructure in the U.S. asphalt market (100% for baseline and 65% for sensitivity scenarios). The error bars in Figure 2 highlight the variation in the average GHG footprint of roadway infrastructure with changing shares of construction and maintenance processes in the total life cycle impacts of this infrastructure (from 10% to 30%; Table 2).

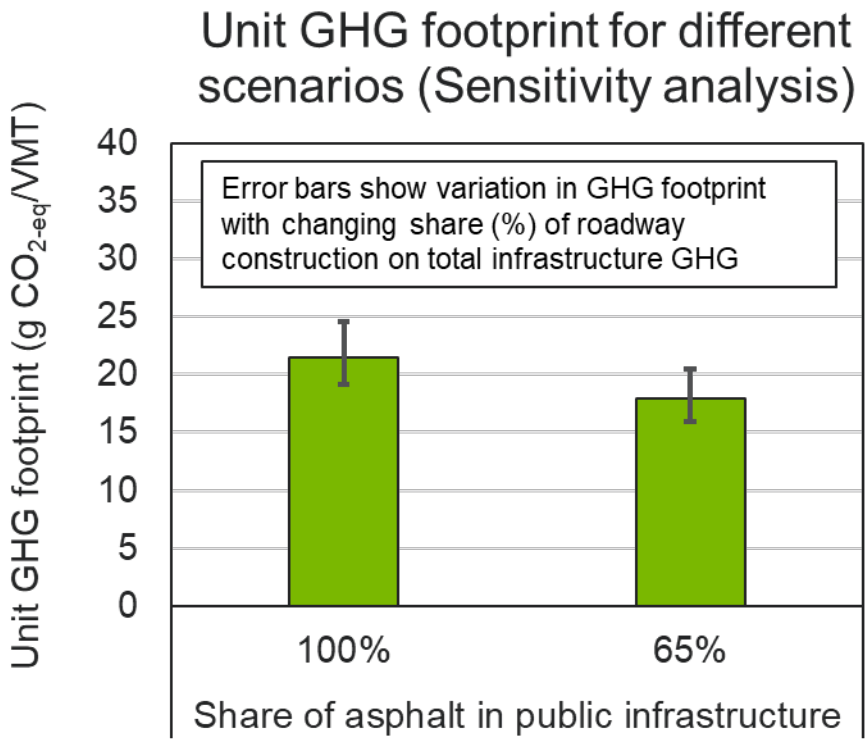

Figure 2: Average GHG footprint of U.S. roadway infrastructure under baseline (100%) and sensitivity (65%) analysis scenarios

Two results stand out from Figure 2. First, a reduction in the share of U.S. roadways in the overall asphalt market (from 100% to 65%) causes a significant decrease (by ~17%) in the average GHG footprint of U.S. roadway infrastructure over the baseline scenario. Second, the variation in the share of construction and maintenance processes in the life cycle GHG impacts of U.S. roadway infrastructure (10-30%, shown in error bars) causes a notable shift (~10-15%) in these life cycle impacts compared to the baseline values. Note that both scenarios overlap with each other to produce similar results. In other words:

a. Regardless of the value of the share of construction and maintenance in the life cycle GHG emissions of roadway infrastructure, reducing the share of U.S. roadways in the asphalt market from 100% to 65% causes a ~20% reduction in the GHG footprint of roadway infrastructure; and
b. Varying the roadway construction GHG intensity between 10% and 30% causes a ~11% reduction and ~14% increase, respectively, in the GHG footprint for roadway infrastructure.

Roadway Infrastructure (Construction & Maintenance) Impacts in the Context of Road Transportation GHGs

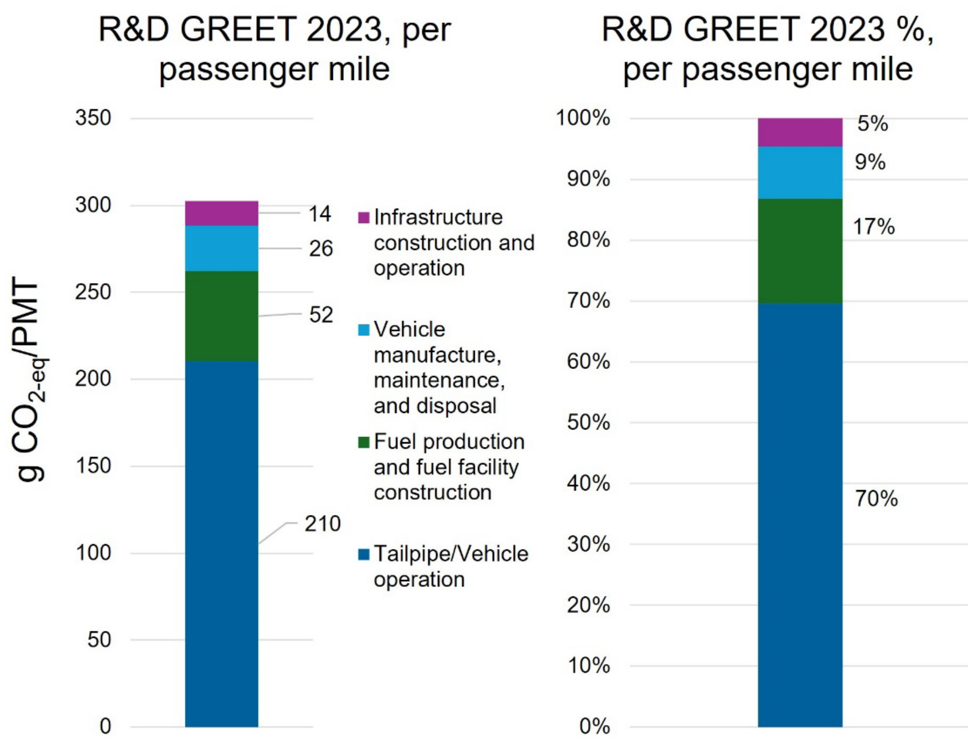

Figure 3: Life cycle GHG impacts of sports utility vehicle (SUV), highlighting GHG contributions from U.S. roadway infrastructure to the total GHG emissions

To place the impacts of U.S. roadway infrastructure in context, these impacts are coupled with the other impacts over the life cycle of a sports utility vehicle (SUV), as an example. The SUV's impacts are based on the R&D GREET 2023 model, which provides these impacts on a VMT basis. These impacts are converted to a passenger-mile-traveled (PMT) basis, assuming 1.54 passengers per car [17]. Figure 3 shows the GHG impact contributions and the corresponding shares of four life cycle stages to the life cycle GHG impacts of an average SUV, namely[2]:

a. Tailpipe emissions during vehicle operation;
b. Fuel production and fuel facility construction;
c. Vehicle manufacture, maintenance, and disposal; and
d. (Roadway) infrastructure construction and operation

Overall, U.S. roadway infrastructure comprises a ~5% share of the life cycle GHG impacts of SUVs. Even if we consider the range of results presented in our sensitivity analysis (see previous section), this

[2] The four life cycle stages of SUV correspond to GHG impact contributions from the following activities (as defined in the DOE EERE R&D GREET 2023 Fact Sheet [18]:

a. Tailpipe emissions during vehicle operation → Use: Vehicle Operation
b. Fuel production and fuel facility construction → Construction: Fuel Production Facility + Production: Fuel
c. Vehicle manufacture, maintenance, and disposal → Production: Vehicle + Production: Battery + End-of-life: Vehicle & Battery disposal; and
d. (Roadway) infrastructure construction and operation → Not included in the Fact sheet

translates to a narrow range of 3-5% share of the life cycle GHG impacts of SUVs. In contrast, tailpipe emissions during vehicle operation (~70% share) and fuel production with fuel facility construction (~17% share) dominate the SUV's life cycle GHG impacts (Figure 3).

Ongoing Research

The above estimated GHG intensity for road infrastructure is based on the current material production technologies (e.g., for cement, steel, and asphalt). R&D efforts are underway to reduce the GHG footprints of these materials, which, if successful, will result in potentially reduced road infrastructure GHG intensities. On the other hand, the impacts of operations of construction and maintenance equipment is approximate in the above assessment, using specific assumptions based on the literature (note that the transportation of these materials is included in R&D GREET LCA). With additional efforts, this assumption can be updated with the use of a bottom-up LCA approach. A bottom-up approach will be able to assess the effects of material substitution, road infrastructure longevity, material durability, and technologies that improve the materials' sustainability on the GHG intensities of roadway infrastructure. Thus, decarbonization efforts in other sectors will be reflected in the sustainability performance of U.S. roadway infrastructure.

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