FINAL REPORT

Regional impacts of telemobility options: Capitalizing on the two-way relationship between infrastructure investments and travel demand

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### Abstract
Communications technologies and e-commerce have profound effects on travel, on the delivery of goods and services, and consequently, on the use of transportation infrastructure. As e-commerce continues to grow, including the spike from pandemic-era lockdowns, an effect of the growth of home deliveries is the potential impact on pavement performance from the increased number of delivery vehicles. Delivery vehicles are heavier than personal vehicles and their greater weight has an outsized impact on pavement wear, especially in the case of residential streets designed for limited traffic volumes. A method of accounting for the increased heavier traffic is presented as slightly changing the pavement design such that the maintenance schedule of these roads remains the same. The analysis is then redone to account for the increased weight of electric delivery vehicles.
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INTRODUCTION

E-commerce and home deliveries have become a significant part of life with the widespread growth of the internet and companies such as Amazon and Alibaba. The ease of being able to shop online and the convenience of shorter delivery times with minimal additional shipping costs have created a very favorable environment for e-commerce. Familiarity with the internet has become much more commonplace at all age levels over the past decade, and connectivity to the internet continues to spread throughout the world. Both factors show how online retail is becoming even more of a competitor with brick-and-mortar retail options. There are many facets of development that have led to this steady growth in e-commerce, but none of these factors had as much of an immediate impact as the abrupt and radical changes to consumer behavior as the COVID-19 pandemic and lockdowns that came along with it.

The pandemic and lockdowns had a direct impact on e-commerce. Consumers were at home with few things available for them to do. There were public health concerns about leaving one’s home and interacting with others. Physical retail stores were closed in many places. Each of these factors would be expected to lead to an increase in home deliveries from online shopping. There were also temporary income increases in the U.S., which led to an overall increase in retail purchases. The temporary increases to income came from programs introduced by the U.S. Federal Government, such as suspending student loan payments, larger tax credits, and direct payments to individuals below certain income thresholds.

Persisting impacts of lockdowns are seen very clearly in travel, work, and consumer behaviors over the past few years. Telework, or work-from-home, became the norm for many during lockdowns and has remained at levels unseen before the COVID-19 pandemic. In May 2020, “42% of the U.S. labor force” was working from home and “33% are not working” Bloom (1). And according to the U.S. Census Bureau (2), “the number of people working from home tripled between 2019 and 2021”. Working from home has also impacted the number of deliveries being made since people no longer were commuting to and from work giving them one less reason to leave their home.

The greater amount of shopping being done online has required e-commerce, logistics, and delivery companies and providers to grow to meet the increased demand. This is a direct and necessary outcome for the companies to function and the customer’s needs to be met. There are also indirect effects that may not need to be dealt with immediately to keep the industry running and are not managed by such companies. The social costs analyzed in this study are the impacts of increased delivery vehicles on the pavement performance and the potential impacts on the environment in residential areas. The pavement performance will be considered through deterioration and the necessary maintenance schedules to keep up the condition of the pavement.

To illustrate, we present a case study where we analyze potential effects of delivery vehicles on the road network of the City of Evanston, Illinois as an example of a suburban area with many residential streets with minimal traffic on them. These types of roads have lesser pavement structures due to the nature of their regular traffic levels, and thus have the most outsized impact made by delivery vehicles of any size greater than a personal vehicle. The minimal traffic in these areas also creates a similar situation when considering the effect of emissions,
which is touched on in the discussion section. Since there are so few vehicles traveling in these areas to begin with, the increase in larger delivery vehicles would also have a relatively greater environmental impact.

An extension of this analysis is projecting the transition to electric delivery vehicles in urban areas and then the impact that their greater weights have on the pavement performance of residential streets. The increased number of delivery vehicles and the increased weight of electric vehicles are each studied to find the requisite changes to the pavement design to keep the pavement maintenance resurfacing schedule approximately the same as the existing schedule to mitigate social costs.

The paper begins with a literature review of existing works that set the foundation for the analysis completed and show examples of similar subject matter studied. This is followed by background information that includes the motivation for the case study building upon the introduction. Then, the methodology and analysis sections present the methods used and the analysis conducted to understand the pavement wear. This is followed by the results section which includes the impacts of increasing delivery vehicles on pavement performance, and then an additional subsection going over how transitioning to electric delivery vehicles has a similar effect as increased loading. At the end of the paper, there is a discussion section going over environmental impacts, and then final conclusions found from the analyses conducted.

LITERATURE REVIEW

There are many examples of previous works that have covered certain aspects of the analysis done in this study. The methods used are established as standards that have been utilized for decades, and there has been a lot of research performed to improve upon these methods. The analysis performed in this study is purposefully simple to exhibit the findings at a level that generates insights that may be useful in formulating public policy, or in other contexts. The methods are based on what is presented as existing standards and new improvements upon them found in Small et al. (3).

One paper that studies a similar subject is from Bushman et al. (4), and they studied commercial vehicle loading in an urban environment using actual traffic and loading data in Saskatoon, a city in Saskatchewan, Canada. Their study analyzed the effect of overloaded commercial vehicles on road wear. They conclude that the excessive and unexpected vehicle loads have “a negative effect on the structural depreciation of the city’s road assets” (4). They also found that the conditions of an urban environment were more so impacted by these increased weights due to the nature of the traffic being stop-and-go or potentially more concentrated. Similar findings were shown in Hajek and Billing (5), which studied different trends in the trucking industry and how those changes impacted pavement design and performance.

A more recent paper, by Intini et al. in 2020, was done specifically on how to design asphalt pavements based on the impact of heavy vehicle traffic (6). Their analysis included looking at traffic growth factors based on historical heavy vehicle traffic data, and then how that influenced traditional asphalt pavement design. Simulations were done to test different pavement structures for different levels of traffic trend estimates. This concept of simulating traffic levels and pavement design is, at a high level, similar to the analysis performed later in this study.
When starting to look at the potential impact of electric delivery vehicles on pavement wear, there were many papers on the general transition to electric vehicles with lots of focus on emissions reduction. One example looked at the reduction in total global warming potential of fleet electrification at different levels including the direct impact on the pavement from Barkh et al. (7). This study involved the development of a pavement Life Cycle Assessment (LCA) model that allowed for variable levels of electric vehicle adoption and determined the global warming potential for different pavement design and construction schedules. This was a foundation for the inclusion of electric delivery vehicles in the pavement wear analysis done, but a key difference in scope is that the levels of EV adoption in the LCA methodology were only for light passenger vehicles. Medium-duty and heavy-duty vehicles were specifically excluded due to less certainty about their adoption. The projections made in our analysis are based only on the transition to electric medium-duty delivery vehicles and no changes to the average weights of other vehicle types.

BACKGROUND
As empirical evidence that supports the ideas studied herein, we observe that in the City of Evanston, IL, the number of locations where pavement patching was completed has nearly doubled over the past five years. In 2018, there were a total of 152 patching locations, and in 2022, there are 296 patching locations. The increase in number of pavement patching locations can be seen in the maps in Figure 1 where each dot represents a patching location. Patching is assumed to extend the life of the road surface by approximately 5 years. An overall decrease in traffic suggests that this is possible evidence of the effect of increased delivery vehicles on residential street deterioration.

To understand the cost impact of the increase in pavement patching, the budget for the 2021 and the estimate for the 2022 patching programs are shown in Table 1. The relationships between the number of patching locations, surface area patched, and the total cost of the program are shown clearly in Table 1. The increasing cost year-over-year makes it clear that if the pavement patching program were to continue to grow, the cost figure has a real impact on a maintenance budget.

<table>
<thead>
<tr>
<th>Year</th>
<th>Patching Locations</th>
<th>Pavement Patching (yd²)</th>
<th>Total Cost (2020 $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021</td>
<td>219</td>
<td>31,118</td>
<td>$562,000</td>
</tr>
<tr>
<td>2022</td>
<td>296</td>
<td>37,500</td>
<td>$642,000</td>
</tr>
</tbody>
</table>

TABLE 1 Comparison of 2021 and 2022 Pavement Patching Programs
METHODOLOGY

Having presented evidence of increased pavement deterioration occurring in Evanston, the next step is to look at the pavement wear analytically. We utilized the AASHO equation, which is included as Equation 1, for the number of equivalent single axle loads that cause pavement quality to decline to the point where resurfacing is required (N). The equation is based on the pavement thickness (D), which in flexible pavements is determined by a linear combination of the pavement, base, and subbase thicknesses. $L_1$ and $L_2$ are parameters that are determined by the weight (18000 lbs. in this analysis) and whether the axle is single or tandem, respectively. This leads to $L_1$ being 18 and $L_2$ being 1 throughout the analysis. The coefficients $A_0$, $A_1$, $A_2$, $A_3$ were estimated by AASHO, and they vary slightly depending on whether the pavement is rigid or flexible (3). For this analysis, only flexible pavements are considered due to the pavement of the residential streets being asphalt throughout almost all of Evanston. The exact coefficients used are presented in Table 2 after the explanation of further assumptions and the different coefficient estimations used.

\[
N = A_0 \times (D + 1)^{A_1} \times (L_1 + L_2)^{-A_2} \times (L_2)^{A_3}
\]  

There are several assumptions made to perform this analysis. These assumptions are based on available project information and data provided by government sources, such as the City of Evanston, the Illinois Department of Transportation (IDOT), and the US Department of Energy. The first assumption made is the average weight of an urban/suburban parcel delivery vehicle
being 14,000 lbs., which came from the median of the gross weights of two different kinds of urban delivery vehicles. These vehicles are both medium-duty as defined by the US Federal Highway Administration. The Greater New Haven Clean Cities Coalition (GNHCCC) combined data from the FHWA and EPA to clearly provide weight range and example vehicles for different vehicle classifications, which led to these weight assumptions (9).

The next assumption made is the average annual daily traffic (AADT) of a residential street in Evanston being 200 vehicles, which was chosen based on a representative road having that as its AADT from IDOT (10).

Another assumption needed for this analysis is that of the pavement type. Most residential streets are asphalt due to it being less expensive and more likely to be used in lower traffic areas. This is also true in Evanston. Based on a project document for redesigning an intersection between an arterial and a residential street, an example of the pavement design used in Evanston can be found (11). The residential street has a surface thickness of 3 inches, and a subbase thickness of 8 inches. These figures are used as the baseline throughout this analysis.

The next set of assumptions are those considering the mix of traffic, as in the amounts of different types of vehicles making up the daily traffic levels. These assumptions are conservative estimates based on a previous study done by Wilde in 2014 to find the impact of heavy vehicles on local roadways (12). This study developed a tool for analyzing heavy vehicles on local roads, and each of their examples involve significantly higher percentage of medium- and heavy-duty vehicles. For residential streets, the mix is set as 5% delivery vehicles, 5% “heavy vehicles” (18000 lbs.), and 90% personal vehicles. The delivery vehicle weight assumption has already been established, the heavy vehicle weight is 1 equivalence factor, and then the rest of the traffic is residential traffic. The personal vehicles are estimated to be evenly split between an average car and an average SUV/pickup truck. The weight of an average car is 4,000 lbs., and the weight of an average SUV/truck is 8,000 lbs. based on the same FHWA data. This mix seemed reasonable since it would account for 10 delivery vehicles and 10 larger trucks/buses each day.

The parameters and coefficients used in the first version of the pavement wear analysis were estimated from the AASHO road test, but Small and Winston estimated updated parameters and coefficients in their book. These Small-Winston estimates are used in the second set of results. These updated estimates are necessary due to the skepticism around the accuracy of the AASHO road test and the formula used overall. An analysis of pavement performance models was completed by Chu and Durango-Cohen in 2008 that covers several different models including the AASHO road test and the Small-Winston estimates used in the analysis performed. The conclusions of this model comparison included that since the AASHO road test was completed in a controlled environment, it may not capture real-world results (13). This is a significant finding, and it is one reason for also using the Small-Winston estimates. Another finding from this model comparison is that both the AASHO and Small-Winston models are best for determining pavement failure, which supports their use in the analysis completed. The exact coefficients estimated from each of these models that were used in the analysis are shown in Table 2.
TABLE 2 Flexible Pavement Coefficient Estimates for AASHO Road Wear Equation (3)

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ln(A_0) )</th>
<th>( A_1 )</th>
<th>( A_2 )</th>
<th>( A_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>AASHO</td>
<td>13.65</td>
<td>9.36</td>
<td>4.79</td>
<td>4.33</td>
</tr>
<tr>
<td>Small-Winston</td>
<td>12.062</td>
<td>7.761</td>
<td>3.652</td>
<td>3.238</td>
</tr>
</tbody>
</table>

ANALYSIS

After establishing these assumptions, the next step of the analysis is to establish a baseline estimate for how long it would take for the pavement to reach a condition that requires resurfacing. This is done utilizing Equation 1, the AASHO equation, and from that, the following pavement lifespans are found. The residential street under its baseline conditions would need to be resurfaced every 11.2 years. This figure is slightly longer than standard resurfacing schedules, but reasonable, especially because interventions, such as patching, are used to extend the service life of pavements.

The same analysis can then be done using the Small-Winston coefficients to find slightly different results due to the updated model. For the residential street at baseline traffic and pavement assumptions, the pavement would need to be resurfaced after 9 years. This reduction in estimated pavement lifespan is expected with the updated model and coefficients used as an improvement over the older AASHO model.

These baseline estimates can now be extrapolated to understand what would happen to the roadways given an increase in delivery vehicles with no other changes to the traffic mix of the street as shown in Table 3.

TABLE 3 Years to Failure of Residential Street (Baseline Pavement)

<table>
<thead>
<tr>
<th>Traffic Mix</th>
<th>AASHO Model</th>
<th>Small-Winston Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Traffic</td>
<td>11.2</td>
<td>9.01</td>
</tr>
<tr>
<td>2x increase of delivery vehicles</td>
<td>9.2</td>
<td>7.43</td>
</tr>
<tr>
<td>4x increase of delivery vehicles</td>
<td>6.82</td>
<td>5.5</td>
</tr>
</tbody>
</table>

For a residential street with all the given assumptions and then the only change being a twofold increase in delivery vehicles per day, the AASHO equation and model results in the pavement lifespan decreasing from 11.2 years to 9.2 years. With a 4-fold increase in delivery vehicles, the residential street now requires resurfacing in 6.8 years compared to 11.2 years at the baseline traffic mix. The change in pavement lifespan is calculated based on an increase in annual total equivalent loadings from approximately 5,995 to 9,827 when going from the baseline to the 4-fold increase in delivery vehicles.
The analysis done with the Small-Winston coefficients also shows decreases in pavement lifespan with increases in delivery vehicles, but with the baseline pavement lifespan being lower, the 2-fold increase in delivery vehicles brings the lifespan of the pavement to a level less than what is being considered standard. With a 2-fold increase in delivery vehicles, the pavement lifespan decreases from 9.01 years to 7.43 years, and then for a 4-fold increase in delivery vehicles, the pavement lifespan decreases from 9.01 years to 5.5 years.

With these new loading levels after the potential 2- and 4-fold increases in delivery vehicles on residential streets, the analysis becomes to understand the impact of changing the structure of the pavement. Given that the resurfacing of pavement primarily involves the surface, the changes considered are increasing the thickness of the surface of the pavement at different increments. Increasing the thickness of the pavement surface is a pavement design change being done to support the increased loads while maintaining the service life of the pavement. This change in pavement design allows for the social costs induced by additional delivery vehicles to be mitigated since the pavement would still have the same service life and similar total maintenance costs.

The baseline assumption is that the residential street has a 3” thick surface, and the first increased thickness tested was 4”, which led to an unreasonable pavement lifespan of 20+ years at all annual loading levels considered. The next step of the analysis was to find the smaller increments of surface thickness increases that resulted in the pavement lifespan remaining approximately the same as the baseline when the number of delivery vehicles is increased.

RESULTS
These first calculations were done by solving for the pavement surface thickness in the AASHO equation to a quarter of an inch under the two increased annual loading scenarios, shown in Figure 4. With a 2x increase in delivery vehicles and a 0.25” increase in pavement surface thickness, the pavement lifespan only increases from 11.2 years to 12.3 years. With a 4x increase in delivery vehicles and a 0.5” increase in pavement surface thickness, the pavement lifespan only increases from 11.2 years to 12.1 years. These findings are shown in Table 4.

<table>
<thead>
<tr>
<th>Traffic Mix</th>
<th>Baseline Pavement</th>
<th>+0.25&quot; Surface Thickness</th>
<th>+0.5&quot; Surface Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Traffic</td>
<td>11.2</td>
<td>14.97</td>
<td>19.92</td>
</tr>
<tr>
<td>2x delivery vehicles</td>
<td>9.2</td>
<td>12.43</td>
<td>16.42</td>
</tr>
<tr>
<td>4x delivery vehicles</td>
<td>6.82</td>
<td>9.13</td>
<td>12.15</td>
</tr>
</tbody>
</table>

The next set of calculations are based off the Small-Winston model with the same pavement surface thickness increases, shown in Table 5. With a 2x increase in delivery vehicles and a 0.25” increase in pavement surface thickness, the pavement lifespan only increases from 9.01 to 9.49 years. With a 4x increase in delivery vehicles and a 0.5” increase in pavement surface thickness, the pavement lifespan slightly decreases from 9.01 to 8.9 years.
TABLE 5 Years to Pavement Failure (Small-Winston)

<table>
<thead>
<tr>
<th>Traffic Mix</th>
<th>Baseline Pavement</th>
<th>+0.25&quot; Surface Thickness</th>
<th>+0.5&quot; Surface Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Traffic</td>
<td>9.01</td>
<td>11.51</td>
<td>14.58</td>
</tr>
<tr>
<td>2x delivery vehicles</td>
<td>7.43</td>
<td>9.49</td>
<td>12.02</td>
</tr>
<tr>
<td>4x delivery vehicles</td>
<td>5.5</td>
<td>7.02</td>
<td>8.9</td>
</tr>
</tbody>
</table>

These changes in pavement lifespan are reasonable increases or slight decreases for keeping the pavement resurfacing schedules the same as they currently are, which allows for a more seamless transition. The increases in pavement surface thickness of 0.25” and 0.5” have minimal impact on cost of resurfacing since the materials costs (asphalt) are relatively constant, while the other costs of road maintenance, which make up a large proportion of the total costs, would not be any different. The “other” costs include social costs, such as road closures, and are much more public facing. These have more of an impact on the community, so the increased materials cost has minimal overall impact. The goal of maintaining the frequency of pavement resurfacing is important because it keeps the fixed, labor, and disruption costs approximately the same. The total costs would remain similar because the slight increase in materials cost can be made up for by not changing the maintenance schedule and avoiding potential increased "other" costs.

Electric Vehicles

The potential transition to electric urban delivery vehicles changes the impact by the nature of the engine and its lack of greenhouse gas emissions, but there will also be an impact on pavement wear. The average “medium-duty urban truck” in 2030 is expected to have an extra 1,444 lbs. of weight compared to the current internal combustion version of that vehicle type Harvey et al. (14). This is a significant increase in vehicle weight that it is worth repeating the pavement wear analysis done to determine the potential effect on pavement deterioration and maintenance schedules.

Under the assumption that 100% of the delivery vehicles will be electric and have the average extra weight of 1,444 lbs., the same pavement wear analysis can be done from the previous section with the greater weight of each delivery vehicle. The results are shown in Table 6 outlining the impact of the electric delivery vehicles on the pavement lifespan in each traffic mix scenario.

TABLE 6 Years to Pavement Failure (Small-Winston) with 100% Electric Delivery Vehicles

<table>
<thead>
<tr>
<th>Traffic Mix (100% Electric Delivery Vehicles)</th>
<th>Baseline Pavement</th>
<th>+0.25&quot; Surface Thickness</th>
<th>+0.5&quot; Surface Thickness</th>
<th>+1&quot; Surface Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Traffic</td>
<td>8.08</td>
<td>10.31</td>
<td>13.07</td>
<td>20.56</td>
</tr>
<tr>
<td>2x delivery vehicles</td>
<td>6.24</td>
<td>7.97</td>
<td>10.1</td>
<td>15.88</td>
</tr>
<tr>
<td>4x delivery vehicles</td>
<td>4.29</td>
<td>5.47</td>
<td>6.94</td>
<td>10.91</td>
</tr>
</tbody>
</table>
There are a few key changes from the previous Small-Winston model analysis shown in this table. The pavement lifespans are all shorter in each case due to the additional weight of the electric vehicles. For each of the given traffic mix scenarios, the preferred pavement surface thickness is now increased such that at the baseline traffic level with all delivery vehicles being electric, the baseline pavement now has a shorter than standard lifespan. This also results in the 4x delivery vehicles scenario to require an additional greater surface thickness increase, which is shown in the rightmost column of Table 6, to get the pavement lifespan to a reasonable level.

DISCUSSION AND ENVIRONMENTAL IMPACTS

The first environmental impact that was investigated was that of the road maintenance itself to see if avoiding or postponing road maintenance was going to have the least impact. The findings on this were that keeping roads in good condition is the most important thing: “Keeping road pavement in good shape saves energy and money and reduces greenhouse gas emissions, more than offsetting pollution generated during road construction” Wang et al. (15).

The next impact studied was the difference in emissions between standard passenger vehicles and the typical delivery vehicles. From the Diesel Technology Forum, 76% of all commercial vehicles and 97% of all heavy-duty trucks in the US are powered by diesel (16). Accordingly, the following analysis of emissions is going to focus on diesel emissions and their overall and relative environmental impact.

When considering CO\textsubscript{2} emissions, a study from The International Council on Clean Transportation by Dornoff and Rodríguez (17), about the Volkswagen Golf model concluded that the diesel vehicles have slightly lower or similar CO\textsubscript{2} emissions as the gasoline powered ones. The most significant factor impacting the level at which both gasoline and diesel engines create emissions is the age of the engines. For diesel engines, EPA emission standards since 2007 have been required them to be designed for Ultra Low Sulfur Diesel, which is cleaner burning and releases significantly fewer particulate emissions. Particulate emissions were previously a major differentiator of the environmental impact between gasoline and diesel engines. For gasoline engines, the implementation of catalytic converters has also brought emissions down (17).

The overall environmental impact of an increase in diesel-powered delivery vehicles on residential streets does not appear to be significantly different from just an increase in any internal combustion engine vehicles. The possible takeaways from this are to consider the impact of electric delivery vehicles in the same scenarios, using smaller vehicles, or simply focusing on reducing overall trips of delivery vehicles to have less of an environmental impact. This would be similar to the study mentioned in the literature review of an LCA methodology for determining global warming potential from different scenarios of electric passenger vehicles and pavement types (7).

CONCLUSIONS

There is a very strong likelihood that the number of delivery vehicles has been increasing on residential streets in areas across the country, and the increased loading with these vehicles has a different impact on the road surface than the previous traffic on these streets. This change in traffic patterns with more heavy vehicles traveling on streets not designed for this type of traffic will inevitably lead to quicker wear on the surface of the roads. Increased wear is seen in the case
of Evanston, IL with the more frequent pavement patching throughout the city, which could be explained by the increase in delivery vehicles. The increased load on the streets was quantified, and then used to analytically determine the change in wear on the surfaces of these streets.

A solution to handling this new heavier traffic is to increase the surface thickness on the pavement of these streets. The additional weight of the traffic could be due to an increase in total vehicles and/or a shift to electric vehicles. In this study, the only vehicles considered are delivery vehicles, but other heavier vehicles would have similar effects. The increase in pavement surface thickness would help manage the greater amount of weight traveling on these streets. The amount which the pavement surface thickness is increased can be calculated using the AASHO pavement wear equation to find the surface thickness at which the maintenance schedule can remain the same as it was for the previous traffic mix and previous surface thickness. Keeping the pavement maintenance schedule at the same frequency limits the social costs of the impact of more heavy vehicles on residential streets.
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AUTHOR CONTRIBUTIONS
The authors confirm contribution to the paper as follows: study conception and background: Yu, Durango-Cohen; study design: Skiles; analysis and interpretation of results: Skiles, Durango-Cohen; draft manuscript preparation: Skiles; All authors reviewed the results and approved the final version of the manuscript.
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