Evaluation of Load Factor Control and Urban Freight Road Pricing Joint Schemes with Multi-agent Systems Learning Models

Joel S. E. Teo,*, Eiichi Taniguchi, Ali G. Qureshi

Department of Urban Management, Kyoto University, Katsura, Kyoto 615-8540, Japan

Abstract

This paper describes the use of the multi-agent systems (MAS) modelling approach, incorporated with reinforcement learning models, that is experimented on a part of Osaka road network with ITS-based travel time information. The MAS model included an exact solution method to solve the vehicle routing problem of carriers' delivery jobs and is used to evaluate the short-term impact of distance-based road pricing on the major stakeholders including the carriers, shippers, administrators and customers. The evaluation is extended to consider the load factor control scheme implemented as a joint scheme with the urban freight road pricing. The results from our experiment show that the city logistics joint scheme has the potential of improving average daily load factors and reduce emissions in comparison with no schemes implemented.

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1. Introduction

The main objective of this research is to evaluate the load factor control (LFC) scheme in the presence of urban freight distance-based road pricing. There are a few definitions of truck load factors in freight research, which depends on the accuracy requirements and the purpose of measurement. One common definition for truck load factors is, “the ratio of the average load to total vehicle freight capacity, in tonnes or volume” (EEA, 2001), where

* Corresponding author. Tel.: +81-75-383-3231; fax.: +81-75-950-3800
E-mail address: joel.teo@kiban.kuciv.kyoto-u.ac.jp
the load is expressed as tonne-km (t-km) and capacity as vehicle-km (v-km). The average load used for calculation accounts for the empty runs; for example a full truck load of 2 tons leaving a depot to reach a customer 2 km away and returning with an empty truck will have a load factor of 50% (4 t-km over 4 v-km divided by 2 tons). The unit “t-km” can be described as the transportation of a ton of goods carried over a distance of a kilometre and “v-km” can simply refers to the movement of a vehicle over a kilometre. In the area of city logistics research, vehicle routing models are commonly used to optimise carriers’ delivery. Some of the models allow pick-up and delivery at every customers location to ensure empty runs are kept to a minimum. In such cases, the load factor can be calculated as the total load in t-km (1) over the total freight capacity for each truck in v-km (2),

\[ \sum_{i=0}^{n} \sum_{j=1}^{0} d_{ij} q_j \]

\[ \sum_{i=0}^{n} \sum_{j=1}^{0} d_{ij} x_{ijk} \]

where \(d\) refers to the distance in kilometres between location nodes, \(q\) refers to the quantity of demand at each location node in tons, \(x_{ijk}\) equals to 1 if truck \(k\) is used and zero otherwise, \(i\) equals \(\theta\) refers to the depot location and \(n\) refers to the number of customers.

It is recognised that increasing a truck’s load factor will help to reduce the negative effects on the environment with less trucks used to transport the same amount of goods, which is also known as reducing the freight transport v-km (EEA, 2001; Taniguchi, Thompson, Yamada & van Duin, 2001). Improving the utilization of trucks on all trips is also expected to reduce transport costs (McKinnon & Edwards, 2010). Gaining inspiration from the past and building on previous research, the concept of our proposed LFC scheme in this research functions differently from similar schemes that are implemented previously. The load factor scheme is implemented in the past to encourage maximum use of truck capacity. As far as the authors know, there are only two European cities, Amsterdam and Copenhagen, who implemented the load factor schemes (Taniguchi, Thompson, Yamada & van Duin, 2001). In the case of Amsterdam, trucks that weighed more than 7.5 tons could access the streets if the trucks that were less than 9 metres were able to achieve load factor more than 80% and meet the Euro II emission standards (Castro & Kuse, 2005). In Copenhagen, vans and lorries that weighed more than 2.5 tons required a certificate to stop in the Medieval City. The scheme named City Goods Ordinance was a trial from February 2002 to 31 October 2003, which issued a green certificate if the trucks achieved a load factor of more than 60% over a 3-month period and an engine that met the criteria of not being older than 8 years. A red certificate can be bought if the trucks were unable to meet the requirements and it was valid for a day’s use (Kjaersgaard & Jensen, 2004). The function of the red certificate was similar to the early Area Licensing Scheme (ALS) implemented in Singapore in 1975 for passenger cars, which allowed vehicles to enter the Central Business District area during peak hours when they purchased area licenses if the vehicles carried less than four passengers (Phang & Toh, 1997). The City Goods Ordinance was found to be effective in maximising the capacity utilisation with trucks having about 70% load factor on average. Load factor schemes are similar to other schemes that were commonly used by policy makers in cities like Prague, Budapest, Maribor, Paris and Stockholm to manage the flow of truck traffic within a city like the truck ban and weight/ size/ time restrictions (Castro & Kuse, 2005; Allen & Browne, 2010; Huschebeck, 2001). Analysis of truck bans was done by Yamada & Taniguchi (2005), where it was found that access restriction schemes might increase delivery costs. In another experiment done by Tamagawa & Taniguchi (2010), a truck ban initiative gave a reduction in NOx emissions. The LFC scheme proposed in this research hopes to meet the suggested principles for setting regulations to control the movement of urban vehicles by ensuring, “simplicity and alleviation of constraints for operators with good organization and sound judgement” (ECMT, 1976). Based on these principles, the proposed LFC scheme aims to provide cost saving incentives to the carriers if they are able to meet the truck load factor threshold by waiving their road pricing charges.
When we use the general term of road pricing in our research, it is referred to an allocation mechanism for scarce road space rather than other “marketing” terms like congestion pricing, environmental charges (Eliasson, 2010) and value pricing. In the assessment done by Holguin-Veras (2008), it was noted that it may not be possible to encourage off-hour deliveries with road pricing alone. Firstly, delivery time has to be jointly agreed with carriers and receivers. Secondly, carriers may face difficulty passing the cost to receivers and lastly, it may cost more for receivers to receive goods during off-hours. However, it was found that incentives provided to the receivers, in an environment where road pricing exists, were able to entice receivers and carriers to agree on off-hour deliveries. Experience from practical application of road pricing has also suggested that the scheme is not the “ultimate solution to traffic congestion in urban areas” (Chin, 2010) and will require a combination of other schemes. These findings coincide with our motivation to consider an appropriate scheme that can coexist with the road pricing schemes considered in our previous research (Teo, Taniguchi & Qureshi, 2011; Teo, Taniguchi & Qureshi, 2012), which can help to meet the key stakeholders’ objectives of reducing the emission levels of the environment, minimising the loss of carriers’ profit and the shippers’ costs in city logistics. Past surveys of private carriers in the United Kingdom (UK) and Singapore have generated mixed responses towards road pricing with freight vehicles. Despite the theoretical benefits of road pricing in managing traffic congestion, some carriers in UK find it difficult to deliver goods outside the road pricing time window due to customers’ requests (Browne, 1999) while other carriers in Singapore were able to consolidate their goods, re-route or re-time their delivery due to the road pricing (Olszewski, Wong & Luk, 2003). Efforts have to be made by the road authorities to ensure that road users have alternative routes or times of travel when road pricing are implemented as suggested by Chin (2010). In city logistics, it may be easier for carriers to choose an alternative route with sophisticated re-routing software but goods with just-in-time delivery criteria may not be as easy for them to negotiate with the receivers for an alternative time of delivery. Therefore, a somewhat new alternative is proposed in this research, to provide carriers with another option to service their delivery at a lower cost if they could meet the threshold truck load factor in a city that is implemented with road pricing.

Negative externalities like congestion and pollution in the city that are linked to freight transport have been discussed actively among researchers and practitioners. However, many suggestions of freight transport schemes that are aimed at eliminating the problems may risk deteriorating business activities in the city (ECMT, 1976) and may also affect the business of shippers and carriers if the proposed schemes do not consider the conflicting interests among the key stakeholders during evaluation. The use of the multi-agent modelling approach in this research incorporated the varying objectives of typical stakeholders involved in the city logistics environment. Our problem considered in this paper fits into the characteristics for the MAS approach (Parunak, 1999; Weiss, 1999; Wooldridge, 2009) along with several other agent-based approaches to transport logistics papers reviewed by Davidsson, Henesey, Ramstedt, Törnquist & Wernstedt (2005) and Anand, Yang, van Duin & Tavasszy (2012). The MAS approach is recognised as a useful methodology for considering the multi-objective nature of an urban logistics system and study the evolving behaviour of the stakeholders, who are influenced by policy measures (Taniguchi, Thompson & Yamada, 2010) by incorporating several autonomous agents interacting in an environment.

Based on previous load factor trials, it is understood that load factors have been enforced using less advanced Information and Communication Technology (ICT). This paper does not aim to suggest the technological knowledge on the development of a real device or system for monitoring the load factors of each truck but it does not deny a possibility for such tool to be available in the market in future. As mentioned by Oehry (2010), the three core aspects for making road pricing a success are technical design, scheme layout and acceptance but the priority order is in fact the other way round and the most difficult may be acceptance. The proposed LFC scheme is more conceptual rather than developed at the moment. However, this paper hopes to provide the methodology for the evaluation of the city logistics joint schemes, while considering all major stakeholders’ objectives. The results are analysed and discussed considering the benefits and disadvantages of such joint schemes.

2. Modelling

The flow of the MAS simulation framework for our problem is shown in Fig. 1 and the notations found in the
framework are described in Fig. 2. A simplified interaction environment between the stakeholders involved in the MAS is shown in Fig. 3.

The typical simplified one step Q-learning algorithm used for carriers’ profit learning is shown in (3) and the administrator’s emission learning and carriers’ and shippers’ complaints learning is shown in (4). The difference in this framework from previous research (Teo, Taniguchi & Qureshi, 2012) is the replacement of the carrier-shipper second price auctioning interaction with the carriers’ mark-up decision due to carriers’ Q-learning from profit earned using a softmax action selection rule (5) typically found in reinforcement learning to consider exploration or exploitation of choices (Sutton & Barto, 1998). To limit the complexity, the concept of exploration is not tested in this experiment. The decision of carriers’ discounting for shippers is incorporated in the model to provide the appropriate discount value based on the customers’ complaints towards the carriers’ late delivery. The shippers’ carrier choice strategy is based on shippers’ Q-learning from customers’ complaints and carriers’ minimum quotations (6). The idea of this probability incorporates consideration of customers’ complaints due to carriers arriving late at customers’ locations, which also considers the minimum quotations given by the carriers. This approach is the initial step to include the multi-objective nature of the shippers when considering the appropriate carrier to service their delivery to customers at the minimum costs with good level of service, in this case, we have considered the customers’ complaints.

Fig. 1. Model framework to evaluate road pricing and load factor control scheme.
\[
C = \{c_i | i = 1, L\} \quad \text{: Set of carriers}
\]
\[
S = \{s_j | j = 1, M\} \quad \text{: Set of shippers}
\]
\[
R = \{r_k | k = 1, N\} \quad \text{: Set of customers}
\]
\[
L \quad \text{: Maximum number of carriers}
\]
\[
M \quad \text{: Maximum number of shippers}
\]
\[
N \quad \text{: Maximum number of customers}
\]
\[
x \quad \text{: Evaluated day}
\]
\[
y \quad \text{: Maximum number of days for evaluation}
\]
\[
d_{r_k,s_j} \quad \text{: Demand of customer } r_k \text{ from shipper } s_j, \text{ where } d_{r_k,s_j} = 0, \text{ if customer } r_k \text{ do not require goods from shipper } s_j
\]
\[
t_{r_k} \quad \text{: Time window requested by customer } r_k \text{ for receiving goods from all shippers } s_j
\]
\[
D_{s_j} = \sum_{k=1}^{N} d_{r_k,s_j} \quad \forall s_j \in S \quad \text{: Demand of shipper } s_j
\]
\[
T_{s_j} \quad \text{: Time window requested by shipper } s_j \text{ for collection}
\]
\[
Q_{ij} \quad \text{: Binary variable; if } Q_{ij} = 1, \text{ shipper } s_j \text{ chooses carrier } c_i, \text{ otherwise } Q_{ij} = 0
\]
\[
D_{s_j,c_i} = D_{s_j} Q_{ij} \quad \forall s_j \in S, \forall c_i \in C \quad \text{: Goods to be collected from shipper } s_j \text{ by carrier } c_i
\]
\[
d_{r_k,c_i} = \sum_{j=1}^{M} d_{r_k,s_j} Q_{ij} \quad \forall r_k \in R, \forall c_i \in C \quad \text{: Consolidated goods to be delivered to customer } r_k \text{ by carrier } c_i
\]

### Fig. 2. Notation for model framework

#### Freight carriers
- Offer pricing with discounts due to complaints
- Carrier choice based on price and complaints
- Complain on late delivery

#### Administrators
- Implementing
  - Distance-based road pricing
  - Load factor control scheme

#### Customers
- Complain on late delivery

#### Shippers
- Complain on late delivery

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\[
Q(s_t, a_t) \leftarrow (1 - \alpha)Q(s_t, a_t) + \alpha[R_{s_t,a_t} + \gamma \max Q(s_{t+1}, a_{t+1})]
\]
\[
Q(s_t, a_t) \leftarrow (1 - \alpha)Q(s_t, a_t) + \alpha[R_{s_t,a_t} + \gamma \min Q(s_{t+1}, a_{t+1})]
\]

where,
$Q(s_t, a_t)$: Q-value of agent in state $t$ due to action of agent in state $t$

$R_{s_t, a_t}$: immediate reward received by agent in state $t$ due to action of agent in state $t$

$Q(s_{t+1}, a_{t+1})$: Q-value of agent in state $t+1$ due to action of agent in state $t+1$

$\alpha$: learning rate of agent ($0 < \alpha < 1$)

$\gamma$: discount rate of agent ($0 < \gamma < 1$)

$s_t$: day of evaluated duration

$a_t$: actions available to agent in state $t$

$P(a_{c,t+1}) = \frac{e^{Q_c^p(s_{c,t+1}, a_{c,t+1})/\tau}}{\sum_{c_{c,t+1}} e^{Q_c^p(s_{c,t+1}, a_{c,t+1})/\tau}}$ (5)

where,

$P(a_{c,t+1})$: Probability of mark-up decision $a_{c,t}$ of carrier $c$ for shipper $p$ in state $t+1$

$Q_c^p(s_{c,t+1}, a_{c,t+1})$: Q-profit of carrier $c$ in state $t+1$ due to action in state $t+1$

$\tau$: Carriers’ exploration signal, where

$\tau = 1$, if $\sum Q_c^p(s_{c,t+1}, a_{c,t+1}) \leq 0$, \( \forall a_{c,t+1} \in A_{c,t+1} \)

$\tau = \max Q_c^p(s_{c,t+1}, a_{c,t+1}), \forall a_{c,t+1} \in A_{c,t+1}$ otherwise

$P(a_{p,t+1}) = \frac{B_p}{K_p}$ (6)

where,

$P(a_{p,t+1})$: probability of shipper $p$ selecting carrier $c$ in state $t+1$

$B_p$: complaint ratio, where $B_p = \frac{Q_p(s_{p,t+1}, a_{p,t+1})}{\sum_{a_{p,t+1}} Q_p(s_{p,t+1}, a_{p,t+1})};$

$Q_p(s_{p,t+1}, a_{p,t+1}) = N$ if $Q_p(s_{p,t+1}, a_{p,t+1}) = 0,$

$Q_p(s_{p,t+1}, a_{p,t+1}) = \frac{1}{Q_p(s_{p,t+1}, a_{p,t+1})}$ otherwise

$N$: a positive large number

$Q_p(s_{p,t+1}, a_{p,t+1})$: Q-complaint values of shipper $p$ in state $t+1$ due to choice of carrier $c$ in state $t+1$

$K_p$: bid ratio of shipper $p$ from carriers’ quotation, where $K_p = \frac{\delta_c}{\sum \delta_c}$

$\delta_c$: bid from carrier $c$

The carriers’ routing decision is managed by a vehicle routing model with soft-time windows solved using an exact solution method. As the routing decision assumes that no pick-up is allowed at the customers’ locations, the method used to determine the load factor will have to be modified to exclude empty runs. Such exclusion will be fair to the carriers in this present experiment since they are not considered to minimise empty runs. Equation (1) for loads will be changed to (7), where the return trip from the last customer to the depot is excluded. The capacity available will be changed from (2) to (8), where the movement of vehicle over a kilometre will change by excluding the load that has previously been delivered. $Q$ refers to the capacity of the truck.

$$\sum_{i=0}^{n-1} \sum_{j=1}^{n} d_{ij}$$ (7)
\[ d_{0,1} + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} d_{ij} x_{ijk} \frac{Q - \sum_{i=1}^{j-1} q_i}{Q} \] (8)

3. Experiment setup

The road network for this research is taken from the Osaka city in Japan as shown in Fig. 4, with hypothetical locations of three shippers, three carriers and thirty customers. Two scenarios were evaluated in the first part of this experiment as listed:

a) Carriers learn from profit and customers’ complaints and decide on their mark-up and discount price respectively. Shippers learn from customers’ complaints too and decide on their choice of carriers besides minimum bids from carriers. No policy scheme is implemented in this scenario.

b) Analysis (a) is done with the administrator learning from the emissions produced in the environment and decide to price the road links.

The demand and time window for each customer is generated dynamically on each day for 330 days. As the purpose of the two analyses is to compare the results when agents (stakeholders) start to learn in each scenario, the demand and time window of customers are kept the same for each analysis. The learning rate, \( \alpha \), and discount rate, \( \gamma \), were kept at 0.5 for all agents throughout the simulation. There are nine performance measurements identified to evaluate the results from the two analyses based on the stakeholders considered in this research; carriers’ profit, carriers’ cost, shippers’ cost, distance travelled by trucks, number of trucks used, number of customer complaints, nitrogen oxide, NO\textsubscript{x} in grams (9), carbon dioxide, CO\textsubscript{2} in grams (10), and suspended particulate matter, SPM in grams (11), where \( l_{ij} \) is the length in kilometres of road link between nodes \( i \) and \( j \) and \( v_{ij} \) is the speed of road links between \( i \) and \( j \) in kilometres per hour (NILIM, 2003).

\[ NO_x = l_{ij} (1.06116 + 0.000213 v_{ij}^2 - 0.0246 v_{ij} + \frac{16.258}{v_{ij}}) \] (9)

\[ CO_2 = l_{ij} (278.448 + 0.048059 v_{ij}^2 - 5.1227 v_{ij} + \frac{2347.1}{v_{ij}}) \] (10)

\[ SPM = l_{ij} (0.03442 - 0.0003939 v_{ij}^2 + 0.0036777 v_{ij} + \frac{1.2754}{v_{ij}}) \] (11)

The second part of our experiment is to consider the load factor of each truck to determine the road pricing waiver for carriers. The load factor is calculated using the total load in t-km (7) over the total capacity in v-km (8). The initial load factor threshold that is used is 99% and the performance measurements, which are similar to the first part of the analysis, are evaluated.
4. Results and discussion

The first part of this experiment was to compare the results of two scenarios with the second scenario implemented with the distance-based road pricing for trucks. A summary of the performance measurements for all two scenarios are shown in the radar plot in Fig. 5. The first scenario was the base case, represented by the blue lines in the plots. The radar plot was plotted in a way that any values beyond one is considered good for the performance measurement while anything below one is considered to worsen the performance measurement.

![Fig. 5. Radar plot with lower markup and discount rate increment for 330 days](image)
The following section discusses the results of part one of the experiment, which included the learning of the administrator and its decision to price road links to minimise emission levels:

i) Based on the radar plot in Fig. 5, almost all the performance measurements with distance-based road pricing are worse off compared to an environment with no road pricing. However, this evaluation was done for only a short period of 330 days with a lower incremental mark-up and discount rate. The results and discussion that follows will be based on such a condition.

ii) According to our previous research (Teo, Taniguchi & Qureshi, 2012), the concern of costs incurred from road pricing may increase the carriers’ cost, which has the same outcome in this experiment as shown in the radar plot. The shippers’ cost (carriers’ revenue) for both scenarios are similar and with the higher carriers’ cost from the road pricing scenario, the carriers experienced a lower profit for scenario two. This effect was also seen in the survey done in Singapore (Olszewski, Wong & Luk, 2003) where 63% of the surveyed private companies reported that the road pricing have caused an increase in their operating costs and some companies reported that the costs amounted to as much as US$400 per truck per month.

iii) A longer distance and an increase of trucks used were recorded in scenario two, which could be the reason for the deterioration of the environmental emissions when distance-based pricing was implemented for the short-term simulation. Further investigations were done on the link usage for specific distances and plotted against the corresponding average speeds and rate of pricing as shown in Figures 6 and 7 respectively. Since there are no road links in the range of 4km to 4.5km, the speed and the rate of pricing are zero as recorded in the graphs. The increase in link usage for each road link category as seen in the figures may be the likely reason for the increase of trucks and longer distance recorded when road pricing was implemented. Although the combination plots of Fig. 6 and Fig. 7 show a higher pricing rate for the shorter distance and lower speed link categories, the increase in link usage frequency was probably the evolving behaviour of the carriers to maintain the shippers’ cost, which could also benefit the consumers. As this initial experiment is for evaluating the short-term effect of road pricing and due to the dynamic pricing of the road links, the carriers may require a longer simulation time to learn and reach their objectives.

The focus of part one of this experiment was to analyse the consequences of distance-based road pricing for all agents. Based on the results, the distance-based road pricing as a single scheme may not increase the shippers’ cost in the short-term but the main disadvantages included a higher cost to the carriers and a tendency of using more short distance links with lower speed, which will increase the emissions, as all the stakeholders try to learn through the multi-agent interactions. The next section will elaborate on the second part of this experiment that included an additional scheme, the LFC scheme, as a joint scheme with the distance-based road pricing scheme.

The main objective of the second part of this experiment was to evaluate the outcome of the joint LFC scheme and the distance-based road pricing scheme. The LFC scheme considered in this experiment assumed that the load factors were measured using equations (7) and (8) only at the depot of each carrier prior to the delivery as the experiment did not allow pick-ups at each subsequent customer locations. Due to the limitations of computation, the evaluation of the second part of this experiment was done for a shorter period of 150 days. Some parameters like the maximum mark-up price and discount price were adjusted to accommodate the shorter simulation run. An initial load factor threshold of 99% was used. The comparison of a single distance-based road pricing scheme and the joint scheme against the no pricing case is shown in Fig. 8 and the joint scheme has shown potential for compensating the carriers’ cost, improving carriers’ profit and emission levels. The distance travelled for the no pricing case had a slight decrease compared to the other schemes, which could be the reason for the higher number of complaints received due to late arrivals associated with the longer distance travelled.
Fig. 6. Average speed of road links for experimental road network

Fig. 7. Trend of average road pricing rate on experimental road network
In addition to the improved emissions with the joint scheme, the average load factor for each day also improved as shown in Fig. 9. The initial idea of the LFC scheme was to encourage the utilization of truck capacity, as it supports the views of past study (EEA, 2001; Taniguchi, Thompson, Yamada & van Duin, 2001) that a higher load factor per truck may lead to a reduction of environment impacts. In another point of view, waiving the road pricing charges is a way to entice carriers to plan their routes better if carriers are willing to use more sophisticated routing tools that are available, which can provide better consolidation of goods and increase load factors further. The cost waivers act as cost saving incentives as shown in Fig. 8 if the carriers meet the load factors as required by the administrator. It is also assumed that the savings experienced by the carriers may lead to more savings for the shippers and the customers provided that the carriers pass on the savings too. As seen from Fig. 8, the shippers’ cost is not affected so much by the introduced schemes. Future extension of this experiment may include the influence of load factor threshold changes by the administrator to test the effect it has on the stakeholders. The load factor threshold adjustment by the administrator can be seen as a major factor influencing the market besides improving environmental emissions.
5. Conclusions

The objective of this paper was to evaluate the potential of a joint freight scheme, which included a distance-based road pricing and load factor control (LFC) scheme and its influence on the major stakeholders (agents) in city logistics. A multi-agent approach was deemed suitable for such analysis and the results showed the effects of the short-term implementation of the joint scheme. The initial experiment on a real network taken from Osaka, Japan, showed that the joint scheme was able to reduce the cost of shippers and carriers as compared to the higher cost experienced when only the distance-base road pricing was implemented alone. The joint scheme in this research was able to increase the average daily load factors and building on these initial findings, future studies may explore how the various load factor thresholds initiated by the administrator can influence the carrier and shipper interaction. This experiment has potential for advancement to consider more sophisticated routing models that allow pick-ups at subsequent customer locations to optimise the truck capacity. This will also allow some modifications on the method of measuring load factors and more conclusive findings can then be made on the feasibility of having distance-based road pricing and LFC scheme as a joint scheme.

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