

A ROUTE-BASED INCENTIVE STRUCTURE FOR TRAFFIC SAFETY ENHANCEMENT

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ABSTRACT

An incentive structure is introduced to improve traffic safety. Drivers are awarded cash bonuses when they follow designated safe routes. The effects of this incentive structure are studied in this paper, with emphasis on driver's route choice behaviour and performance of the traffic network. Sufficient conditions are identified for a win-win situation where both individual drivers and the traffic system benefit from the incentive structure. The results of this study have implications for communities aiming at traffic safety enhancement. Implementation of the incentive structure can be easily made with currently available navigation systems and communication technologies.

KEYWORDS

traffic safety, route choice, incentives, impact assessment

INTRODUCTION

An effective way to improve traffic safety is through the promotion of safe driving. The intervention used to influence driver behaviour is normally either (negative) enforcement or (positive) incentives. Enforcement usually involves legislation, such as speed limit and prohibited use of hand-held mobile phones while driving. Drivers are punished (by warning, fine, and/or imprisonment) if they fail to comply with the prescribed rules. Incentives, on the other end, provide an extrinsic motivation for drivers to follow these rules, for which they would receive certain reward. In general, incentives can be classified into four categories [1]: (a) exchangeable token such as cash or meal coupons, (b) immediate valuable or promotional item such as stickers and T-shirt, (c) chance to win a contest or lottery, and (d) work or society related privilege. Public awareness and information campaigns are also considered as incentives, although of a moral or spiritual nature since they have no material value compared to cash bonuses.

Research on using incentives to promote safe driving has mainly focused on safety belt use. A meta-analysis on 34 journal articles and research reports [2] shows that incentive campaigns can substantially stimulate safety belt use, with a short-term increase of 12 percentage points in average. Safety belt use dropped after withdrawal of the incentive campaigns but was

generally still higher than initial baselines. The main factors that influence the magnitude of the effects are the initial baseline rate (highly correlated to the presence or absence of a safety belt usage law), the type of population involved, and whether the incentives are delivered immediately or delayed.

In other studies, drivers are rewarded for safe speed keeping and peak-hour avoiding. The Dutch practical test on rewarding drivers for maintaining a safe speed and headway [3] showed similar results to those of safety belt campaigns, observing considerable behavioural adaptation during the test period but reduced remnant effects afterwards. Also in the Netherlands, a current project on peak-hour avoiding [4] rewards registered participants with cash bonuses each time they avoid travelling in the peak-hour (compared with their normal travel behaviour). The results are still to be seen.

Another area of research focuses on using incentives to influence the decision to drive: the Pay-As-You-Drive (PAYD) insurance policy [5]. In PAYD, the insurance premium is not fixed but based directly on the actual distance driven. Travellers then have incentives to reduce their car use. A case study [6] showed that, as the result of PAYD, the number of traffic accidents can be reduced by up to 5.7%.

In the present research we are interested in improving traffic safety by encouraging drivers to take 'safe' routes when making their journeys. The incentive (or stimulus) here is a monetary bonus paid to the drivers when they follow a pre-determined safe route. In this paper, the incentive structure is formulated under the framework of generalised cost [7]; impact of the incentive structure is analysed based on the concept of discrete choice and user equilibrium [8]. Sufficient conditions for certain scenarios are identified, such as for a win-win situation where both individual drivers and the traffic system benefit from the incentive structure. A numerical study is included to demonstrate

A questionnaire survey and a field operational test are currently being carried out in order to obtain data on driver behaviour under the influence of this incentive structure. The data will be used to estimate the key parameters in our model. It will help us understand how different factors, including road safety and cash bonus, contribute to driver's route choice. Conclusion can then be made on the expected consequences when the incentive structure is implemented, such as the equilibrium shift and the evolution towards the new equilibrium [9]. Implications can also be drawn on the optimisation of the incentive structure, so as to maximise the system benefit.

The technical deployment of such an incentive structure is also discussed in this paper. User interface is realised on the widely available navigation systems. The safe route is highlighted on the map display and drivers' compliance with it is automatically recorded. Variable settings concerning the payment of the incentives can be introduced, including eligibility (the requirement of complete or partial compliance with the safe route, i.e. whether the incentive is all-or-nothing), and immediacy of the incentive delivery. An overview of these settings is provided in this paper.

FORMULATION OF THE INCENTIVE STRUCTURE

We formulate the route choice of travellers with the logit model. Each alternative route is evaluated by its generalised cost. This would include for example route travel time, fuel cost

and safety levels along the route. The route-based incentive structure brings a change to the route costs and also the consequent traffic assignment. Effect of this incentive structure is evaluated in the next section.

Route choice and traffic assignment

We consider a network with N origin-destination (OD) pairs. Each OD pair i ($i = 1, 2, \dots, N$) is connected by a set of routes, denoted as \mathbf{R}_i , with $m_i = |\mathbf{R}_i|$ as the number of routes connecting the OD pair and $M = \sum_{i=1}^N m_i$ as the total number of OD routes in the network. Routes are numerated as $1, 2, \dots, m_1$ for the m_1 routes in \mathbf{R}_1 , as $m_1 + 1, m_1 + 2, \dots, m_1 + m_2$ for the m_2 routes in \mathbf{R}_2 , ..., and finally as $M - m_N + 1, M - m_N + 2, \dots, M$ for the m_N routes in \mathbf{R}_N .

The daily travel demand is fixed for each OD pair, denoted as d_i for the OD pair i . Travellers' route choices are made according to the logit model. Routes are chosen based on the perceived costs of all the alternative routes on the same OD pair. These route costs are assumed to be random variables following i.i.d. Gumbel distribution. The route cost vector is given as $\mathbf{c} = [c_1, c_2, \dots, c_r, \dots, c_M]^T$, where c_r is the mean perceived cost on route r . For a traveller on OD pair i , the probability of choosing route r ($r \in \mathbf{R}_i$) is then given as

$$p_r = \frac{e^{-qc_r}}{\sum_{s \in \mathbf{R}_i} e^{-qc_s}} = \frac{1}{\sum_{s \in \mathbf{R}_i} e^{q(c_r - c_s)}} = \frac{1}{1 + \sum_{s \in \mathbf{R}_i, s \neq r} e^{q(c_r - c_s)}}. \quad (1)$$

Here $q \geq 0$ is the dispersion parameter, which represents the precision level of travellers' route cost perception. When $q = 0$, all alternative routes are equally likely to be chosen (i.e. indifferently); when $q \rightarrow \infty$, only the route(s) with the minimum mean cost will be chosen.

Traffic flows are (statically) assigned to the routes as

$$\mathbf{f} = \mathbf{D}\mathbf{p}, \quad (2)$$

where $\mathbf{f} = [f_1, f_2, \dots, f_r, \dots, f_M]^T$ gives the traffic flow on each route. The route demand matrix \mathbf{D} is constructed as

$$\mathbf{D} = \text{diag}\{ \underbrace{d_1, d_1, \dots, d_1}_{m_1}, \underbrace{d_2, d_2, \dots, d_2}_{m_2}, \dots, \underbrace{d_i, d_i, \dots, d_i}_{m_i}, \dots, \underbrace{d_N, d_N, \dots, d_N}_{m_N} \}. \quad (3)$$

The M -vector \mathbf{p} is the choice probability vector, in the following form:

$$\mathbf{p} = p(\mathbf{c}) = [p_1, p_2, \dots, p_r, \dots, p_M]^T. \quad (4)$$

With the above assignment we can see that

$$\mathbf{f} \geq 0, \quad (5)$$

so route flows are either positive or zero (non-negativity constraint). Secondly we have that for any OD pair $i = 1, 2, \dots, N$,

$$\sum_{r \in \mathbf{R}_i} p_r = \sum_{r \in \mathbf{R}_i} \frac{e^{-qc_r}}{\sum_{s \in \mathbf{R}_i} e^{-qc_s}} = \frac{\sum_{r \in \mathbf{R}_i} e^{-qc_r}}{\sum_{s \in \mathbf{R}_i} e^{-qc_s}} = 1. \quad (6)$$

Equivalently,

$$\sum_{r \in \mathbf{R}_i} f_r = \sum_{r \in \mathbf{R}_i} d_i p_r = d_i \sum_{r \in \mathbf{R}_i} p_r = d_i, \forall i = 1, 2, \dots, N. \quad (7)$$

This means that all demands are satisfied (demand constraint) Therefore flow conservation holds for the above traffic assignment.

Generalised route cost

The likelihood of a route being chosen as in (1) is determined by the route's perceived cost in relation to those of other routes. This cost reflects the overall undesirability (or disutility) of traversing through the route. It is a generalised cost and should take into account all the factors that could influence a traveller's route choice. The relevant factors include, but are not limited to, travel time, fuel cost, distance, road types along the route, any surcharge (tolls for certain roads, bridges and tunnels), air and noise pollution along the route, and traffic safety. In this paper we only consider three factors: travel time, fuel cost, and safety. The generalised cost is then assumed to follow the function

$$c_r = b_1 t_r + b_2 t_r + b_3 s_r. \quad (8)$$

Here t_r , t_r , and s_r denotes, respectively, the journey time, the fuel cost, and the safety measure of route r . The parameters $b_i > 0, i=1,2,3$ represent the weights of each factor in the overall cost. The smaller a b is, the less important its corresponding factor is in the process of route choice making.

The journey time of travelling on a route is usually dependent on the actual traffic on the network. Travel time is generally longer when the route is highly congested. The route travel time also depends on the traffic flow of other routes that share links with the route. In the case of signalised intersections, two routes that share no links could have an influence on each other's travel time, due to the interaction at intersections. In general we state the route travel time as a function of the network flow,

$$t_r = t_r(f_1, f_2, \dots, f_r, \dots, f_M). \quad (9)$$

In vector form, this gives

$$\mathbf{t} = t(\mathbf{f}). \quad (10)$$

where $\mathbf{t} = [t_1, t_2, \dots, t_r, \dots, t_M]^T$ is the route travel time vector.

The fuel cost of a route is mainly dependent on the distances of different types of road along the route, such as local road and highway. A route with longer distance does not necessary have a higher fuel cost because of the different proportions of road categories in the route composition. On the other hand, the fuel cost of a specific route is less dependent on the traffic flow than travel time is. Fuel cost is imaginably higher when the driver has to brake a lot or cannot maintain a certain speed level. In this paper, however, we assume that the route fuel costs are fixed, i.e. independent of the actual traffic flow along the route,

$$\frac{\partial t_r}{\partial f_s} = 0, \forall r, s. \quad (11)$$

The fuel cost vector $\boldsymbol{\tau} = [t_1, t_2, \dots, t_r, \dots, t_M]^T$ is thus constant.

The safety level can be quantified by the probability of an individual driver getting involved in a traffic accident. There are two aspects of safety: the first being safety as an entity of the road infrastructure along the route (e.g. road surface conditions, geometric design). Another aspect is safety in use, i.e. due to the users of the infrastructure. Only the second part is related to the actual traffic flows along the route. Therefore we can write the probability as

$$s_r = k_r + y_r (f_r - \bar{f}_r). \quad (12)$$

Here k_r represents the mean probability of getting involved in an accident and \bar{f}_r is the average daily traffic (ADT), which can be obtained from the annual traffic census. If we

assume a linear dependence between the accident probability and the actual traffic flow, then we have

$$s_r = k_r + I(f_r - \bar{f}_r). \quad (13)$$

Here $I \geq 0$ gives the slope in the linear function. In vector form, the equation can be written as

$$\mathbf{s} = \boldsymbol{\kappa} + y(\mathbf{f} - \bar{\mathbf{f}}). \quad (14)$$

Or, for the linear case, as

$$\mathbf{s} = \boldsymbol{\kappa} + I\mathbf{f} - I\bar{\mathbf{f}}. \quad (15)$$

Now we note the interaction between traffic flow and network performance. On one hand, the network performance (travel time, safety level) is determined by the actual traffic flow as in (9) and (12); on the other hand, traffic flow is determined by the network performance as in (2). Therefore the state where all these equations hold can be considered as an equilibrium situation, which is stationary over time. The equilibrium flow can be obtained by solving the following:

$$\mathbf{f}^* = \mathbf{D}p(b_1\mathbf{t}^* + b_2\boldsymbol{\tau} + b_3\mathbf{s}^*) = \mathbf{D}p(b_1t(\mathbf{f}^*) + b_2\boldsymbol{\tau} + b_3\boldsymbol{\kappa} + b_3y(\mathbf{f}^* - \bar{\mathbf{f}})). \quad (16)$$

The incentive structure and its influence on generalised cost

To improve traffic safety, a route-based incentive structure is proposed. Drivers are rewarded with monetary bonus if they follow a specific route for their OD trip (e.g. the safest route). We denote $k_i \in \mathbf{R}_+$ as the route being rewarded for OD pair i and $b_r > 0$ the amount of the bonus. The route reward vector can then be expressed as

$$\mathbf{b} = [0, \dots, 0, \underset{k_1}{b_1}, 0, \dots, 0, \underset{k_2}{b_2}, 0, \dots, 0, \underset{k_i}{b_i}, 0, \dots, 0, \underset{k_N}{b_N}, 0, \dots, 0]^T. \quad (17)$$

The generalised cost after the implementation of the incentive structure is

$$\mathbf{c}' = \mathbf{c} - g\mathbf{b}. \quad (18)$$

Here $g > 0$ is a discount rate for the incentives. If the original generalised cost, \mathbf{c} , is already standardised in monetary terms (e.g. in euro), we expect $g = 1$ and therefore

$$\mathbf{c}' = \mathbf{c} - \mathbf{b}. \quad (19)$$

Flow assignment with the incentive structure is then

$$\mathbf{f}' = \mathbf{D}p(\mathbf{c}') = \mathbf{D}p(\mathbf{c} - g\mathbf{b}). \quad (20)$$

We note here that the original generalised cost \mathbf{c} has also changed due to the change in route flows. The route travel time vector is

$$\mathbf{t}' = t(\mathbf{f}'). \quad (21)$$

Fuel cost vector is unchanged. Route safety level with the incentive structure is given by

$$\mathbf{s}' = \boldsymbol{\kappa} + y(\mathbf{f}' - \bar{\mathbf{f}}). \quad (22)$$

And the generalised cost can be written as

$$\mathbf{c}' = b_1t(\mathbf{f}') + b_2\boldsymbol{\tau} + b_3\boldsymbol{\kappa} + b_3y(\mathbf{f}' - \bar{\mathbf{f}}) - g\mathbf{b}. \quad (23)$$

Similar to (16), the equilibrium flow can be solved by

$$\mathbf{f}^{**} = \mathbf{D}p(b_1t(\mathbf{f}^{**}) + b_2\boldsymbol{\tau} + b_3\boldsymbol{\kappa} + b_3y(\mathbf{f}^{**} - \bar{\mathbf{f}}) - g\mathbf{b}). \quad (24)$$

IMPACTS OF THE INCENTIVE STRUCTURE

In this section we evaluate the impacts of the incentive structure. This is made on two levels: a lower level concerning individual drivers, and a higher level concerning the traffic network as a whole. For the individual driver, the incentive structure should bring a personal benefit, in order to gain its acceptance and popularity with the public. For the traffic network, the incentive structure should demonstrate an improvement of traffic safety, and also economic viability. Here economic viability means that the benefit of the incentive structure should be greater than its costs.

Impact on individual drivers

We consider an individual driver on OD pair i . Without the incentive structure his (her) expected travel cost can be said to be

$$e_i = \sum_{r \in \mathbf{R}_i} p_r c_r = \frac{\sum_{r \in \mathbf{R}_i} e^{-qc_r} c_r}{\sum_{s \in \mathbf{R}_i} e^{-qc_s}}. \quad (25)$$

With the incentive structure his expected travel cost is

$$e'_i = \sum_{r \in \mathbf{R}_i} p'_r c'_r = \frac{\sum_{r \in \mathbf{R}_i} e^{-qc'_r} c'_r}{\sum_{s \in \mathbf{R}_i} e^{-qc'_s}}. \quad (26)$$

Comparing the two we get

$$\begin{aligned} e'_i - e_i &= \frac{\sum_{r \in \mathbf{R}_i} e^{-qc'_r} c'_r}{\sum_{s \in \mathbf{R}_i} e^{-qc'_s}} - \frac{\sum_{r \in \mathbf{R}_i} e^{-qc_r} c_r}{\sum_{s \in \mathbf{R}_i} e^{-qc_s}} \\ &= \frac{\sum_{s \in \mathbf{R}_i} e^{-qc_s} \sum_{r \in \mathbf{R}_i} e^{-qc'_r} c'_r - \sum_{s \in \mathbf{R}_i} e^{-qc'_s} \sum_{r \in \mathbf{R}_i} e^{-qc_r} c_r}{\sum_{s \in \mathbf{R}_i} e^{-qc'_s} \sum_{s \in \mathbf{R}_i} e^{-qc_s}} \\ &= \frac{\sum_{s,r \in \mathbf{R}_i} e^{-qc_s} e^{-qc'_r} c'_r - \sum_{s,r \in \mathbf{R}_i} e^{-qc'_s} e^{-qc_r} c_r}{\sum_{s \in \mathbf{R}_i} e^{-qc'_s} \sum_{s \in \mathbf{R}_i} e^{-qc_s}} \\ &= \frac{\sum_{s,r \in \mathbf{R}_i} (e^{-q(c_s+c'_r)} c'_r - e^{-q(c'_s+c_r)} c_r)}{\sum_{s \in \mathbf{R}_i} e^{-qc'_s} \sum_{s \in \mathbf{R}_i} e^{-qc_s}}. \end{aligned} \quad (27)$$

Concerning the acceptance by the general public, the incentive structure should be designed in such a way that gain, or at least non-loss, is assured for individual travellers on each OD pair. That is,

$$e'_i - e_i \leq 0, i = 1, 2, \dots, N. \quad (28)$$

Sufficient conditions for individual gain

Assuming that all link travel times are fixed,

$$\frac{\partial t_r}{\partial f_s} = 0, \forall r, s, \quad (29)$$

and that accident rate per route is constant,

$$l = 0, \quad (30)$$

we have

$$\mathbf{c}' - \mathbf{c} = -g\mathbf{b} \leq \mathbf{0}. \quad (31)$$

That is, for any route $r \in \mathbf{R}_i$,

$$c'_r < c_r \quad \text{if } r = k_i; \quad (32)$$

$$c'_r = c_r \quad \text{if } r \neq k_i. \quad (33)$$

Concerning (27) we have that for any r, s pair where $r \neq k_i, s \neq k_i$,

$$e^{-q(c_s+c'_r)}c'_r - e^{-q(c'_s+c_r)}c_r = e^{-q(c_s+c_r)}c_r - e^{-q(c'_s+c_r)}c_r = 0. \quad (34)$$

For the r, s pair where $r \neq k_i, s = k_i$, we have

$$e^{-q(c_s+c'_r)}c'_r - e^{-q(c'_s+c_r)}c_r = e^{-q(c_s+c_r)}c_r - e^{-q(c'_s+c_r)}c_r < 0. \quad (35)$$

For the r, s pair where $r = k_i, s \neq k_i$, we have

$$e^{-q(c_s+c'_r)}c'_r - e^{-q(c'_s+c_r)}c_r = e^{-q(c_s+c'_r)}c'_r - e^{-q(c_s+c_r)}c_r. \quad (36)$$

To ensure the above expression is also non-positive, we have

$$\begin{aligned} e^{-q(c_s+c'_r)}c'_r \leq e^{-q(c_s+c_{k_i})}c_{k_i} &\Leftrightarrow e^{q(c_{k_i}-c'_r)} \leq \frac{c_{k_i}}{c'_r} \Leftrightarrow q(c_{k_i} - c'_r) \leq \ln \frac{c_{k_i}}{c'_r} \\ &\Leftrightarrow q \leq \frac{\ln c_{k_i} - \ln c'_{k_i}}{c_{k_i} - c'_{k_i}}. \end{aligned} \quad (37)$$

Therefore, (28) is guaranteed as long as the following is true:

$$q \leq \min_{i=1,2,\dots,N} \frac{\ln c_{k_i} - \ln c'_{k_i}}{c_{k_i} - c'_{k_i}}. \quad (38)$$

Impact on the traffic network

After implementation of the incentive structure, reduction in the expected number of accident is given by (here we omit the superscript $*$ for the equilibrium flow \mathbf{f} and \mathbf{f}')

$$S = \mathbf{f}^T \mathbf{s} - \mathbf{f}'^T \mathbf{s}' = (\mathbf{f} - \mathbf{f}')^T \mathbf{\kappa} + \mathbf{f}^T \mathbf{y}(\mathbf{f} - \bar{\mathbf{f}}) - \mathbf{f}'^T \mathbf{y}(\mathbf{f}' - \bar{\mathbf{f}}). \quad (39)$$

The reduction in the total fuel cost with all travellers considered is

$$F = \mathbf{f}^T \boldsymbol{\tau} - \mathbf{f}'^T \boldsymbol{\tau} = (\mathbf{f} - \mathbf{f}')^T \boldsymbol{\tau}. \quad (40)$$

The reduction in system travel time is given as

$$T = \mathbf{f}^T \mathbf{t} - \mathbf{f}'^T \mathbf{t}'. \quad (41)$$

For each of the three measurements above, it takes a positive value if it is a reduction; zero if there is no change; a negative value if it is an increase.

If we assume the same weight for the three factors of travel time, fuel cost, and safety measure here as in the generalised cost function, i.e. $b_i, i=1,2,3$, then the potential system benefit from the incentive structure, without considering the financial expense, is

$$B = b_1 T + b_2 F + b_3 S. \quad (42)$$

If the above expression records a positive value, then the traffic network is benefiting from the incentive structure; otherwise it is a non-improvement.

For economical viability of the incentive structure, we also have to take into account the financial cost of the incentive structure. We consider here only the payment of the rewards,

without including any administration costs. The financial expense for paying out the incentive structure on one day is given by

$$E = \mathbf{f}'^T \mathbf{b}. \quad (43)$$

However, if we only reward those drivers who switch to the safe routes from other routes as a result of the incentive structure, i.e. only those drivers who switch to route k_i from the route $r \in \mathbf{R}_i, r \neq k_i$ are paid with the incentives, then the total incentive payout is reduced to

$$E = (\mathbf{f}' - \mathbf{f})^T \mathbf{b}. \quad (44)$$

The system gain is determined as the difference between the total network benefit and the incentive expense,

$$G = B - E. \quad (45)$$

A summary on the implications of the signs of B and G is provided in Table 1. We note here that E is always positive. The ideal situation of G-G brings a benefit for both the traffic system and the society funding the incentive structure. As a result of the incentive structure, traffic improves, and the economical return of this improvement is greater in value than the expenses spent on the incentive structure. The situation of L-L is a failure for the incentive structure, where traffic deteriorates and even so the society is paying for it. In such cases the incentive structure should be rejected without question. The situation of G-L should be treated with some scrutiny: traffic is at gain yet the society is paying heavily for this gain. It would well be that the payment of reward is more than necessary; if this is a case, there we should be able to revise the incentive structure so as to achieve a G-G situation.

Table 1 – Impact of the incentive structure

	$G \geq 0$	$G < 0$
$B > 0$	G-G: gain in traffic system; non-loss economically.	G-L: gain in traffic system; loss economically.
$B \leq 0$	× (not possible as $E > 0$.)	L-L: non-improvement in traffic system; loss economically.

Sufficient conditions for a win-win situation

Here we look at the conditions for guaranteeing a win-win situation, i.e. a gain for individual drivers as well as a G-G situation for the traffic network. Besides the conditions necessary for individual gain, we further need to ensure

$$B > 0, \quad (46)$$

$$G \geq 0. \quad (47)$$

We notice that (47) is more restrictive than (46) as $G \geq 0$ implies $B > 0$. Extending the equation for G we get (assuming $g = 1$)

$$\begin{aligned} G &= b_1(\mathbf{f}^T \mathbf{t} - \mathbf{f}'^T \mathbf{t}') + b_2(\mathbf{f}^T \boldsymbol{\tau} - \mathbf{f}'^T \boldsymbol{\tau}) + b_3(\mathbf{f}^T \mathbf{s} - \mathbf{f}'^T \mathbf{s}) - \mathbf{f}'^T \mathbf{b} \\ &= \sum_{i=1}^N \sum_{r \in \mathbf{R}_i} d_i p_r c_r - \sum_{i=1}^N \sum_{r \in \mathbf{R}_i} d_i p'_r c'_r - 2\mathbf{f}'^T \mathbf{b} \\ &= \sum_{i=1}^N d_i \left(\sum_{r \in \mathbf{R}_i} p_r c_r - \sum_{r \in \mathbf{R}_i} p'_r c'_r \right) - 2\mathbf{f}'^T \mathbf{b}. \end{aligned} \quad (48)$$

For G to be non-negative, the summation in (48) has to be at least twice as large as the financial expense of the incentive structure, i.e.

$$\sum_{i=1}^N d_i \left(\sum_{r \in \mathbf{R}_i} p_r c_r - \sum_{r \in \mathbf{R}_i} p'_r c'_r \right) \geq 2\mathbf{f}'^T \mathbf{b}. \quad (49)$$

Here the left part is the difference in mean route cost multiplied by OD demands. The inequality makes sense in that the total individual gain, after deduction of the incentives received, still has to be greater than the total incentive expense to ensure a system gain. The condition (49) is in general more strict than (28), implying that it is more difficult to achieve a system gain than an individual gain.

If we only reward switching drivers, the generalised cost function in (18) and the subsequent analysis on the influence of the incentive structure thereof need to be revised. This is because the incentive structure does not benefit drivers who are already on route k_i and therefore does not contribute to a reduction in their route costs. It is then necessary to introduce user classes to separate the different groups of drivers. However, if we expect a similar equilibrium flow shift as in (24) to take place, then we have

$$G = \sum_{i=1}^N d_i \left(\sum_{r \in \mathbf{R}_i} p_r c_r - \sum_{r \in \mathbf{R}_i} p'_r c'_r \right) - (2\mathbf{f}' - \mathbf{f})^T \mathbf{b}. \quad (50)$$

And the condition in (49) is relaxed as

$$\sum_{i=1}^N d_i \left(\sum_{r \in \mathbf{R}_i} p_r c_r - \sum_{r \in \mathbf{R}_i} p'_r c'_r \right) \geq (2\mathbf{f}' - \mathbf{f})^T \mathbf{b}. \quad (51)$$

NUMERICAL EXAMPLE

We consider a network with one OD pair connected by two parallel routes. The general cost functions for both routes are given in Table 2. Assuming a fixed demand of $d = 100$ and the dispersion parameter in the route choice model as $q = 1$, we can derive the current equilibrium flow and the corresponding route and network costs as in Table 3. If the incentive structure $\mathbf{b} = [0, 0.2]^T$ is implemented, a new equilibrium arises as represented by the values in Table 4. We can see that the incentive structure would reduce the route costs on both routes.

Table 2 – Cost functions for the example network

	Travel time	Fuel cost	Safety cost
$b_{1,2,3}$	0.4	1	0.2
Route 1	$t_1 = 0.5 + 0.15 \left(\frac{f_1}{60} \right)^4$	$t_1 = 0.5$	$s_1 = 1 + 0.2 \left(\frac{f_1}{40} \right)^4$
Route 2	$t_2 = 0.6 + 0.15 \left(\frac{f_2}{120} \right)^4$	$t_2 = 1$	$s_2 = 0.8 + 0.2 \left(\frac{f_2}{100} \right)^4$

Table 3 – Current equilibrium and route costs (without incentives)

	Flow	Travel time	Fuel cost	Safety cost	Generalised cost
Route 1	49.0531	0.5670	0.5000	1.4523	1.0173
Route 2	50.9469	0.6049	0.6000	0.8135	1.0046

Table 4 – New equilibrium and route costs (with the incentive structure $\mathbf{b} = [0, 0.2]^T$)

	Flow	Travel time	Fuel cost	Safety cost	Incentive	Generalised cost
Route 1	39.6044	0.5285	0.5000	1.1922	0	0.9498
Route 2	60.3956	0.6096	0.6000	0.8266	-0.2	0.8092

For the traffic network, Table 5 provides an overview on the costs before and after applying the incentive structure. Without considering the financial expense, a positive system benefit B is recorded. However, if the incentive payout is taken into account, whether the system gains or not, as indicated by G in Table 6, depends on the incentive programme set-up.

Table 5 – Overview of system costs: before and after

	Travel time	Fuel cost	Safety cost	Network cost
Before	58.630	55.095	112.685	101.084
After	57.7486	56.0396	97.1402	98.5670
Reduction	$T = 0.8815$	$F = -0.9449$ *	$S = 15.5452$	$B = 2.5168$

*: negative sign here implies that the total fuel cost was not reduced but increased.

Table 6 – System gain

	E	G
Incentives paid to all drivers on route 2	12.0791	-9.5623
Incentives paid only to those drivers who switches to route 2	1.8897	0.6270

DEPLOYMENT WITH IN-CAR SYSTEMS

The incentive programme can be built on currently available navigation systems. The safe routes are calculated in a similar way to the shortest routes. They can be made either static or dynamic. For the latter case, real-time communication with an administration centre is necessary. The administration centre also decides on the incentive structure. Each time a participating driver makes his or her trip, the safe route for that origin-destination pair, as well as the associated bonus amount, is displayed on the navigation system. The GPS unit in the navigation system tracks driver's compliance with the safe route. Eligibility for the reward is established right after the trip is completed.

Qualification for rewards and the consequent amount of remuneration can be determined either on an all-or-nothing basis or pro rata. Three combinations are possible (Table 7). The mathematical analysis earlier in this paper is based on the first combination, i.e. drivers are paid the reward if and only if they follow the safe routes in full. We expect the other combinations will have different impacts on driver behaviour. Different settings can also be chosen on the timing of the reward delivery (Table 8), with different reactions expected from the drivers. From a behavioural point of view, if the reward is established right after the trip then drivers get immediate feedback of their gain; as a result it gives the drivers more motivation to follow the safe routes. We argue that an immediate establishment of the reward

is more important than an immediate payment. Drivers do not mind if the money is paid later as long as they are assured of the amount after each trip.

Table 7 – Settings for reward qualification and remuneration

	<i>Remunerates all or nothing</i>	<i>Remunerates pro rata</i>
<i>Qualifies for reward only at full compliance</i>	full payment for full compliance; no payment otherwise	×
<i>Qualifies for reward by percentage</i>	full payment for compliance above a threshold; no payment otherwise	payment pro rata

Table 8 – Settings for reward delivery

	<i>Immediate payment</i>	<i>Delayed payment</i>
<i>Immediate establishment</i>	reward calculated and transaction made to driver’s account right after each trip	reward calculated right after each trip; transaction made later (e.g. at the end of each day/month)
<i>Delayed establishment</i>	×	reward calculated retrospectively

CONCLUDING REMARKS

Promoting safe route choices is an innovative approach for traffic safety enhancement. If the incentive structure reduces the expected cost for drivers on each OD pair (travel time, fuel cost and potential accident cost combined), as well as improves the overall system performance and benefits the system economically, it then creates a win-win situation. An important question to ask then is how this win-win situation can be guaranteed. We provided some sufficient conditions but they are rather restrictive and to certain extent unrealistic. An ongoing research topic is therefore to further extend these sufficient conditions, in the direction of finding the necessary conditions.

Although motivated by safety enhancement, the incentive structure proposed in this paper can be extended to the improvement of other criteria. Indeed, the impact analysis in this paper is based on a combined criterion rather than safety alone. Flexibility can be achieved by varying the coefficients in (42), i.e. using a different set of weight factors from that of the individual driver’s generalised cost function.

There are also other issues that need to be taken into account before deployment of the incentive structure. First, the incentives should work as an encouragement but not an attraction, in the sense that the programme should not generate too much extra car-use demand or extra trip making. This is important especially when environmental issues are of concern. Demand is fixed in this paper while future analysis should relax this to account for the extra demand effect. Secondly, the incentive structure should be fair and secure. That is, the system is designed in such a way that fraud cannot be easily committed to purposefully obtain the bonuses.

Realisation of such an incentive structure can also be made without the involvement of a 'social body'. One such example is a proposal currently being studied for its feasibility. It concerns individual drivers and an insurance company. The insurance company operates the incentive programme with drivers who purchase insurance policies from the company. The insurance company pays for the incentive programme, while in return receives less accident claims. A cost-benefit analysis similar to that in this paper is performed beforehand to ensure economical gain. We note here that the insurance company is different from the social body in terms that its objective function only concerns safety issues and the overall traffic network performance (travel time, full cost).

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