AN ALGORITHM FOR USING REAL-TIME INFORMATION TO IMPROVE INTER-TIME-POINT BUS MOVEMENT

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Abstract: There are a number of strategies that transit operators may use to mitigate the randomness inherent in a bus' movement along a route. Many of these strategies have evolved to include real-time information in order to make dynamically informed decisions. One such strategy is the holding control strategy, where certain stops are selected as time points, and early buses are instructed to wait until a scheduled departure time at these points. While extensive research has been done incorporating real-time information into bus operations, little attention has been given to potential advantages gained in using real-time information to control inter-time-point movement. An algorithm is proposed for an early bus, comparing on-board and off-board passenger costs to decide whether to continue to run early or attempt to slow down. The proposed algorithm considers two situations: when inter-time-point stops have published arrival times, and when they must be deduced by the passengers.

1 INTRODUCTION

Public transit operations involve a constant struggle with the natural tendencies of the system to become unstable. In order to provide a practically usable service, transit companies need to provide a promise to customers regarding the level of service they provide, by publishing a timetable (scheduled service) or advertising a regular arrival of vehicles along a certain route (regular headway service). Keeping this promise is difficult in the face of constantly fluctuating external factors such as demand for boarding and alighting, traffic, weather, and mechanical issues. While all modes of public transit are exposed to these random factors, buses are the most vulnerable due to their movement in mixed traffic.

There are two general approaches to improving reliability. One way is to try and mitigate the random factors causing variation, for example by providing exclusive right-of-way for buses in the form of bus lanes. The other way is to develop strategies to try and absorb some of the inherent randomness. For a scheduled service, this usually involves adding *slack time* to the schedule at specific points along a route (called time points), and instructing buses that arrive early at those points to wait until the scheduled departure. This strategy is known as *holding control*. For an even headway service, control of buses is done with the intention of keeping headways regular. Buses are instructed to slow down or speed up their operation based on the spacing between them.

There is significant research on the control of buses at these time points, both with and without real-time information. Studies on holding control are concerned with the calculation of the appropriate slack time and location of time points, while travel between the points is considered to fluctuate randomly. In practice, arrival times at regular stops are not published, or are based off of average travel time, and are not guaranteed from an operational standpoint. In the former situation, passengers are forced to perform their own calculation of the bus' arrival time, which may be inconsistent with the actual arrival time at a stop. In the latter method, passengers may time their arrival at a stop in accordance with the estimated schedule, only to find that the bus has already come and gone.

The proposed method is a hybrid of the two general approaches outlined above, as well as the specific strategies mentioned. Buses are first scheduled using the holding control strategy, however between time points the bus' movement is adjusted in real-time based on a number of current and historical inputs. This paper presents an algorithm to determine a suggested speed of buses between time points, based on the cost of on-board and potential boarding passengers. A decision is made, at each regular stop, whether the progression of the bus should be allowed to run normally, or whether an adjustment is needed to change the arrival time of the bus at the subsequent stop. The goal of the algorithm is to provide a simple and practical way to improve inter-time-point operations.

The paper is outlined as follows: Section 2 describes a number of studies with elements related to the current problem. Section 3 outlines the algorithm and method of implementation. Section 4 discusses potential advantages and issues with the proposed system, and Section 5 provides concluding remarks.

2 LITERATURE REVIEW

There have been numerous studies utilizing real-time information to improve both headway regularity and holding control. The majority of research on real-time headway control involves some form of localized control at one or more points along the route. Though the control is localized to specific points, knowledge of the location of each bus on the route is required in order to make a proper analysis of the route. One study developed a system in which a delay is introduced between two stops in order to adjust for a headway that is too small between the bus in question, and the one preceding it (Daganzo 2009). This type of control essentially re-dispatches the buses at a control point based on real-time location information of the rest of the buses on the route. This self-correcting system can compensate even for large disturbances, such as the breakdown of a bus and its subsequent removal from the system, and additional control points can be added to improve the efficacy of the system. This method has been repeated using a slightly different mathematical framework (Bartholdi III & Eisenstein 2012). The practicality of the system was demonstrated through its simple implementation on a real-life bus route in Atlanta, Georgia (Bartholdi III et al. 2012).

Adherence to a set schedule becomes increasingly important as the headway of buses grows larger. There is a transition point at headways around 12-13 minutes where a large fraction of passengers become aware of the published schedule and adjust their arrival to a stop accordingly (Okrent 1974). After this point, controlling the bus so that it does not arrive too early or late at a specific stop becomes more important than maintaining regular headways. One additional advantage of scheduled service is that headways are not required to be even, and can follow some other optimal dispatching policy (Newell 1979; Wirasinghe 1990; Wirasinghe 2003). An early bus may be of more harm than a late bus, since passengers have begun to time their arrivals according to a schedule, and may miss the bus entirely. The longer the headway, the more additional waiting time a passenger will experience due to missing an early bus.

There are two ways in which the introduction of real-time information and bus communication systems can provide an improvement for the holding control strategy. First, if there are many points of contact with a bus along its route, for example at signals and from GPS systems, then holding control can take place almost continuously as the bus progresses along the route. One major advantage of this on-the-fly adjustment is that buses will not be forced to wait for extended periods of time at control points, to the frustration of on-board passengers who do not wish to use this stop. These micro-adjustments can be made by reversing transit signal priority at intelligent intersections (Polgár et al. 2013), or by instructing the driver to “drive slower”, either by reducing speed, or by delaying slightly at intermediate stops. The former allows drivers to focus only on driving and leaves schedule adherence to seemingly external factors, while the latter has smaller effects on surrounding traffic.

Due to the large amount of computing power and information transfer required for centralized real-time control of buses, most strategies use some form of localized control. One study (Dessouky et al. 2003) developed a simulation model of a transit network to evaluate holding control strategies when localized decisions were made with the benefit of real-time information such as bus location tracking and passenger counts. The goal was to minimize the average passenger trip time, weighting passenger counts on board with forecasted passenger arrival counts at downstream stops. Although this method considered an entire bus network, the underlying motivation was relevant to a single-route analysis. The method was found to be most effective when headways were large and there were many connecting buses at the time point. A balance was struck between passengers connecting from a late bus, with the passengers already on board, and the passengers that were forecasted to board at subsequent stops.

Another study (Zhao et al. 2003) presented a negotiation strategy between bus stop and bus “agents”, based on marginal cost calculations. These agents partake in a negotiation based on updated real-time information to decide on the amount of control to implement at a control point. Waiting costs of on-board and off-board passengers were considered, and an optimal holding time was calculated that minimized the total waiting cost.

3 DEVELOPMENT OF ALGORITHM

3.1 Inter-Time-Point Scheduling

When developing a schedule, transit companies can take two approaches concerning the timing of bus’ arrivals at stops *between* time points. They can choose to publish only the time point departure times, leaving the estimation of travel between the two points to passengers, or they can provide a schedule by running the service for some time, and obtaining a probability distribution function for the arrival time at each stop. The mean of this distribution would then be posted.

Passengers (and buses) considered here are of a non-commuter type. This means that passengers are not required to arrive at their destination at a certain time. With commuting passengers, an early arrival is of little advantage; passengers will spend their additional time waiting at their destination. For non-commuter passengers, the extra time can be spent on the activity they are travelling to, such as shopping or leisure. An assumption is made for the calculations in Section 3.5 that all (or at least most) passengers are non-commuter, which is likely only in the off-peak periods, leading to the additional assumption that this algorithm is being used in the off-peak periods only.

In the former method, passengers are assumed to make a linear estimation of the movement of buses between time points. This estimation can differ from the actual movement of the bus along the route (especially with high and low speed sections of travel), and result in passengers missing buses due to simplified calculations. Operationally, the transit agency is not over-promising schedule adherence between the time points. For the purposes of this paper, this method is referred to as *linear estimation.* In the latter method (referred to as *published schedules*), passengers are provided with a more realistic time of arrival for a bus, and are not required to perform rough calculations. This additional information may cause passengers to time their arrival at stops more closely with the scheduled times, and an early bus may miss more passengers than without a published time. Since passengers are not commuters it is reasonable to assume that they do not know the defacto schedule of a given bus based on their experience.

Introducing real-time information into transit operations has also allowed the implementation of real-time bus arrival prediction. Passengers are able to track bus movements and view updated arrival times from their mobile phone. This additional information may help passengers time their arrival at the stop in time with a bus, however the addition of this information is beyond the scope of this paper.

3.2 Algorithm Inputs

With the understanding of the variations in travel time between stops, an “experienced” driver may be able to compensate by adjusting the bus’ speed. Being able to discern underlying trends in movement from the random noise of day-to-day operations can be difficult even for a knowledgeable driver. Instead, a computer program could perform some statistical analysis and real-time decision making, suggesting whether a bus’ instantaneous deviation from the schedule is part of a larger trend, or simply noise. A suggested arrival time at the next stop, along with recommended average speed can be determined and broadcasted to the driver. The algorithm presented utilizes the following information:

- The instantaneous deviation of the bus’ progress along the route from a linear extrapolation (*linear estimation case)*, or
- The instantaneous deviation of the bus’ progress along a route from the published schedule time (*published schedules case)*

- The number of passengers that are potentially affected by this deviation, using projected boarding and alighting rates based on historical passenger counts
- The number of passengers immediately affected by this deviation, using real-time passenger counts.
- The historical movement patterns of the bus as it progresses further down the route.

Based on the information provided the algorithm will make a decision as to whether the bus should remain on its current course, or adjust its speed relative to the average in order to arrive earlier or later at the next stop. This algorithm provides a balance of in-vehicle passenger costs with the potential costs of boarding passengers at the subsequent stop. This decision is translated into an average speed which is broadcasted to the driver. The driver can choose to alter the bus' speed accordingly, accounting for external factors such as safety and congestion.

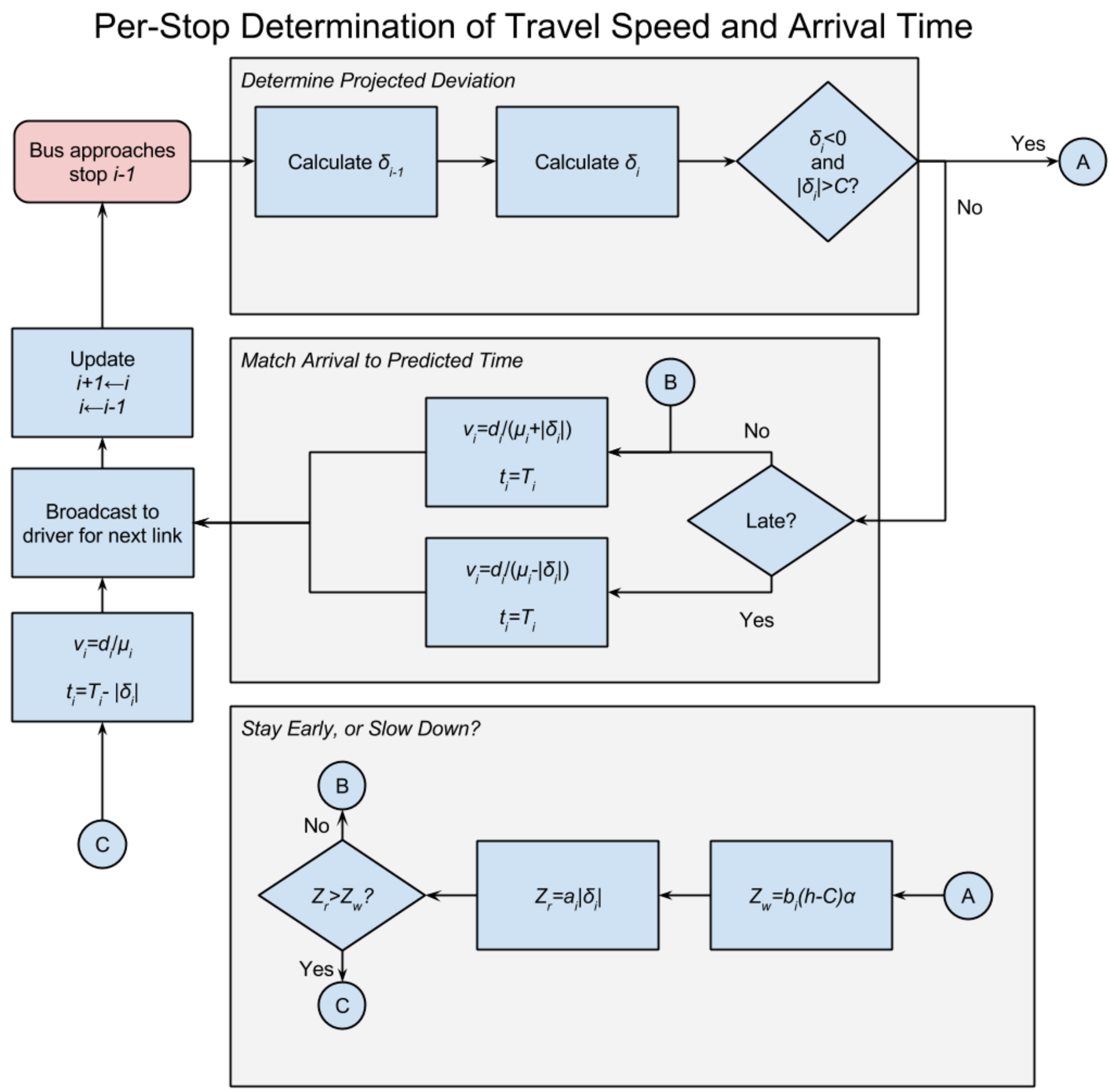

Figure 1. Flow chart of algorithm outlining the determination of travel speed and arrival time in an inter-time-point link

3.3 General Algorithm Outline

The structure of the algorithm proposed is diagrammed in Figure 1. The algorithm moves through two of three possible phases, depending on the current status of a bus. During each cycle of calculation, upon the approach of a bus at a stop, the algorithm determines the bus' current and projected deviations from the estimated schedule as outlined in Section 3.4. If the bus is late, on time, or not sufficiently early, the bus will proceed as if to arrive at the following stop on time. If the bus is sufficiently early, a cost calculation is performed weighting in-vehicle and off-vehicle passenger costs. If the advantage falls to the current on board riders, the bus will aim to be early at the following stop. Otherwise, the bus will slow down to accommodate potential waiting passengers at the next stop. This cost calculation is described in Section 3.5

3.4 Determining Projected Deviation

It is assumed with both the linear estimation and published schedules cases that passengers will arrive quite close to the suggested time of arrival for the bus. It is considered unreasonable to expect passengers to arrive more than one or two minutes ahead of the bus' estimated arrival time. For the purpose of this development, this “arriving early” threshold is denoted as a parameter C. This parameter can be set by the transit agency according to their expectation of passenger arrivals at stops. If a bus' estimated arrival time at stop i is T_i, then it is assumed that all boarding passengers will arrive exactly at time $T_i - C$. In other words, if the bus arrives at the stop earlier than $T_i - C$, all boarding passengers will miss their bus and have to wait for the following bus. If it arrives after that point, all passengers will catch that bus.

In the linear estimation case, passengers are assumed to linearly extrapolate the movement of the bus between time points, based their relative distance along the route. Let x_{AB} be the distance between the two time points A and B, and x_i be the estimated distance of stop i from time point A. If the times published for time-points A and B are S_A and S_B respectively, then the linear estimation time T_{1i} for the ith stop along the route is

[1] $$T_{1i} = \frac{x_i}{x_{AB}}(S_B - S_A) + S_A, \quad i \in \{0, \dots, n\}$$

In the published schedules case, it is assumed that the published times are consistent with the mean travel times between stops. In this case, the projected time at stop i is

[2] $$T_{2i} = \sum_{j<i} \mu_j, \quad i \in \{1, \dots, n\}, \qquad j \in \{0, \dots, i-1\}$$

where μ_j is the mean travel time between stop $i-1$ and i. Understanding that the estimated time can take one of the two forms above, this estimated time will be denoted with the symbol T_i for the purpose of the analysis.

Suppose a non-commuter bus is approaching a regular stop $i-1$. That bus has deviated from the scheduled arrival time by some time δ_{i-1}. Using the mean travel time to the next stop, the projected deviation upon arrival at the next stop i is

[3] $$\delta_i = \delta_{i-1} + \mu_i - (T_i - T_{i-1})$$

This is the deviation from the estimated time, added to the already existing deviation. For the published schedules case the equation simplifies to $\delta_i = \delta_{i-1}$ since the schedules are based on mean travel times. For the linear estimation case the explicit formulation becomes

[4] $$\delta_i = \delta_{i-1} + \mu_i - \frac{S_B - S_A}{x_{AB}} d_i$$

where d_i is the distance between stop $i-1$ and i. If the mean travel time of the bus follows an exact linear form, then this equation simplifies also to $\delta_i = \delta_{i+1}$. After this calculation, if $\delta_i < 0$ (bus is early) and $|\delta_i| > C$ (bus is earlier than threshold), a cost formulation is performed to decide whether to slow the bus down or allow it to remain early.

3.5 Cost Formulation for an Early Bus

If the conditions outlined in the previous section are met, the next procedure is to formulate a cost comparison between the on board and off-board passengers. For on board passengers, time is saved (and cost reduced) if the bus arrives at their stop early, which is only possible if the alighting stop is between the current one and the second time point B (included). First, off-board passenger cost is formulated. This is the number of boarding passengers b_i at stop i who will be missed, multiplied by the time waited (note that because b_i is typically an average, it can take on any nonnegative real number). This time is the following headway h. This cost is also multiplied by a cost of waiting factor γ_w (in dollars per unit time), which accounts for a potential difference in waiting comfort between on board and off-board passengers. The cost for these missed passengers, Z_w is therefore

[5] $$Z_w = b_i h \gamma_w$$

Passengers on board the bus can potentially save time due to an early bus. If the bus arrives at their stop ahead of schedule by an amount $|\delta_i|$, this time is considered “saved” and can be used for other activities. Time is only saved if passengers alight at or before the time point B, since an early bus will be held there regardless. If the number of alighting people at each stop i is given as a_i (as with b_i, this can be any nonnegative real number), and the cost associated with riding time is γ_r (in dollars per unit time) then the surplus cost Z_r of riding passengers due to the deviation is

[6] $$Z_r = a_i |\delta_i| \gamma_r$$

If $Z_r > Z_w$, then the average speed v_i between stop $i-1$ and i will be calculated and broadcasted as

[7] $$v_i = \frac{d_i}{\mu_i}$$

A suggested arrival time of $T_i - |\delta_i|$ can also be included. Otherwise, an average speed v_i will be calculated as

[8] $$v_i = \frac{d_i}{\mu_i + |\delta_i|}$$

with a suggested arrival time of T_i.

3.6 Analysis and Numerical Examples

If the estimation of the boarding and alighting passengers are equal at some stop ($a_i = b_i$), then the decision to continue running early will be made only if

[9] $$\frac{\gamma_r}{\gamma_w} > \frac{h}{|\delta_i|}$$

Since riding time costs are generally accepted to be lower than waiting costs, this would require the bus to be over a full headway early to trigger the algorithm and continue running an early bus. That is an unlikely scenario. A similar comparison can be made when riding times are considered half the cost of waiting times ($\gamma_w = 2\gamma_r$):

[10] $$\frac{a_i}{2b_i} > \frac{h}{|\delta_i|}$$

This inequality gives a strong indication on the type of boarding profile that is required for this algorithm to trigger and continue early service.

For example, consider a bus scheduled with 20 minute headways that is projecting its arrival at a stop 5 minutes early (the threshold C is 2 minutes). If the weather is fair and good facilities are provided for waiting passengers, then riding and waiting time costs can be considered equal. In that case at a given stop the decision to proceed early would be made only if four times as many passengers wish to alight than board, or (for small boarding and alighting numbers) if an alighting is four times as likely as a boarding.

As another example, suppose a bus route meets with a light rail system. The stop before the connection is made, the bus projects its arrival at the rail station 5 minutes early. The bus has 20 people on board who are travelling home from a sporting event, and during late-night service the average number of people who board the bus at the LRT station is 1 (only one person boards as the bus comes). The headways are 30 minutes at this time. Since it is night time, passenger waiting costs are double that of the riding costs, namely $\gamma_w = 2\gamma_r$. In this case, the riding passenger savings outweigh the waiting passenger cost, and the bus proceeds early. These savings are potentially increased if the early arrival of the bus allowed for a connection to the rail service that would not normally be possible. In reality, the LRT station would likely be a time point on the bus route, re-enforcing the strategy to proceed early to that stop.

4 DISCUSSION

The proposed system has a number of advantages over conventional bus movement between time points. From a purely practical standpoint, it provides a simple and intuitive instruction to the driver regarding their movement along the route. It offers a suggested speed and arrival time, and it is left to the driver to accommodate for those provisions safely given the external factors such as traffic and weather. If the proposed time and speed is unreasonable, the driver can choose to ignore the instruction until it becomes an attainable goal. The simplified calculations can be performed quickly by an inexpensive computer and displayed for the driver at each stop. GPS technology can detect when a stop is being approached and the calculation cycle should begin.

The cost comparison outlined in Section 3.5 is of particular advantage during off-peak situations when the number of boarding passengers is low, often less than one. In that case, the advantage gained to already boarded passengers by running consistently early grows with each stop bypassed. It is also possible that during off-peak periods many stops will be passed due to no passenger boarding and alighting, increasing the advantage to on-board passengers.

The calculations from Section 3.5 may suggest that the driver maintain a speed that is slower than the flow of traffic. In this case, the driver can adjust the “pace” of operations, by dwelling slightly longer at stops after servicing passengers, or by changing the acceleration and deceleration patterns of the bus at stops. These small adjustments can compound to produce larger effects, and this category of micro-adjustments is what is referred to as pace.

There are a number of simplifications made to improve the clarity and ease-of-use of the algorithm. These simplifications could be lifted in some cases to improve the robustness of the decision making process. For example, the threshold assumption that all passengers arrive instantaneously at $T_i - C$ is unrealistic. It is, however, a reflection of the fact that transit operators should not assume or demand that passengers arrive significantly ahead of a published schedule. Historical data could be used to determine this threshold for each stop, using a distribution of passenger arrivals. The threshold could be set with a particular confidence of passenger arrival at the stop.

The ratio γ_w/γ_r that accounts for differences in the discomfort of on-board and off-board passenger times is a factor that could be set as a fixed number, or could be adjusted continuously based on the difference between on-board and off-board conditions. For example, the value could scale with temperature difference between the riding and waiting passengers. In inclement weather, the bus is less likely to be instructed to run early due to the additional weight given to off-board passengers.

One issue that may arise is with the collection of historical data. It is important that the system self-update with new passenger counts to accommodate changes in boarding and alighting patterns. If data is collected and considered when the bus is running early, however, then boarding counts will lower continuously as the bus is increasingly likely to run early and skip passengers. Historical counts should only be taken when the bus is running on time, or at least no earlier than $T_i - C$.

It may be that due to inclement weather or other conditions that the cost associated with waiting for the next bus does not scale linearly with the time waited, h. In that case, equation [5] would take on the form

$$[11] \quad Z_w = b_i h^q \gamma_w$$

where q is some positive real number. For the purposes of this paper, $q = 1$.

While inter-time-point control may appear to have only minimal impact on the improvement of transit operations, it is important that investigation be done in improving movement of buses along all aspects of the route. Since regular stops generally outnumber control points, even minor improvements compound quickly compared with time points, and over time this can have a large effect on improving the system. Even a real-time decision making system with speed and arrival time suggestion can be helpful to drivers, since they are able to quickly and intuitively understand how late or early they are running between points. The numerical examples in Section 3.6 outline that the algorithm’s cost calculation feature is useful in accommodating extreme factors.

5 CONCLUSION

Because of the informal way that bus movement is considered between time points, there is potential for a bus to deviate from a projected path as it progresses from stop to stop. If a bus is running ahead of that projection, there is a potential time-saving advantage to on-board passengers, but also a potential loss to off-board passengers who miss their intended bus. During off-peak periods, when passenger boarding and alighting counts are low, and stops are often passed due to no waiting passengers, running early between time points is possible and the potential for missed passengers is low. An algorithm is proposed to suggest a travel speed and arrival time at each subsequent stop. This suggestion is made based on the potential cost savings of on-board passengers, and the costs of off-board passengers. A simple and quick calculation can be made, providing clear instructions to the driver who can make appropriate adjustments while accounting for external factors.

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