**Fig. Results**

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2) To address the impacts of EVs' trips on network performance
1) To investigate the performance of routes
To understand the effect of EVs on the network

**Motivation**

- Incorporating EVs into the NDP
  - Few NDP works have considered that the behavior of EVs is different from that of ICEVs due to the imposed range constraint, which may have a significant impact on the traffic flow pattern.

- Measures taken in the NDP
  - Most previous NDP studies only addressed road capacity enhancement scenarios, and some other works focused on charging station planning for en-route recharge which is vital to operations of distance-constrained EVs, but rarely in combination.

- Traffic considered in the NDP
  - For modelling NDPs with EVs' recharge, previous works rarely accounted for the variation in distance limits of vehicles, whereas the diversity of individual travelling units is commonly observed in traffic networks.

**Background**

- Why electric vehicles (EVs)?
  - Reduction of greenhouse emissions
  - Continuation towards the relief of the energy crisis

- What is the traditional network design problem (NDP)?
  - To select roads for expansion, aiming to maximize the entire social benefit subject to resource constraints, together with the requirement that flow patterns satisfy the user equilibrium conditions.

- How to incorporate EVs into the NDP?
  - To investigate the impacts of EVs' trips on network performance
  - To address the en-route recharge requirement of EVs
  - To accommodate travel demands of mixed-vehicular traffic comprised of both internal combustion engine vehicles (ICEVs) and EVs

**Methodology**

- Mixed-vehicular traffic assignment problem considering en-route recharge (MVTAP-ER)
  - Model formulation:

\[
\begin{align*}
\text{Minimize} & \quad \sum_{r} \sum_{s} \sum_{m} \sum_{u} \left[ \sum_{j} a_{js} x_{js} \right] \mu_{rsu} \\Pi_{rsu}
\end{align*}
\]

- Optimality conditions (obtained by using Lagrangian Function and Karush–Kuhn–Tucker (KKT) conditions):

\[
\begin{align*}
\left( \Pi_{rsu} - \mu_{rsu} \right) = 0, & \quad \forall r, s, u \in N
\end{align*}
\]

- Network design problem with recharge facility allocation (NDP-RFA)
  - Model formulation:

\[
\begin{align*}
\text{Maximize} & \quad \sum_{r} \sum_{s} \sum_{m} \sum_{u} \left[ \sum_{j} a_{js} x_{js} \right] \mu_{rsu} \\Pi_{rsu}
\end{align*}
\]

**Results**

- Case study on well-known Sioux-Falls network
  1) To demonstrate the use of the proposed model and algorithm
  2) To discuss the implications for planning with EVs' en-route recharge considerations

**Conclusion**

- This work develops a bi-level programming model of the aggregated network design problem (NDP) considering distance limit and en-route recharge of electric vehicles (EVs). The proposed modelling device plays an essential role in transport planning.

- Both distance limits and budget levels have significant influences on the project rankings and evaluations. In most cases, the total system travel costs could decrease with the extension of the distance range or the increase of the construction budget. However, the extent to which different network performance metrics will change due to different design scenarios is unpredictable without using the proposed approach.

- To explore factors that influence project evaluation and selection
- To investigate network performance improvement in terms of multiple design objectives.