5

E-VeT: Economic Reward/Penalty-based System for Vehicular Traffic Management

5.1 Overview

The proliferation of mobile devices with embedded GPS sensors coupled with the growth in the popularity of infotainment services for vehicles have created new avenues for improving vehicular traffic management in road networks. Thus, schemes for improving transportation system efficiency are becoming increasingly popular [AWX+12, SWYX11].

Given that vehicles generally tend to autonomously select shorter routes with lower traffic congestion, a relatively large number of vehicles often choose the same ‘popular’ (i.e., relatively shorter and congestion-free) routes, thereby causing congestion. Such traffic congestion typically results in increased vehicular fuel consumption and delayed arrival at destinations. Thus, coordi-
nation among the routes allocated to different vehicles becomes a necessity to reduce traffic congestion. However, vehicles trying to coordinate their routes among themselves in a vehicle-to-vehicle (V2V) manner in vehicular ad hoc networks (VANETs) would cause privacy concerns, communication traffic congestion and selfish behaviors.

Incentives have been proposed for stimulating content sharing in mobile-P2P networks [PMG+11,WXS04,XWR06]. However, these works do not address traffic management and vehicular routing issues such as congestion. Moreover, a P2P traffic information system for dynamic route guidance has been discussed in [RSKM09]. However, these works do not incentivize vehicles in following system-assigned traffic routes.

This work proposes the E-VeT system for efficiently managing the vehicular traffic in road networks using economy-based reward/penalty schemes. In this work, the cost of traversing a path in the road network corresponds to the time required for the path traversal, unless otherwise specified. Hence, we shall use the terms “path cost” and “path time-cost” interchangeably. Observe that defining path cost in terms of time encompasses factors such as path distance, the speed limit relevant to the path and the path’s traffic congestion.

In E-VeT, base stations collaboratively facilitate dynamic vehicular route assignments for mitigating the traffic congestion, thus reducing the average time of arrivals and fuel consumption. However, vehicles may not follow the paths assigned by the base stations e.g., when they can find lesser-cost paths. To incentivize vehicles towards following the system-assigned paths, E-VeT uses rewards/penalties (payoffs), which are in terms of real currency. Hence, these payoffs can be used towards paying road taxes, car registration, and license/toll fees.

This work assumes that all the vehicles fall under the purview of the E-VeT reward/penalty framework, which could be implemented as part of a government-mandated program for facilitating traffic management. Note
that the proposed scheme is a government-mandated system, it is always operational, but only the price changes dynamically based on the congestion. Thus users, will not know the pricing scheme and congestion information well ahead of time. Though the system suggests and offers options to users, they still have a choice of paying the penalty and taking the higher-priced paths; the objective is not to force users for explicit load-balancing. Since we have a reward/penalty system, it is using incentives for load-balancing. It is also different and better than randomization where users can get one of the options, which they have to follow, and they have no choice to alter the option they received. Thus, in our scheme, we preserve the notion that a user is the final entity to decide the path taken.

This work can be seen as a further extension to the initial proposal for routing of the VS-scheme for parking introduced in [AWX+12]. In the VS-scheme, a central authority (CA) makes an optimal assignment, and penalizes vehicles severely for deviating from it. Furthermore, in the VS-scheme, the CA guarantees that each vehicle $v$ will pay a travel-cost to slots that is not higher than $v$’s cost in equilibrium. Since in an optimal assignment some vehicles may travel longer than in equilibrium, the CA compensates them in dollars so that the total cost that $v$ pays is not higher than $v$’s travel-time in equilibrium. The CA also charges vehicles that travel less in the optimum assignment than in the equilibrium assignment. This dollar-charge is equivalent to the saving in travel-time.

Our work here is mainly focused on routing in V2V different from parking of vehicles in [AWX+12] in terms of policies for route allocation of vehicles based on revenues, modeling the pricing problem for revenue generation and finding a suitable reward/penalty scheme that adapts to changing behavior of drivers over period of time. In addition, the performance metrics directly focus on the impact of different revenue allocation schemes on the average fuel saving, average time of arrival and the number of messages exchanged among others.

In summary, our proposed schemes differ from existing proposals [Bra96,
5.1. Overview

Mor10, Xu06, Yan12, Iss11] in mainly two ways. First, we introduce a reward/penalty framework for controlling the traffic congestion. Second, users’ good behavior (i.e., following the system advice) is considered in the congestion control decision-making in the sense that the system remembers past behavior and rewards/penalty earned in the past. Thus, our scheme is user-centric and it inspires users to earn rewards so that they can get preferred assignment of paths when needed by redeeming rewards.

The contributions of E-VeT are three-fold:

1. It proposes an $R^2A$ (Revenue-based Route Allocation) scheme, which rewards vehicles for following system-assigned longer-time paths, and charges a fee for following system-assigned shorter-time paths. Furthermore, it penalizes (charges much higher fee) vehicles for any deviations from the system-assigned paths.

2. It presents the $R^2A^+$ (extended $R^2A$) scheme by incorporating the notion of revenue-scales for further incentivizing vehicles based on their past system usage.

3. It discusses a route allocation algorithm, which gives lesser-time paths as a preference to vehicles that have earned higher revenue based on the scheme used i.e., either $R^2A$ or $R^2A^+$.

Note that both $R^2A$ and $R^2A^+$ schemes are designed to ensure fairness in the sense that vehicles pay when they travel faster, and they earn currency when they travel slower. Both schemes penalize vehicles, which deviate from system-assigned paths, thereby incentivizing them to adhere to the system-assigned paths. Furthermore, when vehicles follow the system-assigned paths, they are rewarded either in terms of time-savings (i.e., lower time-cost routes being allocated) or in terms of real currency (i.e., payments for following longer time-cost routes).

$R^2A$ and $R^2A^+$ differ in that while $R^2A$ assigns payoffs to vehicles based on every individual journey, $R^2A^+$ performs the payoff assignment based
on the consistency of a given vehicle in following the system-assigned paths across multiple journeys. To achieve this, \( R^2A^+ \) uses a set of pre-defined revenue-scales and provides better payoffs to the vehicles that are associated with higher revenue-scales. This entices vehicles to consistently follow the system-assigned routes. Our performance study shows that the proposed schemes are indeed effective in managing vehicular traffic in road networks by reducing the average time of arrival and fuel consumption.

The remainder of this chapter is organized as follows. Section 5.2 presents the architecture of E-VeT, while Section 5.3 discusses the proposed \( R^2A \) and \( R^2A^+ \) economic reward/penalty-based schemes and the route allocation algorithm. Section 5.4 provides the proof of correctness. Section 5.5 reports the performance study. Finally, we conclude in Section 5.6.

## 5.2 Architecture of E-VeT

This section discusses the architecture of E-VeT. The architecture of E-VeT consists of the road network, checkpoints, base stations and vehicles. E-VeT envisages the road network as an overlay graph, where each vertex represents a checkpoint, and each edge represents a route connecting these checkpoints. Here, a checkpoint is a landmark such as a major road intersection, a hospital or a well-known tourist spot. Thus, the journey of each vehicle comprises a traversal of a set of such checkpoints, and we designate the route between two checkpoints as a path. We define the source and destination of a given vehicle’s journey as the checkpoints that are nearest to the starting point and the desired end-point of the journey respectively. A base station is a powerful, reliable and static node. For simplicity, we assume that each checkpoint is associated with a single base station and vice versa.

When a given vehicle \( V \) approaches a checkpoint \( C \), it sends information about its destination to the base station \( B \) corresponding to \( C \). Upon receiving this information from multiple vehicles in its vicinity, \( B \) executes a route
allocation algorithm (discussed later in Section 5.3) and assigns a path to each vehicle for travelling to the next checkpoint. We shall henceforth refer to the path assigned to a given vehicle by a base station as the system-assigned path. Notably, the route allocation algorithm is executed by the corresponding base station at every checkpoint (that falls along a given vehicle’s route) until it is routed to its destination checkpoint.

In E-Vet, base stations assign rewards/penalties (i.e., payoffs) to the vehicles. As we shall see in Section 5.3, E-VeT performs route allocation by providing preference to vehicles, which have earned more payoffs, thereby incentivizing vehicles to follow system-assigned paths. Payoff allocation to the vehicles is performed on a checkpoint-to-checkpoint basis. Suppose vehicle $V$ traverses the path from checkpoint $C1$ to checkpoint $C2$. Let us refer to the base stations corresponding to $C1$ and $C2$ as $B1$ and $B2$ respectively. Here, $B2$ performs the payoff allocation to $V$, after communicating with the base station $B$ at the checkpoint that was previously traversed by $V$. If $V$ had followed the system-assigned path, $B=B1$, otherwise $B$ could be any of the neighboring base stations of $B2$.

Observe how base stations collaborate with each other to facilitate revenue-based dynamic vehicular routing for reducing traffic congestion. Such collaboration becomes a necessity for coordinating smooth traffic flow among vehicles, which do not directly interact with each other to preserve their privacy. Incidentally, traversal of a path between two given checkpoints is associated with a cost, which we shall discuss now.

### 5.2.1 Computation of path cost

Recall that in E-VeT, the path cost corresponds to the time required for traversing the path. The cost $t_j$ of traversing path $j$ is computed by a given base station in two steps (a) Compute the path cost $t_{rec_j}$ for the current time-period (b) Compute $t_j$ as the exponential moving average of the path costs over the most recent time-periods to account for fluctuations in path
usage. $t_{rec_j}$ depends upon factors such as path distance, speed limit of the path and path congestion. Thus, path cost can change temporally depending upon path congestion. Since path congestion is related to path flow, let us first compute the path flow $F_{j,t}$ for path $j$ as follows:

$$F_{j,t} = NL_{j,t}/NE_{j,t}$$  (5.1)

where $NE_{j,t}$ and $NL_{j,t}$ are respectively the number of vehicles that entered or left path $j$ during time-period $t$. We assume that $NE_{j,t}$ and $NL_{j,t}$ are both non-zero i.e., there are always vehicles on the road. Let us henceforth refer to the path flow as flow. Consistent with real-world scenarios, we consider that bi-directional flow values may differ e.g., the flow value from a given checkpoint X to a checkpoint Y may differ from that of the flow value from Y to X. However, such differences in flow values do not impact our proposed schemes.

$t_{rec_j}$ is computed as follows:

$$t_{rec_j} = \begin{cases} 
(D_j/S_{max}) & \text{if } F_{j,t} = 1 \\
(D_j/S_{max})/F_{j,t} & \text{otherwise} 
\end{cases}$$  (5.2)

where $D_j$ and $S_{max}$ are the distance and speed limit of path $j$ respectively. Observe that the term $(D_j/S_{max})$ in Equation 5.2 concerns the congestion-free path cost (i.e., $F_{j,t}=1$). Moreover, $t_{rec_j}$ increases with decrease in $F_{j,t}$ because more congested paths typically entail higher path costs.

Using the value of $t_{rec_j}$, the computation of $t_j$ according to the exponential moving average (EMA) formula follows:

$$t_j = ((t_{rec_j} - EMA_{prev}) \times 2/(T + 1)) + EMA_{prev}$$  (5.3)

where $EMA_{prev}$ is the EMA that was computed for the previous time-period and $T$ is the number of time-periods considered in the moving average computation. Results of our preliminary experiments suggest that $T=5$ is suitable...
for traffic management application scenarios. Notably, EMA gives higher weights to recent time-periods, hence it is appropriate for dynamically changing path costs that may occur in traffic management application scenarios.

5.2.2 Illustrative example for road network topology in E-VeT

Figure 5.1 depicts an illustrative example of the road network topology in E-VeT at a certain point in time. In Figure 5.1, the checkpoints C1 to C6 are connected by weighted paths P1 to P8, whose respective path costs are shown in parentheses. Here, path costs are indicated in case of congestion-free paths. Observe that path costs are essentially dynamic in that they increase as path congestion increases. For simplicity, all the vehicles V1 to V5 are associated with the same source checkpoint C1. The destination checkpoints for \( \{V1, V2, V3\} \) and \( \{V4, V5\} \) are C5 and C6 respectively. For simplicity, this example assumes that bi-directional path costs are equal.
5.3. Revenue-based route allocation in E-VeT

Assume that each vehicle prefers to take the least-cost path to its respective destination. Observe that all the vehicles V1 to V5 would have to traverse C4 on their way to their respective destinations. From C1 to C4, three paths are possible, namely \{P1, P4\}, \{P2\} and \{P3, P5\} with path costs of 3 (i.e., 2+1), 8 and 5 (i.e., 2+3) respectively. Thus, all the vehicles would want to take the least-cost path \{P1, P4\} to C4. However, all five vehicles taking path P1 would increase traffic congestion there, thus effectively increasing the path cost.

For reducing path congestion, coordination among vehicular routes becomes a necessity for ensuring smooth traffic flow. As we shall see in the next section, such coordination in E-VeT is performed by the base stations, which incentivize vehicles towards following system-assigned paths.

5.3 Revenue-based route allocation in E-VeT

This section discusses our proposed R²A and R²A⁺ economic reward/penalty-based schemes. Based on the scheme used (i.e., either R²A or R²A⁺), E-VeT assigns payoffs to the vehicles. These payoffs are used as inputs for E-VeT’s incentive-based route allocation algorithm, which is also presented in this section.

5.3.1 The R²A scheme

Recall that we define path costs in terms of time. For computing rewards and penalties in R²A, we define the notions of lower-cost paths and higher-cost paths as follows. Consider the existence of multiple possible paths between two given checkpoints. Each path, whose cost is below the median path-cost of all these paths, is defined to be in the set of lower-cost paths. Conversely, each path, whose cost equals or exceeds the median path-cost of all the paths between the two given checkpoints, is defined to be in the set of higher-cost paths. R²A rewards vehicles, which follow system-assigned higher-cost
paths, and charges a fee for following system-assigned lower-cost paths. Furthermore, it penalizes vehicles for any deviations from the system-assigned paths, thereby incentivizing them to adhere to the system-assigned paths. Thus, vehicles pay (in the form of fees) when they travel faster, while they get paid (in terms of rewards) when they travel slower, thereby achieving fairness.

Given that a path is the route between two given checkpoints, a given vehicle \( V \) has to traverse multiple paths during its journey from its source to its destination. Thus, its revenue from a given journey equals the difference between the rewards and the fees/penalties over all these paths. During a given journey, suppose \( V \) follows (a) \( r_1 \) system-assigned higher-cost paths (b) \( r_2 \) system-assigned lower-cost paths and (c) \( r_3 \) paths that are not assigned by the system. Then \( V \)'s revenue \( REV \) from the given journey is computed as follows:

\[
REV = \sum_{i=1}^{r_1} REW_i - \left( \sum_{m=1}^{r_2} Fee_m + \sum_{n=1}^{r_3} LY_n \right) \quad (5.4)
\]

where \( REW_i \) is the reward for the \( i^{th} \) system-assigned higher-cost path followed by \( V \). \( Fee_m \) is the fee that is charged for the \( m^{th} \) system-assigned lower-cost path followed by \( V \), while \( LY_n \) is the penalty for the \( n^{th} \) non-system-assigned path followed by \( V \). Thus, given that the revenue of \( V \) from its \( p^{th} \) journey is \( REV_p \), its total revenue equals \( \sum_{p=1}^{P} REV_p \), where \( P \) is the total number of journeys performed by \( V \).

Now let us see how the rewards and penalties are computed for \( V \) for a given path. The reward depends upon the cost difference between the system-assigned path and the corresponding median-cost path. Thus, the base station computes the reward \( REW_{R^2A} \) earned by \( V \) for a given path as follows:

\[
REW_{R^2A} = (t_j - t_{median}) \times \lambda \quad (5.5)
\]

where \( t_j \) is the path cost of the path \( j \) that the system assigned to \( V \), and \( t_{median} \) is the median-cost path between the two checkpoints associated with
path \( j \). \( \lambda \) is a parameter for converting time-cost to dollar-cost. Notably, the value of \( \lambda \) is a constant, which is fixed by the system. Observe that \( REW_{RA} \) increases with increase in the difference between \( t_j \) and \( t_{\text{median}} \) because higher rewards should be provided to vehicles for incentivizing them to follow relatively higher-cost system-assigned paths.

In Equation 5.5, both \( t_j \) and \( t_{\text{median}} \) are computed using Equations 5.2 and 5.3. Thus, both \( t_j \) and \( t_{\text{median}} \) are system-estimated time-costs based on current conditions of congestion as opposed to being actual times. Observe that if actual times had been used, vehicle users would have an incentive to spend significantly large amounts of time on the system-assigned path for obtaining increased amount of rewards. Furthermore, observe that if there is only one path between two checkpoints, the reward would be zero because both the median-cost path and the system-assigned path would be the same in this case.

To better understand the computations of \( t_j \) and \( t_{\text{median}} \), let us refer to Figure 5.1. For simplicity, assume that in Figure 5.1, all paths are congestion-free. Suppose a vehicle needs to find a path \( j \) between the two checkpoints C1 and C4. Here, the median-cost path is \{P3, P5\} with path cost of 5, hence \( t_{\text{median}} = 5 \). If the system assigned the path P2 to V, \( t_j = 8 \) because the path cost of P2 equals 8. On the other hand, if the system had assigned the path \{P1, P4\} to V, \( t_j \) would have been 3.

The fee \( Fee_{RA} \) is charged to V for following a given system-assigned lower-cost path \( j \). It depends upon the difference between the cost of taking the median path and the cost of taking path \( j \). Notably, we consider the cost of the median path to effectively handle scenarios involving outliers. Thus, given that \( t_j \) is the cost of the system-assigned lower-cost path \( j \) and \( t_{\text{median}} \) is the cost of taking the median path between the two checkpoints corresponding to \( j \), \( Fee_{RA} \) is computed as follows:

\[
Fee_{RA} = (t_{\text{median}} - t_j) \times \lambda
\]  

(5.6)
Both $t_j$ and $t_{\text{median}}$ are computed using Equations 5.2 and 5.3. Referring to Figure 5.1, consider the paths between C1 and C4. Suppose the system has assigned the path \{P1, P4\} to V, hence $t_j=3$. Here, $t_{\text{median}}=5$ because it corresponds to the cost of taking the path with the median cost \{P3, P5\} between C1 and C4. Notably, the significance of $\lambda$ in Equation 5.6 is essentially the same as in Equation 5.5.

A penalty is incurred by V when it deviates from the system-assigned path. E-Vet assigns different values of $LY$ depending upon whether the opted path is in the set of lower-cost paths or in the set of higher-cost paths. When the opted path is in the set of higher-cost paths, the system shall levy no penalty, hence $LY=0$. Conversely, when the opted path is in the set of lower-cost paths, the system shall levy a penalty proportional to the difference between $t_{\text{median}}$ and $t_{j'}$, where $t_{\text{median}}$ is the median-cost path and $t_{j'}$ is the cost of the opted path, as shown in Equation 5.4.

$$LY_{R^2A} = \begin{cases} (t_{\text{median}} - t_{j'}) \times \lambda & \text{if } t_{j'} < t_{\text{median}} \\ 0 & \text{otherwise} \end{cases} \quad (5.7)$$

where $t_{\text{median}}$ is the median-cost path, and $t_{j'}$ is the path cost of the path $j'$ taken by the user. Here, $\lambda$ is the dollar-cost for penalty, and it is system-defined.

Observe that $R^2A$ assigns payoffs without taking into account the past system usage of a given vehicle in following the system-assigned paths across its multiple journeys. Thus, it suffers from the drawback of not being capable of incentivizing consistent behavior by the vehicles in adhering to the system-assigned paths.

### 5.3.2 Illustrative example for $R^2A$

Figure 5.2 depicts an illustrative example for the computation of rewards and penalties in $R^2A$ for a given vehicle $V$. The values of the reward $REW_{R^2A}$
and the penalties $Fee_{R^2A}$ and $LY_{R^2A}$ are computed using Equations 5.5, 5.6 and 5.7. Suppose $C_{curr}$ is the checkpoint at which $V$ is currently located, while C1 to C6 are the possible next-checkpoints for its journey towards its destination, as indicated in the column $C_{next}$ of Figure 5.2a. The second column $t_j$ in the same figure refers to the cost of traversing the path from $C_{curr}$ to $C_{next}$.

Observe that C6 is the checkpoint that is associated with the minimum-cost path from $C_{curr}$ to any of the next-checkpoints. Figure 5.2a also indicates the values of $\lambda$ and $t_{median}$ that will be used for computing the rewards and penalties. For simplicity, in this example, we show the computation of $LY_{R^2A}$ (see Equation 5.7) using only the current time-period instead of averaging the values over the past $T$ time-periods.

Figures 5.2b and 5.2c depict the rewards and penalties when the system-assigned next-checkpoints for $V$ are C2 and C4 respectively. In Figure 5.2, observe that $V$ earns rewards only when it follows the system-assigned path to C2, which is in the set of higher-cost paths, hence its revenue $REV_{R^2A}$ is
positive only in this case. The reward for \( V \) in this case is computed using
Equation 5.5. Thus, \( REW_{R^2A}^- = (1.07 - 0.97) \times 10 \) i.e., 1.00. Furthermore,
observe that in Figure 5.2, the value of \( Fee_{R^2A} \) is 0 for all the cases because
the system-assigned path to \( C_2 \) is in the set of higher-cost paths, thereby
making the penalty \( Fee_{R^2A} \) inapplicable.

Observe that here the applicable penalty for deviating from the system-
assigned path and opting for a lower-cost path are computed using Equa-
tion 5.7. For example, the value of \( LY_{R^2A} \) when the next-checkpoint is \( C_1 \) is
zero because \( C_1 \) is associated with a higher-cost path, whereas the value of
\( LY_{R^2A} \) is -6.30 in the case of \( C_5 \), where \( C_5 \) is associated with the lower-cost
path. The values of \( REV_{R^2A} \) are computed using Equation 5.4, which are
also indicated in Figure 5.2.

5.3.3 The \( R^2A^+ \) scheme

The \( R^2A^+ \) scheme extends the \( R^2A \) scheme by incorporating the notion of
revenue-scales for taking into account a given vehicle’s consistency in ad-
hering to the system-assigned paths across multiple journeys. \( R^2A^+ \) defines
\( M \) revenue-scales, each of which is associated with a range of revenues. Then
it associates a given vehicle with a revenue-scale based on the vehicle’s rev-
ue. Suppose \( M = 4 \), where revenue-scales \{1, 2, 3, 4\} correspond to revenue
ranges \{0-1000, 1001-2000, 2001-3000, 3001-4000\} respectively. Here, the
vehicle with revenue of 2500 units is associated with revenue-scale 3.

\( R^2A^+ \) uses these revenue-scales for distributing the payoffs. Vehicles, which
are associated with higher revenue-scales, earn better payoffs. This provides
an additional incentive to the vehicles to consistently follow the system-
assigned paths so that they can earn adequate currency to qualify for higher
revenue-scales, at which their payoffs would improve. Given \( M \) revenue-scales
with a given vehicle being associated with revenue-scale \( m \), \( R^2A^+ \) computes
the payoffs as follows:

\[
REW_{R^2A^+} = (m/M) \times REW_{R^2A} \\
Fee_{R^2A^+} = (m/M) \times REW_{R^2A} \\
LY_{R^2A^+} = (m/M) \times LY_{R^2A}
\]

where \(REW_{R^2A}\), \(Fee_{R^2A}\) and \(LY_{R^2A}\) are computed using Equations 5.3, 5.6 and 5.7 respectively. Similar to \(R^2A\), \(R^2A^+\) computes a given vehicle’s revenue using Equation 5.4.

### 5.3.4 Route allocation algorithm

A given base station performs the route allocation to all the vehicles that are moving towards its corresponding checkpoint. When a vehicle approaches a checkpoint, it communicates to the corresponding base station the following information: its destination, its previous checkpoint, the checkpoint assigned to it at the previous checkpoint and its revenue. Notably, this communication is done by the tamper-resistant software module in the vehicle to the base station, thereby ensuring that a vehicle cannot provide false information to the base station concerning its system-assigned checkpoint.

Upon receiving the information from all the vehicles during a system-defined time-period, the base station computes the payoffs of the vehicles based on either \(R^2A\) or \(R^2A^+\). Moreover, it uses the route allocation algorithm to assign paths to the vehicles. Then it performs the following actions for each vehicle: (a) updates their revenues based on whether they followed the system-assigned paths, (b) sets its value as the last visited base station, and (c) sets the cost of the assigned path in the vehicle’s system.

Notably, the route allocation algorithm uses a path flow threshold, which we designate as \(PF_{th}\). The implication of \(PF_{th}\) is that the route allocation algorithm would assign vehicles to a given path only up to the value of \(PF_{th}\), thereby not allowing a path to go beyond a given level of traffic congestion. Once the threshold \(PF_{th}\) is reached for a given path (when path flow keeps
5.3. Revenue-based route allocation in E-VeT

decreasing due to traffic congestion), the path is considered to be full, hence the algorithm would not assign any more vehicles to that path for that time interval.

The value of the $PF_{th}$ threshold can be decided based on the acceptable time of travel between two checkpoints C1 and C2 during different time intervals. Recall that flow in a given path $P$ is the ratio of the number of vehicles exiting $P$ to the number of vehicles entering $P$ during a given time interval. Thus, for example, the flow threshold can be set to 0.6 and 0.8 during peak hours and non-peak hours respectively for maintaining smooth traffic flow. The acceptable threshold can be determined based on the distance between the two given checkpoints and the average possible speed (i.e., (maximum speed limit + minimum speed limit) / 2), which can provide the ideal time of travel between the two checkpoints. This can then be calculated for peak hours and off-peak hours based on the threshold selected and the time determined should be within the acceptable limit set by the travel authority for smooth flow of traffic at different times.

Algorithm 5.1 discusses how a base station identifies the top-$k$ preferred checkpoints for a given vehicle, given the overlay graph $G(V, E)$ of the road network, and the respective destination of each vehicle as input. First, it determines the least-cost $k$ paths to the destination of the vehicle based on the path cost using the approach in [Epp98]. Then, for each of these least-cost $k$ paths, it identifies the next checkpoint that the vehicle needs to traverse for following that path to its destination, and stores these checkpoints in a list $PL$. Now, for each checkpoint in $PL$, it computes the path cost. Finally, it sorts the checkpoints in $PL$ in ascending order of the path costs. Thus, the sorted $PL$ list essentially reflects the preference of the vehicle towards its route assignment in terms of path cost minimization.

Algorithm 5.2 presents the economy-based route allocation algorithm in E-VeT using the preference list for each vehicle, as generated by the Algorithm 5.1. Incidentally, vehicles with relatively higher revenues are likely to be those that have either adhered more frequently to their system-assigned
5.4. Proof of correctness of E-VeT

Algorithm 5.1 Greedy algorithm for identifying the preference list of next-checkpoints for a given vehicle

begin
Input: (a) G(V,E): Overlay graph of the road network
      (b) dest: Destination of the vehicle
Output: PL: Sorted list of top-k preferred next-checkpoints for the vehicle
(1) Determine least-cost k paths to dest based on path cost
(2) for each least-cost k path
(3) Identify corresponding next-checkpoint and add it to list PL
(4) for each checkpoint in PL
(5) Compute the path cost
(6) Sort the checkpoints in PL in ascending order of the path costs
end

Algorithm 5.2 Algorithm for route allocation in E-VeT

begin
Input: (a) Destination, previous checkpoint and the checkpoint assigned
      by the previous checkpoint's base station for each vehicle i
      (b) Preference list PL_i for each vehicle i
      (c) Revenue of each vehicle
Output: Assignment of next-checkpoint to each vehicle
(1) Sort the vehicles in descending order of revenue into a list LV
(2) for each vehicle i in LV
(3) for each checkpoint C_j in PL_i
      /* The path from the base station to checkpoint j is designated as path j
(4) if (path flow > PF_{th})
(5) Assign vehicle i to path j
(6) Recompute the path flow
(7) break
end

paths or taken longer-time paths more often. Thus, observe how the route allocation Algorithm 5.2 incentivizes vehicles with higher revenues by providing them with preference in route allocation. Furthermore, from Line 4 of Algorithm 5.2, notice how the algorithm assigns vehicles to a given path depending upon the $PF_{th}$ threshold criterion.

5.4 Proof of correctness of E-VeT

The proof aims to show that the mechanism is designed in a way that the dominant strategy for all the vehicles is to follow the system assigned path.

Definition. For a given vehicle $V$, we define two possible decisions, namely
(a) follow the system-assigned path and (b) not follow the system-assigned
5.4. Proof of correctness of E-VeT

path. We denote the former and latter as $f$ and $\bar{f}$ respectively. Let us denote the corresponding payoffs for the former and the latter cases as $P_f$ and $P_{\bar{f}}$ respectively.

To prove the correctness of the mechanism, we shall prove that $P_f > P_{\bar{f}} \text{ i.e., } (P_f - P_{\bar{f}} > 0)$ for all possible cases. (We shall also derive the minimum value of penalty that should be levied to hold the above condition.)

Proof: The following two cases arise:

Case 1: The system-assigned path $j$ is among the higher-cost paths. ($t_j > t_{\text{median}}$)

In this case, observe that the fee $\text{Fee}_{R^2A}$ is not applicable. Hence, $P_f = \text{REW}_{R^2A} - \lambda t_j$, where $\text{REW}_{R^2A}$ is computed using Equation 5.5 and $t_j$ represents the path cost as computed using Equations 5.2 and 5.3. Moreover, when $V$ follows a non-system-assigned path $j'$, $P_{\bar{f}} = -\text{LY}_{R^2A} - \lambda t_{j'}$, where $\text{LY}_{R^2A}$ is computed using Equation 5.7, and $t_{j'}$ is the cost of path $j'$, which is computed using Equations 5.2 and 5.3.

Now, let us find the minimal value $\text{LY}_{R^2A}$ of penalty for which $P_f \geq P_{\bar{f}}$: (Equating it to get minimal value)

$$
P_f \geq P_{\bar{f}} \implies (t_j - t_{\text{median}})\lambda - \lambda t_j \geq -\text{LY}_{R^2A} - \lambda t_{j'}$$
$$\implies \lambda(t_{j'} - t_{\text{median}}) \geq -\text{LY}_{R^2A}$$
$$\implies \text{LY}_{R^2A} \geq \lambda(t_{\text{median}} - t_{j'})$$

The penalty algebraically becomes negative when the vehicle deviates from the system by opting for a path higher than the median cost path. In such a scenario, the system levies no penalty on the vehicle keeping $\text{LY}$ to be zero.

Case 2: The system-assigned path $j$ is among the lower-cost paths. ($t_j < t_{\text{median}}$)

In this case, observe that the fee $\text{Fee}_{R^2A}$ becomes applicable and $\text{REW}_{R^2A}$ is not applicable. Hence, $P_f = -\text{Fee}_{R^2A} - \lambda t_j$, where $\text{Fee}_{R^2A}$ is computed using Equation 5.6 and $t_j$ represents the path cost as computed using Equations 5.2
5.5. Performance Study

and 5.3. Moreover, when $V$ follows a non-system-assigned path $j'$, $P_f = -LY_{R^2A} - \lambda t_{j'}$, where $LY_{R^2A}$ is computed using Equation 5.7, and $t_{j'}$ is the cost of path $j'$, which is computed using Equations 5.2 and 5.3.

Now, let us find the minimal value $LY_{R^2A}$ of penalty for which $P_f \geq P_f$:

(Equating it to get minimal value)

$$P_f \geq P_f \implies -(t_{\text{median}} - t_j)\lambda - \lambda t_j \geq -LY_{R^2A} - \lambda t_{j'} \implies \lambda(t_{j'} - t_{\text{median}}) \geq -LY_{R^2A} \implies LY_{R^2A} \geq \lambda(t_{\text{median}} - t_{j'})$$

The penalty algebraically becomes negative when the vehicle deviates from the system by opting for a path higher than the median cost path. In such a scenario, the system levies no penalty on the vehicle keeping $LY$ to be zero.

### 5.5 Performance Study

This section reports the performance evaluation of our proposed $R^2A$ and $R^2A^+$ schemes by means of simulation. We consider a universe of 30 km by 30 km, which is divided into 10 regions of equal area. Table 5.1 summarizes the parameters used in the performance study.

We consider a total of 200 checkpoints. The number of checkpoints in each region is determined using a Zipf distribution with a zipf factor $ZF_C$ of 0.5 (i.e., high skew) over 10 buckets, where each bucket corresponds to one of the 10 regions. Then for each region, the required number of checkpoints is randomly selected from the points within that region. Moreover, we consider a total of 25000 vehicles, which are homogeneous in terms of gas mileage and speed. The number of journeys for each vehicle during the course of our experiment is randomly chosen to be between 2 and 6. Furthermore, the source checkpoint for a given vehicle for each journey is chosen randomly from the 200 checkpoints.

For selecting the destination checkpoint for a given journey for a vehicle, we make the observation that in real-world scenarios, destinations for journeys
5.5. Performance Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Default</th>
<th>Variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of journeys ( (N_J) \ (10^4) )</td>
<td>10</td>
<td>2, 4, 6, 8</td>
</tr>
<tr>
<td>Number of vehicles ( (N_V) \ (10^4) )</td>
<td>25</td>
<td>5, 10, 15, 20</td>
</tr>
<tr>
<td>Number of checkpoints ( (N_C) )</td>
<td>200</td>
<td>40, 80, 120, 160</td>
</tr>
<tr>
<td>Skew in checkpoint distribution ( (ZF_C) )</td>
<td>0.5</td>
<td>0.1, 0.3, 0.7, 0.9</td>
</tr>
<tr>
<td>Skew in destination ( (ZF_D) )</td>
<td>0.5</td>
<td>0.1, 0.3, 0.7, 0.9</td>
</tr>
<tr>
<td>Percentage of users who are not revenue-conscious ( (P_U) )</td>
<td>40</td>
<td>20, 60, 80, 100</td>
</tr>
</tbody>
</table>

Table 5.1: Parameters of the performance study

are typically skewed across regions. In other words, some of the ‘popular’ regions would contain destinations for a disproportionately large number of journeys, while other regions would contain destinations for only a relatively smaller number of journeys. Thus, given the total of 100000 journeys (performed by different vehicles) in our experiments, we first select the destination region for each journey using a Zipf distribution with zipf factor \( ZF_D=0.5 \) (i.e., high skew) over 10 buckets corresponding to the 10 regions. Then given a destination region, we randomly select any one of the checkpoints contained in that region as the destination for a given journey.

Performance metrics are average fuel savings (AFS), average time savings (ATS), success rate (SR) and communication cost in terms of the total number of messages (MSG). AFS and ATS are both computed based on the differences in fuel consumption and journey time respectively between the minimum-cost route and the system-assigned route. AFS is computed as follows:

\[
AFS = \frac{1}{N_J} \sum_{i=1}^{N_J} (FC_{minP_i} - FC_{SA_i})
\]

(5.9)

where \( FC_{minP_i} \) and \( FC_{SA_i} \) are the fuel consumption corresponding to the minimum-cost route and the system-assigned route respectively for the \( i^{th} \) journey. Observe that AFS is computed as the average value of fuel savings across the total number \( N_J \) of journeys.
5.5. Performance Study

Similarly, ATS is computed as follows:

$$ATS = \frac{1}{N_J} \sum_{i=1}^{N_J} (TC_{\text{min}P_i} - TC_{SA_i})$$

(5.10)

where $TC_{\text{min}P_i}$ and $TC_{SA_i}$ are the time consumption for the minimum-cost route and the system-assigned route respectively for the $i^{th}$ journey. ATS is computed as the average value of time savings across $N_J$ journeys.

The success rate SR depends upon the number of journeys that completed within $x\%$ of the time required when following the minimum-cost route. Here, required time when using the minimum-cost route is estimated by the route’s cost divided by vehicle speed. Our experiments use $x=20\%$. For example, suppose the time required when using the minimum-cost route for a given journey is 20 minutes. Then, only the journeys, which were completed within 24 (i.e., $20 \times 1.2$) minutes are deemed to be successful. Thus, SR is computed as the ratio between the number of successful journeys and the total number of journeys.

Finally, $MSG = \sum_{i=1}^{N_J} MSG_i$, where $MSG_i$ is the number of messages for the $i^{th}$ journey. Thus, MSG is a cumulative metric over the total of $N_J$ journeys. Notably, the interaction between a vehicle and the base station at any given checkpoint incurs two messages. The first message is from the approaching vehicle to the base station, while the second message is sent by the base station to the vehicle for informing it about the system-assigned path.

Recall that in Section 5.3.1, we defined the notion of a lower-cost path between two given checkpoints as a path, whose cost is below the median path-cost of all the paths connecting the two checkpoints. As reference, we use a scheme in which only the lower-cost routes carry a fee (akin to toll-road fees), while other paths do not entail any fees. The fee for the lower-cost paths is computed using Equation 5.6. We shall henceforth designate this scheme as the **Congestion-Pricing (CP)** scheme. CP does not provide any rewards to vehicles for taking longer time-cost routes. Moreover, in CP, the base stations do not coordinate vehicular traffic routing, hence they do not
provide any economic incentives to the vehicles towards following the system. Furthermore, CP does not necessitate any interactions between base stations and vehicles. In essence, CP charges fees to vehicles when they travel faster, but it does not reward vehicles when they travel slower, and CP does not incorporate the reward/penalty mechanism of E-Vet.

Notably, in case of $R^2A$, $R^2A^+$ and CP, the implicit assumption is that every vehicle is trying to maximize its revenue. However, in practice, there could be a percentage of vehicle users, who do not care about maximizing their revenue i.e., these users are not revenue-conscious. Hence, we also examine the performance when 40% of the users are not revenue-conscious, while the other 60% are trying to maximize their revenue. In the experimental results, we designate the performance of $R^2A$, $R^2A^+$ and CP under the above condition as $R^2A^+_U$, $R^2A_U$ and $CP_U$ respectively.

5.5.1 Performance of E-VeT

We conducted an experiment using the default values of the parameters in Table 5.1. Figure 5.3 depicts the results. As the number $N_J$ of journeys increases, performance in terms of AFS (measured in fuel units (f.u.)), ATS (measured in time units (t.u.)) and SR improves for both $R^2A$ and $R^2A^+$ due to their effective economic reward/penalty-based route allocation, which reduces traffic congestion, thereby resulting in both fuel and time savings as well as higher success rates. Both $R^2A$ and $R^2A^+$ outperform CP essentially due to their economic reward/penalty-based route allocation approach. In contrast, in case of CP, the vehicles acting selfishly in trying to follow the least-cost routes to their respective destinations cause traffic congestion. This further increases both fuel consumption and average time of journey.

$R^2A^+$ performs better than $R^2A$ because it provides additional incentives for the vehicles to consistently follow the system-assigned paths across multiple journeys. Moreover, $R^2A$ outperforms $R^2A_U$, and $R^2A^+$ outperforms $R^2A^+_U$. 
This is because in case of $R^2A_U$ and $R^2A^+_U$, 40% of users are not revenue-conscious, thereby reducing the effectiveness of these schemes. Furthermore, $R^2A^+_U$ outperforms $R^2A$ (in terms of AFS, ATS, SR) up to a certain number of journeys primarily because $R^2A^+_U$ better incentivizes vehicles in consistently following the system-assigned paths. However, as the number of journeys exceeds 80,000, $R^2A$ performs better than $R^2A^+_U$. This occurs because as the number of journeys increases beyond a certain point, the implication is that a larger absolute number of users are not revenue-conscious, thereby reducing the effectiveness of $R^2A^+_U$. 

Figure 5.3: Performance of E-VeT
5.5. Performance Study

Observe that MSG equals zero for CP in all cases because in CP, the vehicles do not need to interact with the base stations. On the other hand, MSG increases over the number of journeys in our proposed schemes since it is a cumulative metric. MSG is comparable in case of $R^2A$, $R^2A^+$, $R^2A_U$ and $R^2A^+_U$ as these schemes involve similar interactions between the vehicles and the base stations at the corresponding checkpoints. These interactions occur through the software in each vehicle, regardless of whether the users are revenue-conscious.

5.5.2 Effect of varying the number of vehicles

We conducted an experiment to examine the scalability of E-VeT w.r.t. the number of vehicles. Figure 5.4 depicts the results of varying the number $N_V$ of vehicles. As $N_V$ increases, performance in terms of AFS, ATS and SR degrades for both $R^2A$ and $R^2A^+$ due to increased traffic congestion arising from a larger number of vehicles. Observe that the performance degradation is only slight essentially due to the effective incentive-based route allocation performed by both $R^2A$ and $R^2A^+$. As $N_V$ increases, MSG increases for both $R^2A$ and $R^2A^+$ because the number of interactions between the base stations and the vehicles increases, given the increase in the number of vehicles. Furthermore, the explanation for the relative performance of $R^2A^+_U$ and $R^2A$ is essentially the same as in case of Figure 5.3.

5.5.3 Effect of varying the number of checkpoints

We conducted an experiment to investigate the effect of varying the number $N_C$ of checkpoints. Figure 5.5 depicts the results. As $N_C$ increases, the route assignments are performed at a relatively larger number of checkpoints, thereby implying more opportunities for fine-tuning the route assignments. Hence, performance (in terms of AFS, ATS and SR) improves for all our proposed schemes. This performance gain comes at the cost of higher MSG because vehicles and base stations exchange messages at a larger number of
5.5. Performance Study

![Graphs showing AFS, ATS, SR, and MSG](image)

Figure 5.4: Effect of variations in the number of vehicles

checkpoints. However, we believe that the increase in MSG is a small price to pay for the performance gain in reducing the overall traffic congestion. Furthermore, the results indicate that R²A performs better than R²A⁺. This occurs because 40% of the users are not revenue-conscious in case of R²A⁺, which reduces its effectiveness in reducing traffic congestion.
5.5.4 Effect of variations in skew in checkpoint distribution

Recall that $ZF_C$ is the zipf factor, which quantifies the skew in the distribution of checkpoints across the 10 regions considered in our experiments. Figure 5.6 depicts the results of varying $ZF_C$. As $ZF_C$ increases, the implication is that a disproportionately large number of checkpoints occur in only a few of the regions, while other regions contain only a relatively small numbers. Hence, in most of the regions, there are fewer opportunities for
Figure 5.6: Effect of variations in skew in the distribution of checkpoints

fine-tuning the route assignments. Thus, given that vehicular journeys cut across different regions, the performance (in terms of AFS, ATS and SR) of our proposed schemes degrades as the checkpoint distribution becomes more skewed. However, MSG remains comparable for our proposed schemes because it depends upon the number of checkpoints, regardless of the skew in the distribution of checkpoints.
5.5.5 Effect of variations in the percentage of users who are not revenue-conscious

Recall that the $R^2A_U$, $R^2A^+_U$ and $CP_U$ schemes were defined to take into account that a certain percentage of the users are not revenue-conscious i.e., they do not care about maximizing their revenue. Let us designate this percentage as $P_U$. In Figure 5.7 as $P_U$ increases, the performance of our proposed schemes degrade because an increasing number of users become indifferent.

![Graph](image)

Figure 5.7: Effect of variations in the percentage of users who are not revenue-conscious
to the revenue-maximization objective, which is used by our schemes to incentivize vehicles to follow the system-assigned paths, thereby reducing the overall effectiveness of our schemes. Interestingly, when \( P_U = 100\% \) the performance of our proposed schemes becomes comparable to that of CP because at that point, 100\% of the users are not revenue-conscious, thereby implying that the users are not incentivized by our proposed schemes. However, MSG remains comparable across variations in \( P_U \) because the interactions between the vehicles and the base stations occur through the software in each vehicle, regardless of whether the users are revenue-conscious.

### 5.6 Summary

We have proposed the E-VeT system for efficiently managing vehicular traffic in road networks using economy-based reward/penalty schemes. E-VeT aims at reducing traffic congestion by enabling base stations to collaboratively facilitate dynamic vehicular route assignment. Our proposed R\(^2\)A scheme rewards vehicles for following system-assigned longer-time paths, and charges a fee for following system-assigned shorter-time paths. R\(^2\)A\(^+\) extends R\(^2\)A by incorporating the notion of *revenue-scales* for additionally considering a given vehicle's past history in following system-assigned paths across multiple journeys. Thus, in E-VeT, vehicles earn revenues based on either the R\(^2\)A scheme or the R\(^2\)A\(^+\) scheme. The route allocation algorithm used by E-VeT provides preference to vehicles earning higher revenues by assigning them to shorter-time paths, thereby incentivizing them to follow the system-assigned paths. Our performance study shows that the proposed schemes are indeed capable of effective traffic management in road networks by reducing the average time of arrival and fuel consumption.

In the near future, we will validate the results of spatio-temporal variations of vehicular traffic in VANETs [BK09] within our framework of economic reward/penalty schemes.