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To cite this version:
Yunfei Fang, Feng Chu, Said Mammar, Ada Che. Iterative algorithm for lane reservation problem on transportation network. IEEE International Conference on Networking, Sensing and Control (ICNSC 2011), Apr 2011, Delft, Netherlands. pp.305-310, 10.1109/ICNSC.2011.5874932. hal-00653974

HAL Id: hal-00653974
https://hal.science/hal-00653974v1
Submitted on 16 Jan 2020

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Iterative Algorithm for Lane Reservation Problem on Transportation Network

Yunfei Fang, Feng Chu, Saïd Mammar and Ada Che

Abstract—In this paper, we study an NP-hard lane reservation problem on transportation network. By selecting lanes to be reserved on the existing transportation network under some special situations, the transportation tasks can be accomplished on the reserved lanes with satisfying the condition of time or safety. Lane reservation strategy is a flexible and economic method for traffic management. However, reserving lanes has impact on the normal traffic because the reserved lanes can only be passed by the special tasks. It should be well considered choosing reserved lanes to minimize the total traffic impact when applying the lane reservation strategy for the transportation tasks. In this paper, an integer linear program model is formulated for the considered problem and an optimal algorithm based on the cut-and-solve method is proposed. Some new techniques are developed for the cut-and-solve method. Numerical computation results of 125 randomly generated instances show that the proposed algorithm is much faster than a MIP solver of commercial software CPLEX 12.1 to find optimal solutions on average computing time.

I. INTRODUCTION

With the development of economy, high urbanization has been achieved in many countries today. For a sustainable economic development, traffic management is one of the strategic issues that must be considered by government. Many transportation problems, such as design and configuration for transportation network [1], transportation planning and scheduling [2] have been drawn much attention by researchers over the last few decades. The freight transportation is an important part of the economy. It supports production, trade and consumption activities by providing safety, timely and reliable transportation of raw material or finished products. However, the increasing intensified traffic situation and saturated transportation network make the freight transportation difficult. Constructions of new transportation infrastructure are constrained by the heavy funding and long duration. Finding a flexible management that can adapt quickly to new situation is a complementary way with the construction of infrastructure.

Lane reservation strategy on the existing transportation network is such a flexible and economic option for traffic management. With this strategy, some lanes on roads are temporarily reserved for the transportation tasks. Only these transportation tasks can pass through the reserved lanes, and these tasks could be performed satisfying the conditions of time and/or safety. Moreover, lane reservation strategy can be generalized to a wide range of application, such as city public transportation, transportation of hazardous materials, design and configuration of network for automated robot-driven trucks. In fact, the lane reservation strategy has been applied successfully during the Olympic Games held in Athens and Beijing. In Paris, some lanes are reserved for public bus and taxis. Lane reservation strategy has been qualitatively studied by some researchers [3], [4].

However, reserving lanes has impact on the normal traffic, since only the special tasks can pass through the reserved lanes and congestion can be generated for other users in the transportation network. In this context, we study such a transportation problem: select lanes to be reserved on the existing transportation network for the special tasks and minimize the total traffic impact of reserving lanes on the normal traffic.

We call it the lane reservation problem on transportation network (LRPTN). To the best of our knowledge, there are very few studies about it in the literature. Wu et al. [5] are the first to propose a mathematical model for studying lane reservation strategy. A simple heuristic algorithm is proposed for the considered problem to obtain near-optimal solutions. The LRPTN is different from the classic vehicle routing problem (VRP) and facility location problem (FLP). VRP is to minimize the total transportation cost for a fleet of vehicles to serve a set of customers. In an optimal solution of VRP, each edge can be visited only once by a vehicle. But for the LRPTN, to minimize the total traffic impact on the normal traffic, a reserved lane can be passed by several tasks in an optimal solution. In classical FLP, facilities is located on nodes. The change of the location of a facility will influence partially transportation path. For the LRPTN, lanes are selected to be reserved and the change of the reserved lanes can affect the full path of the tasks. For more detail information of VRP and FLP, please see [6], [7] and [8].

For solving transportation problems, various heuristic and exact methods have been proposed in the literature, such as metaheuristic methods [9], [10], [11], [12], methods based on Lagrangean relaxation [13], [14], hybrid methods [15], branch-and-bound [16], [17] and branch-and-cut [18].

This work was partially supported for the Cai Yuanpei program by the French Ministries of Foreign and European Affairs and the Higher Education and Research and the Chinese Ministry of Education, under Grant No. 24021SH.

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advantage of metaheuristic is its flexibility. For evaluating the performance of metaheuristic, it should be helped by other methods or tools such as methods based on Lagrangean relaxation. It provide a lower bound of the studied problem and useful information to construct feasible solutions. But methods based on Lagrangean relaxation is effective only for certain types of problems, such as FLP. Exact methods can obtain an optimal solution of the problem, but the computation time will increase exponentially with the size of NP-hard problem. Analysis of properties of the problem and appropriate use of methods can help solve large scale NP-hard problem [19]. Cut-and-solve exact method was introduced by Climber and Zhang in 2006 [20]. Authors claimed that it outperformed the state-of-the-art solvers for the asymmetry traveling salesman problem (ATSP). Yang et al. [21] applied the principle of cut-and-solve method to the single source capacitated facility location problem (SSCFLP) and improved results in the literature. Fang et al. [22] developed an optimal algorithm based on cut-and-solve method for solving a lane reservation problem.

In this paper, we study a lane reservation problem on transportation network and formulate it as an integer linear program model. New techniques of generating cuts for cut-and-solve method are developed and a cut-and-solve based algorithm is proposed for the considered problem. Computational results show that the proposed algorithm is much faster than the commercial solver CPLEX 12.1 [23].

The remainder of the paper is organized as follows. In section II, the problem is described and it is formulated as an integer linear program. Section III presents the solution approach. An optimal algorithm based on cut-and-solve method is proposed by developing new techniques of generating cuts. Computational results are reported in section IV. In section V some conclusions and related future work are discussed.

II. PROBLEM DESCRIPTION

The lane reservation problem we consider is as follows: select lanes to be reserved on an exist transportation network and determine the path for each task to ensure that this one can be accomplished in the path composed of reserved lanes within a deadline, while the total traffic impact of these lanes on the normal traffic is minimum. To well describe the problem, some assumptions are given as follows. Firstly, there are at least two lanes on each road. Otherwise, the impact on the normal traffic of reserving the lane on the road is very great. Secondly, a reserved lane may be shared by several task paths. Since the objective of the problem is to minimize the total impact of reserving lanes, the less lanes are reserved, the less the total impact is. Thirdly, we assume that each lane in the path for any task is a reserved one so as to facilitate traffic management and safety of hazardous transportation. Fig. 1 is an illustration of the problem. There are two tasks (from node 1 to 9 and 2 to 10) to be accomplished. Lanes on arcs (1, 3), (3, 6), (6, 9) and (2, 3), (3, 6), (6, 10) are reserved for the two tasks, respectively. And the reserved lane on arc (3, 6) are shared by both the two tasks. The transportation network can be considered as a directed graph \( G = (V, A) \), where \( V \) is the set of nodes and \( A \) is the set of directed arcs \((i, j)\). Let \( K \) be the set of tasks. \( S = \{s_k \in V | k \in K\} \) and \( D = \{d_k \in V | k \in K\} \) be the sets of source nodes and destination nodes for the tasks, respectively. \( p_k \) is the deadline for task \( k \). \( t_{ij} \) is the travel time on a reserved lane on arc \((i, j)\) and \( c_{ij} \) is the impact on the normal traffic of reserving a lane on arc \((i, j)\). The binary decision variable \( Z_{ij} \) is equal to 1 if and only if a lane on arc \((i, j)\) is reserved. The binary decision variable \( X_k^{ij} \) is equal to 1 if and only if task \( k \) passes arc \((i, j)\). With assumptions and notations given above, the LRPTN can be formulated by the following integer linear program (P0).

\[
(P0) \quad \min \sum_{(i, j) \in A} c_{ij} Z_{ij} \\
\text{s.t.} \quad \sum_{j: (s_k, j) \in A} X_{s_kj}^k = 1, \forall k \in K, s_k \in S \quad (2) \\
\sum_{i: (i, d_k) \in A} X_{id_k}^k = 1, \forall k \in K, d_k \in D \quad (3) \\
\sum_{j: (j, i) \in A} X_{ji}^k = \sum_{j: (j, i) \in A} X_{ij}^k, \forall k \in K, \forall i \neq s_k, d_k \quad (4) \\
\sum_{(i, j) \in A} t_{ij} X_{ij}^k \leq p_k, \forall k \in K \\
X_{ij}^k \leq Z_{ij}, \forall (i, j) \in A, \forall k \in K \\
X_{ij}^k \in \{0, 1\}, \forall (i, j) \in A, \forall k \in K \\
Z_{ij} \in \{0, 1\}, \forall (i, j) \in A 
\]

The objective function (1) is to minimize the total impact of reserving lanes on the normal traffic. Constraints (2) (resp. (3)) represent that there is only one path for each task \( k \) starting from (resp. arriving at) the source node \( s_k \) (resp. destination node \( d_k \)). Constraints (4) ensure the flow conservation. Constraints (5) assure that the total travel time for task \( k \) does not exceed the deadline \( p_k \). Constraints (6) guarantee that any lane in the path for task \( k \) is reserved.

It is not hard to see that the LRPTN is NP-hard. If all the tasks have the same source node and \( p_k = +\infty \) for any \( k \in
of the travel time on arc $p$ from $j$ to $E$, and then all the variables in this pre-processing, the linear relaxation problem of the following steps of the algorithm, a new integer program is obtained by solving its linear relaxation problem. If this lower bound is the global optimal value and the iteration is terminated.

For a similar case, set $E = \{E_{ij} \mid \text{reduced cost of } Z_{ij} > a_i, \forall (i, j) \in A\}$, where $a_i$ is a given number. The value for $a_i$ is dependent on the distribution of reduced cost. We solve the linear relaxation problem of the current problem and obtain the reduced cost of each variable at each iteration. Then we select $n$ variables $Z_{ij}$ with largest reduced cost, $a_i$ is set to the minimum reduced cost among these $n$ variables. Once we obtain $U_l$, the $PC_l$ is defined as follows

$$(PC_l) \sum_{Z_{ij} \in U_l} Z_{ij} \geq 1.$$ (13)

By the cut-and-solve method, the current problem at $l$-th iteration is defined as $RP_{l-1}$ (for $l = 1$, the current problem is $P_1$). Then the $SP_l$ is defined as follows

$$(SP_l) \min \sum_{(i,j) \in A} c_{ij} Z_{ij}$$

s.t. constraints (2) – (8) and (11)

$${\sum_{Z_{ij} \in U_l} Z_{ij} \geq 1, \quad t = 1, \ldots, l - 1} \quad (14)$$

$${\sum_{Z_{ij} \in U_l} Z_{ij} = 0} \quad (15)$$

And $RP_l$ is defined as follows

$$(RP_l) \min \sum_{(i,j) \in A} c_{ij} Z_{ij}$$

s.t. constraints (2) – (8), (11), (13) and (14).
For the first iteration \( l = 1 \), there is no (14) in \( SP_l \) and \( RP_l \). It is not hard to see that \( SP_l \) and \( RP_l \) are \( RP_{l-1} \) with additional constraints (15) and (13), respectively.

2) Improved piercing cut: When the problem size becomes large, the \( PC \) above is not very effective. To make some improvement, we firstly give the following theorem.

**Theorem 1:** For \( l \geq 2 \), if

\[
U_1 \supseteq \cdots \supseteq U_{l-1} \supseteq U_l,
\]

holds, then \( SP_l' \) is equal to \( SP_l \) and \( RP_l' \) is equal to \( RP_l \), where \( SP_l' \) is

\[
(SP_l') \min \sum_{(i,j) \in A} c_{ij}Z_{ij}
\]

s.t. constraints (2) – (8), (11) and (15)

\[
\sum_{Z_{ij} \in U_{l-1} \setminus U_l} Z_{ij} \geq 1,
\]

and \( RP_l' \) is

\[
(RP_l') \min \sum_{(i,j) \in A} c_{ij}Z_{ij}
\]

s.t. constraints (2) – (8), (11) and (13).

**Proof:** To prove \( SP_l' \) is equal to \( SP_l \), we just have to prove that (14) is equal to (17). If (14) is true, then we have \( \sum_{Z_{ij} \in U_{l-1} \setminus U_l} Z_{ij} \geq 1 \). Meanwhile, \( \sum_{Z_{ij} \in U_{l-1} \setminus U_l} Z_{ij} = \sum_{Z_{ij} \in U_{l-1} \setminus U_l} Z_{ij} + \sum_{Z_{ij} \in U_l} Z_{ij} \), because \( U_{l-1} \supseteq U_l \). Since \( \sum_{Z_{ij} \in U_l} Z_{ij} = 0 \) by (15), so we have \( \sum_{Z_{ij} \in U_{l-1} \setminus U_l} Z_{ij} \geq 1 \), i.e. (17) is true.

If \( \sum_{Z_{ij} \in U_{l-1} \setminus U_1} Z_{ij} \geq 1 \), i.e. (17) is true. Because \( U_1 \supseteq \cdots \supseteq U_{l-1} \supseteq U_{l-1} \setminus U_l \), then \( \sum_{Z_{ij} \in U_{l-1} \setminus U_l} Z_{ij} = \sum_{Z_{ij} \in U_{l-1} \setminus U_l} Z_{ij} + \sum_{Z_{ij} \in U_{l-1} \setminus U_l} Z_{ij} \), because \( U_1 \supseteq U_{l-1} \supseteq U_l \). Since \( \sum_{Z_{ij} \in U_l} Z_{ij} = 0 \) by (15), so we have \( \sum_{Z_{ij} \in U_{l-1} \setminus U_l} Z_{ij} \geq 1 \), i.e. (14) is true. So (14) is equal to (17), and \( SP_l' \) is equal to \( SP_l \).

All the constraints are the same both in \( RP_l' \) and \( RP_l \) except that there is no (14) in \( RP_l' \). To prove \( RP_l' \) is equal to \( RP_l \), we just have to prove that (14) is redundant in \( RP_l' \). By (13) we have \( \sum_{Z_{ij} \in U_l} Z_{ij} \geq 1 \). Because \( U_1 \supseteq \cdots \supseteq U_{l-1} \supseteq U_l \), then \( \sum_{Z_{ij} \in U_l} Z_{ij} = \sum_{Z_{ij} \in U_{l-1} \setminus U_l} Z_{ij} + \sum_{Z_{ij} \in U_{l-1} \setminus U_l} Z_{ij} \geq \sum_{Z_{ij} \in U_{l-1} \setminus U_l} Z_{ij} \geq 1 \), i.e. (14) is true. So \( RP_l' \) is equal to \( RP_l \).

There are \( l-1 \) equalities in (14) for \( SP_l \), but only one in (17) for \( SP_l' \). In addition, the equalities in (14) for \( RP_l \) are totally removed for \( RP_l' \). \( SP_l' \) and \( RP_l' \) have less constraints than \( SP_l \) and \( RP_l \), respectively, it will be more efficient to solve \( SP_l' \) and \( RP_l' \) instead of \( SP_l \) and \( RP_l \).

As explained above, the set \( U'_l \) \( (l \geq 1) \) used in the proposed algorithm is defined as follows

\[
U'_l = \{Z_{ij} \mid Z_{ij} \in U_l \cap U_{l-1}, \forall (i,j) \in A\},
\]

where \( U_0 = \{Z_{ij} \mid \forall (i,j) \in A\} \). The piercing cut \( PC_l' \) is defined as follows

\[
(PC_l') \sum_{Z_{ij} \in U'_l} Z_{ij} \geq 1.
\]

\( SP_l'' \) is defined as follows

\[
(SP_l'') \min \sum_{(i,j) \in A} c_{ij}Z_{ij}
\]

s.t. constraints (2) – (8), (11)

\[
\sum_{Z_{ij} \in U'_l} Z_{ij} = 0
\]

and \( RP_l'' \) is defined as follows

\[
(RP_l'') \min \sum_{(i,j) \in A} c_{ij}Z_{ij}
\]

s.t. constraints (2) – (8), (11) and (19).

For \( l = 1 \), there is no (21) in the \( SP_l'' \).

The overall algorithm is presented as follows.

**Algorithm 1**

1) Do the pre-processing for \( P_0 \) and obtain \( P_1 \).
2) Initialize \( UB_{\min} := +\infty \), \( l := 0 \) and the current problem as \( P_1 \).
3) Solve the linear relaxation problem of the current problem and obtain its reduced cost of each variable.
4) do
   a) Set \( l := l+1 \), define \( U'_l \) by (18) and \( PC_l' \) by (19).
   b) Use \( PC_l' \) to cut the solution space of the current problem and obtain the \( SP_l'' \) and the \( RP_l'' \).
   c) Solve the \( SP_l'' \) and obtain its optimal value \( UB_l \) if exists, update the \( UB_{\min} \) if necessary.
   d) Solve the linear relaxation problem of the \( RP_l'' \) and obtain its lower bound \( LB_l \) and reduced cost of each variable.
   e) Set the current problem as \( RP_l'' \).
   while \( LB_l < UB_{\min} \)
5) return \( UB_{\min} \) as the global optimal value, algorithm is terminated.

**IV. Computational results**

In this section, the performance of the proposed algorithm is compared with a commercial solver CPLEX 12.1. The algorithm is implemented in Visual C++ and run on a PC with 3.00GHz CPU and 4.00GB RAM. We use a LP and MIP solver CPLEX in default setting to solve the linear relaxation problem of the remaining problem and the sparse problem, respectively.

The random instances are generated in the following way. The network is generated by Waxman’s random network model [25]. The nodes of the network are randomly distributed in a rectangle. The probability of arc existence between nodes \( i \) and \( j \) is given by

\[
P(i,j) = \alpha \exp \left( \frac{-d(i,j)}{\beta L} \right),
\]

where \( d(i,j) \) is the Euclidean distance from \( i \) to \( j \), and \( L \) is the maximum distance of all pairs of nodes. \( \alpha \) and \( \beta \) are parameters in \((0, 1]\). Large value of \( \alpha \) results in high average
node degree, while large value of $\beta$ yields a high ratio of long arcs to short ones. The travel time on a reserved lane on $(i, j)$ is set to $t_{ij} = r_{ij}d(i, j)$, where $r_{ij}$ is randomly generated in [0.5, 0.8]. The deadline $p_k$ is equal to $b_k \cdot d(s_k, d_k)$, where $d(s_k, d_k)$ is the shortest travel time from $s_k$ to $d_k$ in a reserved path and $b_k$ is randomly generated in $[1, \sqrt{2}]$. The impact of reserving lanes on the normal traffic $c_{ij}$ is difficult to evaluate. [5] defined it by $d(i, j)/(M_{ij} - 1)$, where $M_{ij}$ is the number of lanes on road $(i, j)$ and is randomly and uniformly generated in [2, 4].

The problem instances are divided in 25 sets of 5 each. The average node degree of each instance is 7 to denote a sparse network [26]. Let $LP_0$ and $LP_1$ denote the lower bound of $P_0$ and $P_1$ obtained by linear relaxation, respectively. With the notations given in Table I, the computational results are summarized in Table II and Fig. 2.

In Table II the Gap between the lower bound of $P_0$ and $P_1$ varies from 0.85% to 3.86% and the average value of Gap for all instances is 3.03%, which shows that the pre-processing tightened the lower bound of $P_0$. With the increase of $|K|$, the Gap becomes larger. Take instances sets 5 and 25 for example, both have 150 nodes but 10 and 30 tasks, respectively. The Gap is 2.05% for S5 while 3.78% for S25. The computational time by Algorithm 1 is less than that by CPLEX for all the instances sets. And Algorithm 1 takes 1.47-3.93 times less computation time than that by CPLEX. Our algorithm is 2.45 times faster than CPLEX in terms of an average computation time. Moreover, we observe that the computation time increases much sharply with the number of tasks for both CPLEX and Algorithm 1. In Fig. 2 (a), both of CPLEX and Algorithm 1 take no more than 20s for the instances with 10 tasks. While in Fig. 2 (b), the computation time by both of CPLEX and Algorithm 1 increases quickly to several hundred seconds or even more for instances with 30 tasks. However, Algorithm 1 is more effective for instances with 30 tasks than with 10 tasks. For sets S21-S25, which are the instances with 30 tasks, Algorithm 1 is 2.35% times faster than CPLEX on average computational time. While for S1-S5 with 10 tasks, Algorithm 1 is 2.02% times faster than CPLEX on average computational time.

V. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this paper, we studied a lane reservation problem on transportation network. The problem is to choose reserved lanes to minimize the total impact of reserving lanes while the tasks could be completed within the deadlines. The considered problem is NP-difficult. For solving the problem, an integer linear program model was formulated and an optimal algorithm based on cut-and-solve method was proposed. A pre-processing was done to accelerate the convergence of the algorithm by tighten the linear relaxation of the original problem. In addition, new techniques of generating piercing cut were developed for our problem. The computational results showed that the proposed algorithm outperform the MIP solver of commercial software CPLEX 12.1.

B. Future Works

The study of lane reservation problem in this paper is the first part of our project. In the future, more transportation problems, such as dynamic transportation network design for automated trucks, and more practical transportation factors will be considered in our work. In addition, a further study of more advanced techniques in cut-and-solve method will be developed in future work.

### Table I

| $|V|$ | number of nodes of the network |
|-----|-------------------------------|
| $|K|$ | number of tasks |

| $Gap$ | $100 \times (LP_0 - LP_1)/LP_1$ |
|---|---|
| $T_a$ | computation time by Algorithm 1 in seconds |
| $T_{cp}$ | computation time by CPLEX in seconds |
| $T_{cp}/T_a$ | ratio of computation time by CPLEX and Algorithm 1 |

### Table II

| set | $|V|$ | $|K|$ | Gap (%) | $T_{cp}$(s) | $T_a$(s) | $T_{cp}/T_a$ |
|-----|-----|-----|--------|--------|--------|------------|
| S1  | 110 | 10  | 0.85   | 4.57   | 2.37   | 1.93       |
| S2  | 120 | 10  | 2.26   | 6.01   | 2.45   | 2.45       |
| S3  | 130 | 10  | 2.97   | 8.18   | 5.05   | 1.62       |
| S4  | 140 | 10  | 2.08   | 14.54  | 4.36   | 3.34       |
| S5  | 150 | 10  | 2.05   | 12.35  | 8.40   | 1.47       |
| S6  | 110 | 15  | 2.24   | 45.05  | 11.45  | 3.93       |
| S7  | 120 | 15  | 1.04   | 90.49  | 45.80  | 1.98       |
| S8  | 130 | 15  | 2.11   | 151.46 | 52.02  | 2.91       |
| S9  | 140 | 15  | 3.43   | 178.30 | 64.09  | 2.78       |
| S10 | 150 | 15  | 2.56   | 274.81 | 114.81 | 2.39       |
| S11 | 110 | 20  | 3.34   | 240.56 | 111.62 | 2.16       |
| S12 | 120 | 20  | 3.05   | 417.17 | 166.41 | 2.51       |
| S13 | 130 | 20  | 2.89   | 1075.65| 438.96 | 2.45       |
| S14 | 140 | 20  | 3.65   | 1370.31| 551.62 | 2.48       |
| S15 | 150 | 20  | 3.65   | 1648.54| 591.96 | 2.78       |
| S16 | 110 | 25  | 2.73   | 958.79 | 349.40 | 2.74       |
| S17 | 120 | 25  | 2.84   | 1014.07| 422.98 | 2.40       |
| S18 | 130 | 25  | 3.47   | 1689.28| 671.37 | 2.51       |
| S19 | 140 | 25  | 3.31   | 2014.52| 765.84 | 2.63       |
| S20 | 150 | 25  | 3.81   | 2202.74| 840.97 | 2.62       |
| S21 | 110 | 30  | 3.25   | 1418.11| 613.34 | 2.31       |
| S22 | 120 | 30  | 3.62   | 2038.60| 672.55 | 3.03       |
| S23 | 130 | 30  | 3.10   | 2660.95| 1631.65| 1.63       |
| S24 | 140 | 30  | 3.86   | 3038.63| 1172.22| 2.59       |
| S25 | 150 | 30  | 3.78   | 4058.54| 1543.43| 2.63       |

Average | 3.03 | 1065.29 | 434.22 | 2.45 |
Fig. 2. Computation time of Algorithm 1 and CPLEX. (a) instances with 10 tasks (b) instances with 30 tasks

VI. ACKNOWLEDGMENTS

The authors are grateful to the anonymous reviewers for their insightful remarks and suggestions on improving the quality of the paper.

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