ANALYSIS OF EMISSIONS AT CONGESTED AND UNCONGESTED INTERSECTIONS USING MOVES2010

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ABSTRACT
The U.S. Environmental Protection Agency’s (EPA’s) Motor Vehicle Emission Simulator (MOVES) modeling software enables researchers and practitioners to model vehicle emissions at the project level. With this tool, agencies have the capability to identify and evaluate the effectiveness of local traffic control strategies to reduce emissions at project hot spots, such as congested intersections.

This paper analyzes vehicle emissions at congested and uncongested signalized intersections. Emissions are analyzed under three traffic intersection scenarios, ranging from level of service (LOS) B to LOS E. Emissions are much less sensitive to congestion than control delay. A shift in operation from LOS E to LOS B reduced per-vehicle nitrogen oxide (NOx) emissions by 15% and particulate matter (PM) emissions by 17%, while control delay decreased by 40%. The largest sources of emissions were cruising and acceleration, accounting for more than 80% of total emissions under all scenarios. Idling accounted for less than 18% of all intersection emissions.

This analysis calculates emissions using a time-in-mode (TIM) methodology that combines emission factors for each activity mode (i.e., acceleration, deceleration, cruise, idle) with a calculation of the total vehicle time spent in that mode. This approach demonstrates the contribution of each activity mode to intersection emissions and suggests opportunities for control strategies with the potential to affect intersection emissions.

The streamlined methodology presented here may be a helpful tool for agencies that are interested in analyzing project-level emissions and control strategies but lack staff resources or expertise for microsimulation-based scenario analysis.
INTRODUCTION
In March 2010, the MOVES emission factors (EFs) model was officially released by EPA for use in State Implementation Plans (SIPs). In December 2010, EPA officially released its finalized guidance on conducting hot-spot analyses of Particulate Matter (PM) hot-spot projects, which enables a quantitative approach to PM project-level assessments. MOVES gives practitioners the tools to model vehicle emissions at an individual intersection or other project type. Furthermore, it provides them with the capability to not only analyze emissions at an intersection but also to evaluate the benefits of a variety of intersection improvement strategies.

The goal of this paper is to evaluate the magnitude of Nitrogen Oxides (NO\textsubscript{X}) and PM emissions at a signalized intersection in both congested and uncongested states. In addition, we will explore the time spent in each activity mode (acceleration, deceleration, cruise, idle) at an intersection and how both the aggregate vehicle time, measured in vehicle-seconds per hour, and the breakdown of each mode vary with congestion. We will also analyze intersection congestion under three scenarios, which are typical of proposed projects during traffic planning: 1) a baseline intersection with light volume and low congestion (LOS B), 2) a project scenario with heavy volume and high congestion (LOS E), and 3) a mitigated project scenario in which intersection geometry has been expanded to return congestion levels to LOS B. Aggregate and per-vehicle emissions will be examined under each case.

Each scenario (see Figure 1) is treated as an isolated intersection, and we assume that the approaching vehicle flow is uniformly distributed across the cycle. The intersections are configured with a major arterial traveling E/W with an approach speed of 40 mph and a minor road traveling N/S with an approach speed of 30 mph. The signal timing was kept fixed in each scenario rather than actuated, however, in each scenario, signal timing is optimized to achieve the best operation given the traffic flow. All volumes are measured over the course of an hour, and emissions are presented as total intersection emissions per hour. All intersections are at grade.

For each of these scenarios, we estimated intersection emissions in three steps. In the first, we used MOVES to determine EFs for each of the four activity modes; second, we calculated the total amount of time spent in each activity mode per hour; and third, we multiplied the total time-in-mode (TIM) calculations by the corresponding EFs to determine total hourly intersection emissions. Each of these three elements is discussed in detail below. We also discuss general relationships between activity, emissions, and intersection congestion and show the sensitivity of emissions to key variables, such as approach speed and acceleration rate.

While numerous prior studies have investigated emissions at intersections or other specialized cases, most have been done with previous generation emissions models, such as from the MOBILE or EMFAC series (for example, (3, 4), or have relied on unique, and intensive datasets or complex methods. Notably, (5) developed methods for integrating MOVES with a traffic microsimulation model and...
demonstrated results for an analysis of project-level analysis for a 3-leg intersection. However, cases such as this suffer from the onerous data requirements of paring microsimulation models with MOVES. (6) investigated the instantaneous emissions estimated by MOVES for prescribed driving cycles and found that, for high power modes, significant errors are produced by the model compared to measurements. (7) derived signal timing effects through direct VSP calculations. On the other hand, (8) developed polynomial models of acceleration and deceleration profiles for generalized intersections, but did not explore the implications for emissions. However, a few studies have been conducted with the MOVES model, especially those that consider a time-in-mode analysis with a simplified approach to intersection activity. This paper presents a middle-road approach to this issue.

ANALYSIS OF EMISSION FACTORS FOR EACH ACTIVITY MODE

The first step in this analysis is to develop Emission Factors (EFs) for each of the four activity modes (acceleration, deceleration, cruise, idle) in units of grams per vehicle-second (g/veh-s). The resulting modal EFs are tailored to specifics about the project area, including location, time of year, vehicle mix, and approach speeds, but are independent of data on intersection operation, such as vehicle volume, control delay, and intersection geometry. Because of this, EFs can be calculated independently of the intersection scenarios to be modeled later with TIM calculations.

Methodology

The EFs for each activity mode are calculated through a project-level analysis in MOVES.(9) A description of MOVES inputs is shown in Table 1. The four activity modes are captured in a single composite drive schedule of a vehicle entering the intersection, decelerating to the limit line, idling, and accelerating out of the project area. This drive schedule is divided into four individual links, with each link representing a single activity mode. This schedule is shown in Figure 2.

<table>
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<th>Parameter</th>
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Table 1. Inputs used for modeling activity mode emission factors in MOVES2010.
The drive schedule is constructed as follows, based on approach speed inputs as well as acceleration and deceleration rates. The cruising and idling links of the drive schedule are treated as constant speed, either at the approach speed defined in the project description or idling at zero.

Prior modeling work (8) has shown relationships between behavior of vehicles as they approach and depart an intersection, and parameters such as approach speed and acceleration or deceleration rates. For our analysis, the deceleration and acceleration links are treated as a trajectory in the shape of a sine curve where maximum acceleration or deceleration rates at low speeds taper down near the approach speed. By basing the links on sine curves, the shape of the trajectory, as well as the drive schedule, can be directly calculated. The instantaneous velocity, duration, and distance traveled during acceleration and deceleration are calculated in the following equations:

\[
V(t) = V_{\text{max}} \cdot \sin \left( t, \frac{a_{\text{max}}}{V_{\text{max}}} \right) \quad (1)
\]

\[
T_a = \frac{V_{\text{max}}}{2a_{\text{max}}} \quad (2)
\]

\[
D_a = \frac{V_{\text{max}}^2}{2a_{\text{max}}} \quad (3)
\]

Where: \( t \) is the point in time within the drive schedule, \( V_{\text{max}} \) is the approach speed, and \( a_{\text{max}} \) is the maximum acceleration or deceleration rate. For acceleration, \( a_{\text{max}} \) is a positive value; for deceleration, \( a_{\text{max}} \) is a negative value. These three equations calculate: \( V(t) \) is the speed at time \( t \), \( T_a \) is the time spent accelerating from 0 to \( V_{\text{max}} \) (or decelerating from \( V_{\text{max}} \) to 0), and \( D_a \) is the distance traveled over duration \( T_a \).

The following section of this paper investigates the sensitivity of modal emissions and EFs to acceleration and deceleration rates. This analysis uses a “moderate” level of acceleration of 4.0 miles per hour per second (mphps) and a level of deceleration of 7.6 mphps.(10) The result of this sensitivity analysis is a set of EFs for each activity mode specific to the project area, with defined geography, year/month of analysis, and vehicle approach speed. In the case where these variables vary for a particular project (i.e., the streets at an intersection have different approach speeds, as seen in Figure 1) or a project includes scenarios in different analysis years, a set of EFs can be developed for each unique set of inputs.

Results
Figure 3 shows the EFs calculated for each activity mode. EFs are measured in g/veh-sec and disaggregated by activity mode and approach speed. Because the intersection scenarios in Figure 1 include approaches at 40 mph and approaches at 30 mph, it is necessary to break out EFs for each speed. The results show that EFs vary greatly by activity mode, with acceleration EFs dominating those from all

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Figure 2. Representative intersection drive schedule for MOVES emission factors analysis.
other modes. Under all approach speeds and pollutants, acceleration EFs are at least 170% larger than cruising rates at that speed. In contrast, deceleration EFs are at least 50% less than cruising, and idling EFs are 67% to 84% less than cruising. These patterns are consistent with the vehicle-specific power (VSP) required from each mode.\(^{(11)}\) Although cruising occurs with moderate VSP (high-speed, zero-acceleration), much of the acceleration operating mode distribution occurs with high VSP (low- to high-speed, positive-acceleration). In contrast, deceleration is dominated by low VSP (low- to high-speed, negative acceleration), and idling occurs at VSP equal to zero (zero speed, zero acceleration). Differences in VSP explain higher EFs for modes with 40 mph approach speeds compared with modes with 30 mph approach speeds, with EFs for the former ranging from 33% to 75% larger than EFs for the latter.

**Figure 3. NO\(_X\) and PM emission factors for each activity mode (g/veh-sec).**

Although both NO\(_X\) and PM emissions follow similar trends between activity modes and approach speeds, PM is shown to be more sensitive to differences between these variables.

**ANALYSIS OF INTERSECTION TIME-IN-MODE CALCULATIONS**

In the TIM approach, the modal EFs are combined with the time spent in each activity mode to determine total intersection emissions. The methodology to calculate TIM is presented here, along with TIM results for each scenario.

**Methodology**

The first step of the TIM analysis is a calculation of the control delay at each intersection, which is modeled using Synchro™ software and based on traffic relationships in the *Highway Capacity Manual*.\(^{(12)}\) Inputs into the model include intersection geometry and vehicle volumes. Signal timing is optimized using the software to provide the optimal operation for the given level of volume. The outputs of the Synchro™ analysis include the control delay of each movement, vehicle queue in each movement, and cycle time. Using these variables, the aggregate intersection TIM is calculated using Webster relationships\(^{(13)}\) of vehicles at a signalized intersection, as shown in the form of an X-T plot in Figure 4. TIM calculations for idling, deceleration, and acceleration are shown graphically as areas on the plot.

Idling TIM is denoted by area BCF, deceleration is shown as ABFG, and acceleration is shown as CDEF. Additional intersection variables are shown on the plot, including q, the flow of approaching vehicles; V, the approach speed; R, the red time; and C, the cycle time. Individual vehicle trajectories are shown as grey lines.
Because only a portion of vehicles stop at a red light while the remainder pass through on green, TIM for deceleration, idle, and acceleration depends on the percentage of vehicles that are delayed. In each signal cycle, the number of vehicles that are delayed at a red light is equal to the number of vehicles that enter the idling queue. The number of vehicles in this queue divided by the number of vehicles that approach the intersection within a single cycle equals the delay percentage. For each movement, the total queue length is an output of the Synchro™ model. The delay percentage is shown in Equation 4.

\[
\%_{d} = \frac{Q \cdot n \cdot C}{l \cdot q}
\]  

Where: \( \%_{d} \) is the delay percentage, \( Q \) is the queue length, \( n \) is the number of lanes in the movement, \( l \) is the vehicle spacing in the queue, \( q \) is the vehicle flow, and \( C \) is the cycle length.

The TIM for acceleration and deceleration is equal to the time spent by an individual vehicle to accelerate to departure speed or decelerate to zero, as shown in Equation 2, multiplied by the number of vehicles that accelerate or decelerate. This is shown in Equation 5.

\[
TIM_{A,D} = T_{A,D} \cdot q \cdot \%_{d}
\]  

Where: \( TIM_{A,D} \) is the TIM for acceleration or deceleration; \( T_{A,D} \) is the duration of each mode, as shown in Equation 2; and \( q \) and \( \%_{d} \) are as defined above.

Idling time on a vehicle movement is related to the control delay of that movement. Similar to queue length, the control delay on each movement is a direct output of the Synchro™ model. For a single vehicle that stops, the total delay experienced by that vehicle equals the sum of idling time, delay due to deceleration, and delay due to acceleration. For the entire intersection, total idling TIM equals the product
of the idling time per delayed vehicle, the percentage delayed, and the vehicle flow. This relationship is shown in Equation 6:

\[ \text{TIM}_I = q \cdot \text{\%}_{\text{id}} \cdot \left( \frac{C_d}{q_{\text{eq}}} + \frac{D_A + D_D}{V_{\text{MAX}}} - (T_A + T_D) \right) \]  

(6)

Where: \( \text{TIM}_I \) is the total time spent idling and \( C_d \) is the control delay for an intersection movement.

Lastly, the time a vehicle spends cruising is back-calculated from the distance that vehicles travel when cruising versus accelerating or decelerating. For vehicles that do not experience delay, the entire project area is traversed in cruise mode. For vehicles that are delayed, a portion of the project area is traversed when decelerating or accelerating. The distance traveled while cruising equals the difference between the total distance traveled in the project area and the distance covered through acceleration and deceleration. The cruising \( \text{TIM} \) is equal to the cruising distance divided by velocity.

\[ \text{TIM}_C = \frac{q}{V_{\text{MAX}}} (L - q_{\text{eq}}(D_D + D_A)) \]  

(7)

Using Equations 5, 6, and 7, the \( \text{TIM} \) on an intersection movement is determined for cruise, deceleration, idle, and acceleration. The total intersection \( \text{TIM} \) is equal to the sum of \( \text{TIM} \) over all movements.

Results

Figure 5 shows the breakdown of \( \text{TIM} \) for each scenario, both as aggregate for the intersection and per vehicle. In terms of the total intersection, the aggregate time spent in the intersection increases much more rapidly than vehicle volume because of the effects of increased congestion. In the congested Scenario 2, compared with the uncongested Scenario 1, vehicle volumes increase 96%, but aggregate time spent in the intersection increases 234%. Of the additional intersection time, 66% of the added time is spent idling. The effect of congestion is starker when considering \( \text{TIM} \) per vehicle, which normalizes intersection \( \text{TIM} \) to vehicle flow. From Scenario 1 to Scenario 2, per-vehicle travel time increases 70%, from 55 seconds per vehicle to 94 seconds per vehicle. Of this increase, 96% is due to additional idling time in the intersection.

Figure 5. Time-in-mode breakdown, entire intersection (veh-sec) and per-vehicle (sec)

These trends are also seen when comparing Scenario 2 with Scenario 3, which returns operation from LOS E to LOS B by expanding intersection geometry while carrying the same level of volume. For
the intersection as a whole, aggregate time drops by 40%, 97% of which is due to reductions in idling. On a per-vehicle basis, the time spent in the intersection is nearly constant between Scenario 1 and Scenario 3, which would be expected because each scenario operates at LOS B, with very similar levels of the control delay, as specified in Figure 1.

ANALYSIS OF INTERSECTION EMISSIONS UNDER CONGESTION
For each scenario, intersection emissions are calculated as the product of the modal EFs and the aggregate time spent in each activity mode. Figure 6 presents the final emission results for NOX and PM emissions for each scenario, both for the intersection as a whole and per vehicle traveling through the project area. Emissions are further disaggregated by activity mode, demonstrating the contribution of each mode to total emissions.

The results show that emissions are much less sensitive to congestion than control delay. When transitioning from congested Scenario 2 (LOS E) to uncongested Scenario 3 (LOS B), emissions of NOX drop 15%, and emissions of PM drop 18%, even though vehicle delay drops by 40%. This disparity is due to the contribution of idling to congestion delay; nearly all of the reduced delay is due to decreased idling, and idling has the lowest EF per second of any mode. Thus, the emission benefits are smaller than would be expected by the reduced delay.

As can be seen in the figure, emissions are dominated by cruising and acceleration modes, both of which occur in high-VSP states. Under all scenarios and with all pollutants, acceleration accounts for 46% to 55% of emissions. In these scenarios, which assume uniform arrivals, the delay percentage drops from 85% in the congested Scenario 2 to 71% in the uncongested Scenario 3. This suggests that strategies that may affect the delay percentage, such as coordinated signal timing, would have a larger effect on acceleration and intersection emissions as a whole. (5) (15)

Cruising is the second-largest source of emissions, accounting for 28% to 47%, depending on scenario and pollutant. One component of cruise emissions is related to the distance driven by vehicles that cruise through the intersection without any delay. As the delay percentage increases, the number of vehicles that cruise through the intersection decreases, and cruise emissions decrease. This explains the contrary trend of cruise emissions compared with other modes (i.e., as congestion decreases between Scenario 2 and Scenario 3, cruise emissions increase, while emissions from other modes decrease).

A second component of cruise emissions is related to the size of the project area. At a minimum, to capture all emissions from a scenario, each intersection approach must be long enough to include all deceleration, idling, and acceleration on that approach. As the approach length is extended beyond this distance, cruise emissions increase across all scenarios. This serves to reduce the relative changes
between scenarios as the project size is increased. Care must be taken to choose a project size that captures all delay activities under congested conditions but is not so large that it includes an excessive amount of cruising.

**GENERAL TRENDS IN EMISSIONS AT CONGESTED INTERSECTIONS**

The analysis of emissions in the three identified scenarios can be expanded to reveal general relationships among control delay, TIM, and intersection emissions. These trends are shown in Figure 7, which illustrates the impacts of a range of intersection control delay values, from 15 seconds (LOS B) to 75 seconds (LOS E), on total TIM and emissions per vehicle. In this figure, both intersection emissions and TIM are normalized, with values at the 15-second control delay normalized to 100%. This comparison uses the intersection configuration in Scenario 1, with volumes modified by a growth factor that achieves different levels of control delay. The figure shows how TIM increases rapidly at an intersection as control delay increases. In total, the time that vehicles spend in the intersection increases by 123%, with 15 seconds to 75 seconds of control delay. Further, 94% of the additional intersection time is added from the idling mode, while acceleration and deceleration times increase only slightly, and cruise times decrease somewhat.

**Figure 7. Time-in-mode and normalized emissions as a function of intersection control delay (sec/veh)**

In contrast, vehicle emissions increase much more slowly than total TIM, growing 36% (NO\textsubscript{X}) and 49% (PM) between 15-second and 75-second control delays. PM emissions are more sensitive to delay than NO\textsubscript{X} emissions, primarily because of the relatively higher idling EFs. In general, because idling EFs are the smallest of all modes and the primary increase in TIM occurs in the idling mode, intersection emissions are much less sensitive to congestion than would be expected given the increase in delay.

**SENSITIVITY OF INTERSECTION EMISSIONS TO ACCELERATION RATES**

Because acceleration emissions and EFs dominate those of other modes (Figure 3, Figure 6), the sensitivity of these outputs at a chosen acceleration rate is a key concern. A sensitivity analysis shows that although acceleration EFs are very sensitive to the acceleration rate, total intersection emissions are much less so.

The calculations above use a “moderate” acceleration rate of 4.0 mphps and a deceleration rate of 7.6 mphps. Figure 8 shows the acceleration and deceleration EFs when using moderate rates compared with “gentle” (acceleration: 2.0 mphps; deceleration: 5.1 mphps) and “aggressive”
acceleration: 6.0 mphps; deceleration: 10.1 mphps) rates. The EFs vary wildly among these rates: the acceleration EF for NO\textsubscript{X} varies by up to 135% between gentle and aggressive scenarios, while the acceleration EF for PM varies by up to 235%. Deceleration EFs show less sensitivity to rate, varying up to 33% between the gentle and aggressive scenarios. However, total intersection emissions are far less sensitive to acceleration rates than EFs.

Figure 8. Sensitivity of NO\textsubscript{X} and PM emission factors to acceleration and deceleration rates (g/veh-sec)

![Graph showing Sensitivity of NO\textsubscript{X} and PM emission factors](image)

Decel: gentle = 5.1 mphps, moderate = 7.6 mphps, aggressive = 10.1 mphps. Accel: gentle = 2.0 mphps, moderate = 4.0 mphps, aggressive = 6.0 mphps.

Figure 9 shows the sensitivity of Scenario 1 emissions to gentle, moderate, and aggressive acceleration rates. NO\textsubscript{X} emissions vary by up to 5% between scenarios, and PM emissions vary by up to 17%.

Total emissions are much less sensitive to rate than EFs because of the contrary effects of emission rate and the duration of the acceleration segment. Although aggressive acceleration has a much higher emission rate than gentle acceleration, a vehicle reaches cruising speed in a much shorter time. As a result, intersection emissions are much more robust with respect to acceleration rates than would be implied by the EFs in Figure 3.

Figure 9. Sensitivity of intersection emissions to acceleration rate (grams)

![Graph showing Sensitivity of intersection emissions](image)

Accel: gentle = 2.0 mphps, moderate = 4.0 mphps, aggressive = 6.0 mphps.
CONCLUSIONS

For intersections with uniform traffic flow, intersection emissions are much less sensitive to congestion than would be expected, varying just 17% (NO\textsubscript{X}) and 23% (PM) between the LOS E conditions in Scenario 2 and the LOS B conditions in Scenario 3. This lack of sensitivity has implications for environmental mitigation in traffic planning. Although traffic mitigation such as the intersection expansion shown in Scenario 3 can greatly reduce congestion and improve intersection operation, the benefits for emission reduction are smaller.

However, control strategies that reduce the percentage of vehicles delayed may have a greater impact on emissions than strategies that target control delay alone. For example, coordinating arterial signals to platoon the vehicle flow would maximize the number of vehicles that would pass through on a green signal and greatly reduce time spent in the acceleration mode.\cite{17} Similar reductions in acceleration would occur by upgrading unsignalized four-way stops to signalized intersections, allowing a portion of the vehicle fleet to move through the intersection without delay.

Similarly, strategies that allow vehicles to pass through the intersection without coming to a complete stop could have a great impact on emissions. Compared with a signalized intersection, roundabouts allow most vehicles to pass through at a slow speed, with yields instead of stops. This reduces the amount of acceleration needed to reach cruising speed, which could have a significant effect on emissions. Similarly, intersections with a large amount of right-turn movements could benefit from dedicated right-turn yield lanes.

Future research can explore these scenarios to compare the emission benefits of different intersection control strategies. In the case of projects in which vehicles slow but do not come to a stop, new representative drive cycles would need to be developed to calculate appropriate EFs and TIM.

Need for validation of the emission factor methodology

The approach to calculating modal EFs begins with constructing a representative drive schedule for vehicles passing through the intersection, using moderate acceleration and deceleration rates and a sine-curve shape for acceleration and deceleration. To develop a more rigorous methodology, this representative drive schedule should be validated against microsimulation trajectories of vehicles passing through the modeled intersection. This analysis may uncover commonalities among vehicle trajectories across different types of intersections, which would allow for a calibrated generalized approach similar to the one presented here.

However, it is not necessary for a vehicle trajectory under the TIM approach to precisely track the trajectories under the microsimulation approach. For acceleration and deceleration modes, all that is needed is for the activity to be the same duration under each approach and produce the same op-mode distribution. Because most acceleration movements would be clustered in a small number of operating mode bins, there is flexibility for differences in an acceleration trajectory that produce similar op-mode distributions.

Benefits of the time-in-mode methodology for workflow in a planning level intersection emission analysis

The TIM methodology developed in this analysis is directly applicable for practitioners developing planning-level traffic analysis and offers a streamlined approach and simplified workflow with many benefits over emission analyses using microsimulation or average speed. Unlike microsimulation or average speed methods in which each traffic analysis scenario requires an independent and concurrent MOVES model run, the TIM approach separates the MOVES component of the analysis from the traffic component of the analysis. Once a project area is defined (geography, approach speeds), a MOVES analysis can establish modal EFs specific to that project. Separately, a traffic analysis of volumes, control delay, and intersection geometry produces the aggregate TIM results to which the EFs are applied to determine total emissions. In this way, several traffic scenarios can be quickly iterated using the TIM calculations, without needing to rerun MOVES for each scenario.
This approach is beneficial for practitioners with deep experience in traffic analysis but less experience in MOVES modeling. At the beginning of a project, the MOVES component can be completed once, either by an air quality team or a third party, and the resulting EFs applied in the traffic analyses of the rest of the project. More generally, a lookup table of EFs could be produced for scenarios with a variety of speeds, calendar years, and months of analysis to produce a set of modal EF data for application in various projects. With this approach, transportation agencies gain the ability to model the emissions impacts of intersection congestion and several control strategies, without taking on the data and analysis burdens of microsimulation modeling for each individual scenario.
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