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Research article

Tradable mobility permit with Bitcoin and Ethereum – A Blockchain application in transportation

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ABSTRACT

Blockchain and its underlying technology have intrigued researchers with its promising applications and implications as "the second internet". There is a wide range of Blockchain applications in transportation and logistics. In this paper, we present the basic principle of cryptocurrencies and Blockchain as well as Ethereum. This is followed by the potential applications of Blockchain in transportation, logistics, and supply chain industries in which the concept of a tradable mobility permit (TMP) to combat traffic congestion is formulated and numerically tested. We then discuss the deployment of the TMP scheme based on a Blockchain platform and its by-products such as dynamic toll pricing, priority for emergency vehicles, heavy truck platooning, as well as connected vehicles.

1. Introduction

'Bitcoin' is morphing from being a novel 'buzzword' in the media into a household name. It was the first so-called 'crypto-currency,' which means a medium of exchange and store of value based on limited entries in a digital database that no one can change without fulfilling specific control conditions. Recent volatility in the Bitcoin exchange market [8] has attracted huge interest from investors, hedge funds, bankers, politicians, legislators, as well as technologists, scholars, think tanks, writers, entrepreneurs, and venture capitalists.

Underlying Bitcoin is the technology called 'Blockchain'. A good analogy for understanding the Blockchain is to consider it as electricity and Bitcoin as a lamp [49]. Blockchain is a distributed ledger, a form of 'record book' in which all transactions are recorded [55] and it is distributed, meaning that the record book is shared widely. A block per se can also be considered

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synonymous with several lines of records of the shared record book, which are time-stamped and are chained in the book chronologically. Any new record line needs first to be validated and accepted by all before being recorded in the book.

These characteristics result in several striking features that have made Blockchain a beacon leading to a new era and a paradigm shift in many fields such as data security, finance, economy, transport, logistics etc. The main features of Blockchain are:

- *Decentralization:* Blockchain obviates any need for a centralized authority or regulator or supervisor or intermediaries (such as banks), thus providing a cheaper system.
- *Resiliency:* being decentralized means the entire system is more resilient as the system does not stand on a single centralized component, rather it relies on many separate components which is less risky (if one component fails, others can take the burden).
- *Durability:* with no central point of control, it stands stronger against a malicious attack.
- *Transparency and immutability:* since all the entries of the record book are publicly viewable by everyone, so creating transparency and rendering the record book immutable to any alteration is possible.
- *Authenticity:* transactions need to be validated before being saved on the record book, hence the record book is a complete, consistent, timely, accurate, and widely available database; and
- *Speed:* settlement of transactions is made faster by the exclusion of the intermediaries.

The Blockchain technology is among the top trending technologies [66] next to 'Big Data' and 'Artificial Intelligence'. As indicated above, it is especially disruptive to various intermediary services and can be applied to all types of transactions [66], be they of tangible value such as finance [45] or intangible value such as patent, copyright [46] as well as for digital assets [34] such as files, videos etc. The potential footprints of the Blockchain technology in society and business are far-reaching, such as with payments, banking, asset management, real estate, land administration, voting systems, supply chains, transport, etc. [25,48,54].

According to Nijland and Veuger [43], "the two main traits of real estate assets are heterogeneity and immobility. As a result, the market for buying real estate tends to be illiquid, localized, and highly segmented, with privately negotiated transactions and high transaction costs due to the involvement of a vast amount of trusted third parties [35]. In this context, the lack of transparency, high transaction costs, and the need for digitalization in commercial real estate companies give Blockchain its game-changing potential [28]. The results have shown that the pre-marketing phase and due diligence phase are most suitable for the implementation of Blockchain. This is due to the characteristics of the phases, characteristics of the stakeholders, and the characteristics of Blockchain. The main aspect here can be focused on the benefit of Blockchain as a data-sharing program, which could add value creating a safer and more secured way of sharing data. What should be mentioned is that the technology is in an early stage of development and therefore not (yet) suitable for the implementation in the real estate sector. Although multiple pilots and user cases could be mentioned, the technology needs to overcome some obstacles to be a success in the current buying process of commercial real estate."

Transportation, logistics, and supply chain are perceived as early adapters given the size of their economies and rapid advances in the communication technology as a significant enabler [18,29,31]. Wang and Qu [62] have cited decentralization, open data, and authenticity of data as key characteristics which make Blockchain a platform for a variety of transport applications such as smart contract, fast payment, information sharing, track and trace, and supply chain finance. Intelligent Transportation Systems (ITS) encompasses a broad range of technologies, including information and communication technologies, transportation and communication infrastructures, connected vehicles, and emerging technologies such as Internet-of-Things (IoT). There are still many unsolved challenges that hinder the large deployment of advanced ITS systems. Recent studies have proposed using Blockchain, an emerging technology that enables decentralized coordination, to address inherent challenges in ITS such as security and scalability [58].

In this paper, we propose the concept of a tradable mobility permit (TMP) on a Blockchain platform as a means to address traffic congestion. The permits can be tradable in an open market like Bitcoin.

In this paper, we first provide an overview of Bitcoin, Blockchain, Ethereum and the concept of the "smart contract" in Section 2. A use-case as an application of the Blockchain in the logistics and transportation, namely a traffic congestion pricing scheme, is mathematically discussed and numerically tested in Section 3. Deployment of the proposed scheme, on a Blockchain platform is elaborated in Section 4. We conclude the paper in Section 5.

2. Bitcoin, Blockchain, and Ethereum

The cryptocurrency came to life with the advent of the Bitcoin as the first decentralized digital currency [41]. Digital electronic cash (or e-cash) had been envisaged by economists as a defining feature of the new millennium [20]. It was in November 2008 that a pseudonymous software developer operating under the name of Satoshi Nakamoto, published a white-paper on the Cryptography Mailing List which proposed Bitcoin as an electronic payment system based on a mathematical proof [41]. She/he then released the first version of Bitcoin software in 2009 as an open-source software. As discussed above, Bitcoin works with no central administrator, nor a central bank. It, in fact, works as peer-to-peer direct transactions with no mediator on a decentralized and distributed network in which each user is represented by a node, with no centralized hub or authority (see Fig. 1).

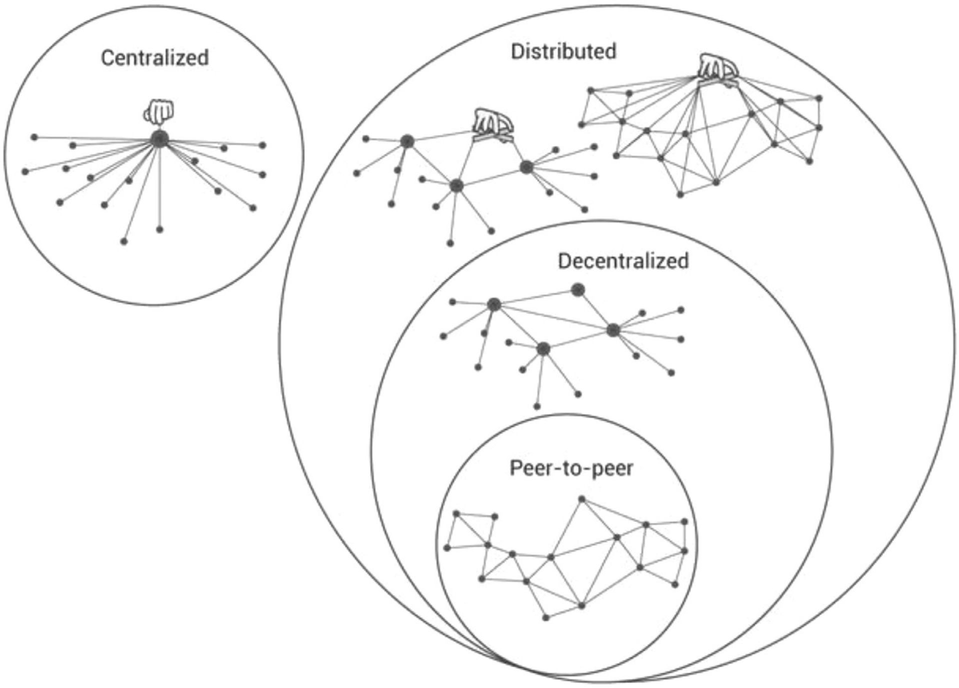

Fig. 1. Types of networks [38].

A bunch of transactions is bundled together as a block to be verified by the network's nodes using cryptography, which are then added to the chain of records in the record book. Cryptography is a mathematical procedure to convert raw data into a format that is unreadable for an unauthorized user, aiming to secure the database. Nodes can get involved in the verification process and are rewarded with new Bitcoins to compensate their expense, including bespoke computational power and electricity bills, which are called 'mining'.

Bitcoin is a mathematically protected digital currency, which is maintained by a network of peers. Digital signatures authorize individual transactions, ownership is passed via transaction chains, and the ordering at those transactions is protected in the Blockchain. By requiring difficult math problems to be solved with each block, would-be attackers are pitted against the entire network in a computational race, hence they're unlikely to win. Bitcoin promises many interesting ideas, such as insulation from government meddling, anonymity, and potentially lower transaction fees.

The Bitcoin's underlying technology (i.e. the Blockchain) has been generalized by Ethereum to something more than just a cryptocurrency. "Ethereum is a decentralized platform that runs smart contracts: applications that run exactly as programmed without any possibility of downtime, censorship, fraud or third-party interference" [16], that is to supersede the central servers and make communication through peer-to-peer channels. The kernel of the Ethereum is the concept of smart contracts, which are used to create decentralized applications. [64].

Like Bitcoin and Blockchain, a user has to open an account, which has a certain balance in terms of the unit of transaction, namely here 'ether'. Each account is also identified with an address, a public key, to receive ether. Each account is also controlled by a private key to send ether. There is also a second type of account called smart contracts (see Fig. 2). In contrast to the user account and private keys, smart contracts are controlled by computer codes. These codes are programmed into the smart contracts and no one can alter them (which is where the word Ethereum comes from). User accounts and the smart contract can interact with one another. Just like Bitcoin, there is no administrator that has the power to interfere in the system. Hence, the codes and smart contracts are immutable.

A smart contract is therefore like a bunch of codes and commands to make a transaction (or an action), so long as the permissions or the rules written in the associated codes dictates how that's going to happen. A smart contract once created can be imagined as an object with a code instructing it how to behave in an object-oriented environment [14].

For example, imagine Alice and Bob place a bet about tomorrow's weather, Alice bets for sunny weather, whereas Bob bets for rainy weather. The loser has to pay the winner $100. How does one enforce the loser to keep his/her promise? They can either trust each other, get help from a mutual friend, or sign a legal agreement. However, obviously, each such option has its shortcomings. The first two options bring up the question of trust and intermediary again. Forcing a legal agreement could be very expensive, and hence practically infeasible.

Ethereum's smart contract can do this job as a trusted mutual friend but written in a code. Ethereum allows them to write a software that accepts ether worth $100 from Alice and Bob, and then the next day uses an open weather API

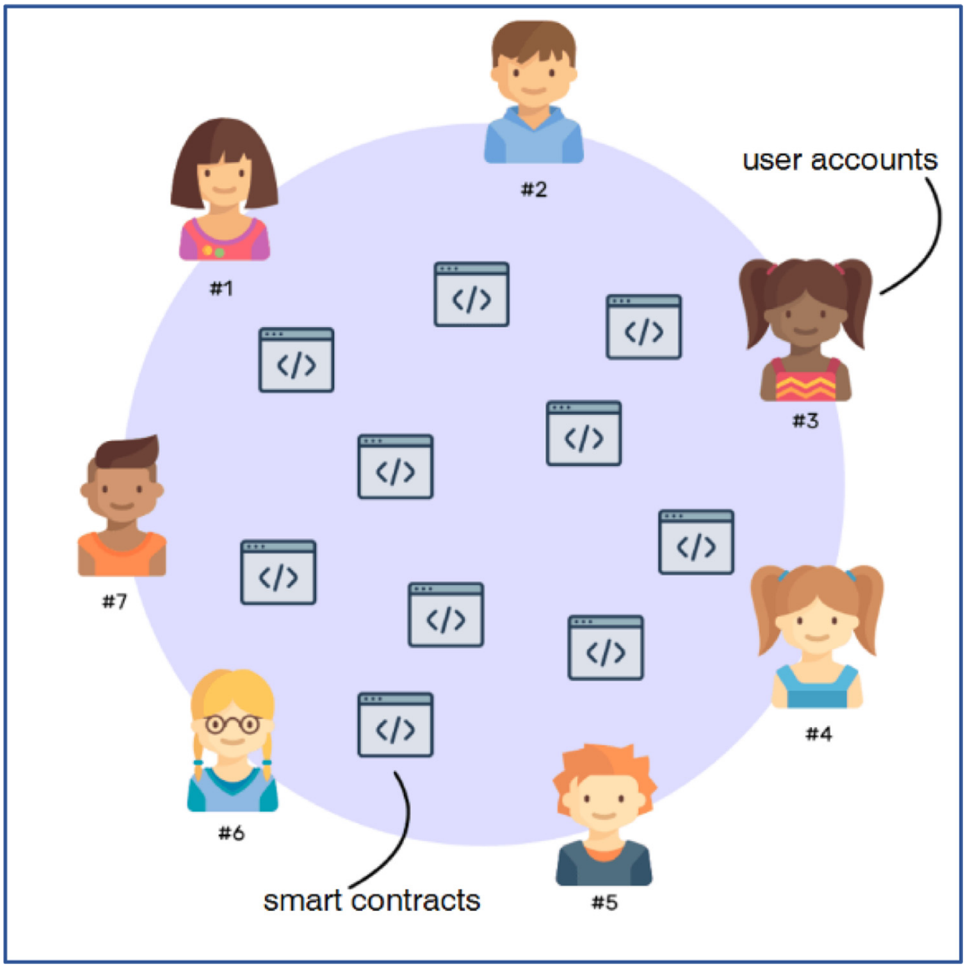

Fig. 2. Ethereum, smart contract and user contract [39].

(application program interface) to check the weather and transfer the total ether worth of $200 to the winner (see Fig. 3). The smart contract can be a decentralized autonomous object to act as per programmed like the smart contract described above to settle a betting process.

The structure of the Ethereum's Blockchain is very similar to Bitcoin's, in that, it is a shared record of the entire transaction history. Every node on the network stores a copy of this history. The big difference with Ethereum is that its nodes store the most recent state of each smart contract as well as all of the ether trading. In other words, one can consider each transaction as a change to the state of the ledger (or Blockchain) as a whole. A simple definition of state for the Ethereum is that the Ethereum as it stands includes all the smart contracts codes and accounts' ether balance. Similar to Bitcoin's Blockchain, Ethereum's states are encrypted and added to the chain of blocks [23].

A clear analogy of Bitcoin and Ethereum is provided by Quora [47]: "Bitcoin Blockchain is like gold. It has its value because people "think" it's valuable; while Ethereum is like crude oil, its value is for its practical usability in numerous areas". A detailed description of the Ethereum can be found in [10].

3. Proposed model and application

In this section, inspired by the idea of the smart contract and Blockchain, we provide a use-case scenario in transport, in which traffic authorities impose a mobility cap to the use of private cars, aiming to shift travel demand towards public transport. The idea is to let traffic authorities issue a limited number of mobility credits (or mobility permit), distributed equally among all users. The mobility credits are limited to curb traffic congestion and they are tradable in a free market [65]. We will numerically show that the tradable mobility permit (TMP) can effectively reduce traffic congestion.

It is postulated that drivers (or users) choose the fastest route, which is known as the user-equilibrium (UE) traffic pattern. However, from the point of total costs of users' travel as a system, the UE is not an efficient pattern. Instead, the

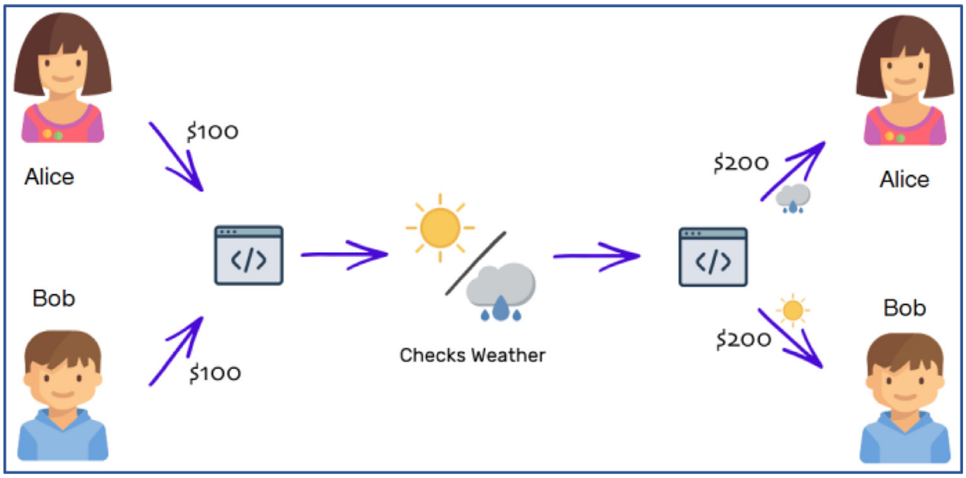

Fig. 3. Smart contract to handle a bidding example [39].

least cost traffic pattern, also known as system-equilibrium or system optimal (SO), is the one where the total cost of a transport system is minimized.

Using travel time as a proxy for the cost of a transport system and in terms of the total travel time (as an index for the traffic congestion), the gap between UE and SO can reach as high as 2.15 [50]. In other words, by enforcing SO rather than the UE traffic pattern, one can significantly improve the congestion level by up to 2.15 times.

This gap has been a driving force and motivation in a variety of traffic management measures (or control) including the notion of public transport. To this end, transport authorities are supposed to design public transport (bus/tram/rail routes) based on the SO, while private vehicles drive according to the UE pattern. For the sake of a sustainable and economically efficient transport system, the aim is to shift from UE (private modes) to SO (public modes) as much as possible.

One way is to restrict the market share of the UE, that is, to set a cap on the total travel demand (or the total number of private cars) and shift the excess demand to the public modes. Alternatively, one can put a cap on the capacity of the individual roads [2]. Imagine a road with a capacity of 1000 vehicle per hour, whereas, the demand is 1500. It is likely to issue only 1000 permits to avoid congestion and shift the excess demand (i.e. 500) to the public transport. By projecting this small case and the single road to a network of roads and a city, traffic authorities can issue a limited number of UE pass permits, distributed equally to everyone, that can be tradable in an open market. In light of the ever-increasing use of all sorts of sensors, detectors, cameras, RFID, radars and lidars, enforcing traffic restriction is now a doable task. However, the tradable part is not an easy task, for which the Blockchain technology and smart contracts can be a valid, promising and workable solution.

In the following exposition, we provide a proof of concept (a mathematical representation and a numerical test) for such a traffic management scheme in which the UE is capped, and both the UE and the SO flows share the same transport network.

3.1. Formulation

Let us consider the following notations:

A	Set of road segments
N	Set of nodes
x_a	UE traffic flow on the road $a \in A$
x	A vector of the UE traffic flows $x = \{x_a,\ a \in A\}$
$\bar{x}_a$	SO traffic flow on the road $a \in A$
$\bar{x}$	A vector of the SO traffic flows $\bar{x} = \{\bar{x}_a,\ a \in A\}$
X	The vector of both UE and SO traffic flow $X = \{x,\ \bar{x}\}$
z	Beckmann objective function to be minimized for the UE, ensuring that everyone chooses Shortest path; it is a function of the vector of roads' traffic flow
q_i^k	UE travel demand from i to k
$f_{p,i}^k$	UE flow on the path p from i to k
p_i^k	Set of all paths available to UE from i to k
$\delta_{a,p,i}^k$	Road-path incidence matrix (1: if road a belongs to the path p from i to k available to UE, and 0 otherwise)
x_{ij}^k	UE traffic flow of the road $(i,\ j)$ heading towards a destination k

(continued on next page)

t_i^k	Minimum travel time from node i to node (destination) k, pertaining to the UE traffic flow
$t_a(.)$	Delay or travel time function of the road $a \in A$
$\bar{q}_i^k$	SO travel demand from node i to k
$\bar{f}_{p,i}^k$	SO flow on the path p from the node i to k
$\bar{P}_i^k$	Set of all paths available to SO from i to k
$\bar{\delta}_{a,p,i}^k$	Road-path incidence matrix (1: if road a belongs to the path p from i to k available to SO, and 0 otherwise).
$\bar{x}_{ij}^k$	SO traffic flow of the road (i, j) heading towards the destination k
$\bar{t}_i^k$	Minimum travel time from node i to node (destination) k, pertaining to the SO traffic flow
$\bar{z}$	Total travel time (or cost) function to be minimized for the SO
D	Set of destinations ($D \subset N$) such that $k \in N \mid \sum_i (q_i^k + \bar{q}_i^k) > 0$
α_{ij}, β_{ij}	Parameters of the delay function used for the Sioux Falls network
Q_i^k	Total travel demand (UE and SO combined) from i to k (i.e., $Q_i^k = q_i^k + \bar{q}_i^k$)

In the presence of the SO traffic flow ($\bar{x}_a$) as a background traffic on road $a \in A$, the UE can be formulated as an optimization problem (i.e., nonlinear programming problem) [5,44,53]:

$$\min z(x) = \sum\nolimits_{a \in A} \int_0^{x_a} t_a(x_a + \bar{x}_a)\, dx \tag{1}$$

$$\text{s.t.} \quad \sum\nolimits_p f_{p,i}^k = q_i^k \qquad i \in N, \quad k \in D \tag{2}$$

$$x_a = \sum_i \sum_k \sum_p f_{p,i}^k . \delta_{a,p,i}^k \qquad a \in A, p \in P_i^k, i \in N, k \in D \tag{3}$$

$$\begin{cases} f_{p,i}^k \geq 0 \; p \in P_i^k, \quad i \in N, \quad k \in D \\ \qquad x_a \geq 0 \quad a \in A \end{cases} \tag{4}$$

where the objective function (1) is the Beckmann formulation [4], to ensure that every driver chooses the fastest (or the shortest) path. Constraint (2) describes the nodes' flow conservation and it is to make share that travel demand from node i to node k, denoted by q_i^k is met. Constraint (3) computes roads' traffic flow based on the paths' traffic flows. Constraint (4) is to make sure that all flows are non-negative.

In a similar fashion, by considering UE (x_a) as background traffic, the SO formulation can be written as follows:

$$\min \bar{z}(\bar{x}) = \sum\nolimits_{a \in A} \bar{x}_a . t_a(\bar{x}_a + x_a) \tag{5}$$

$$\text{s.t.} \quad \sum\nolimits_p \bar{f}_{\bar{p},i}^k = \bar{q}_i^k \qquad i \in N, \quad k \in D \tag{6}$$

$$\bar{x}_a = \sum_i \sum_k \sum_p \bar{f}_{p,i}^k . \bar{\delta}_{a,p,i}^k a \in A, p \in \bar{P}_i^k, \quad i \in N, \quad k \in D \tag{7}$$

$$\begin{cases} \bar{f}_{p,i}^k \geq 0 \; p \in \bar{P}_i^k, \quad i \in N, \quad k \in D \\ \qquad \bar{x}_a \geq 0 \quad a \in A \end{cases} \tag{8}$$

As can be seen, the only difference between these two formulations is their objective functions: one has an integral term, and the other does not. In order to have a consistent formulation, one can replace the delay function $t_a(\bar{x}_a + x_a)$ of the SO formulation with: $\bar{t}_a(\bar{x}_a + x_a) = t_a(\bar{x}_a + x_a) + \bar{x}_a.\ \partial t_a(\bar{x}_a + x_a)/\partial \bar{x}_a$, also called the marginal delay function [12], which results in a similar formulation of the UE. Therefore both UE- and SO-flows can now be represented in a single formulation, a nonlinear complementarity problem (NCP), with two different delay functions and travel demand matrices [3,21,22].

The NCP is a system of equations to find vector θ given a function $F(\theta)$ [17]. More precisely, θ is a vector of variables and so the $F(\theta)$ is a vector function. The aforementioned formulation is also denoted with a more compact notation as follows: $0 \leq \theta \perp F(\theta) \geq 0$(note, the symbol "$\perp$" represents the projection of θ over $F(\theta) = 0$). The NCP-UE-SO formulation can be written as follows:

$$0 \leq x_{ij}^k \perp \left\{ t_j^k + t_{ij}(X) - t_i^k \right\} \geq 0 \qquad (i, j) \in A, k \in D \tag{9}$$

$$0 \leq t_i^k \perp \left\{ \sum_{j|(i,j) \in A} x_{ij}^k - \sum_{j|(j,i) \in A} x_{ji}^k - q_i^k \right\} \geq 0 \qquad i \in N, k \in D \tag{10}$$

Table 1
Numerical results for various UE penetration rates.

UE penetration rate	total travel time	UE total travel time	SO total travel time	UE average travel time	SO average travel time
0	49,965.14	0.00	49,965.14	NA	84.02
10	49,973.29	4983.49	44,989.80	83.80	84.06
20	49,994.49	9989.37	40,005.12	83.99	84.09
30	50,003.39	14,994.40	35,009.00	84.05	84.10
40	50,004.24	19,997.56	30,006.69	84.07	84.10
50	50,005.29	24,999.45	25,005.85	84.08	84.10
60	50,008.18	30,002.86	20,005.32	84.09	84.10
70	50,012.55	35,007.42	15,005.12	84.10	84.11
80	50,012.55	35,007.42	15,005.12	73.59	126.17
90	50,022.75	45,020.40	5002.35	84.12	84.12
100	50,028.34	50,028.34	0.00	84.13	NA

$$0 \le x_{ij} \perp \left\{ x_{ij} - \sum_k x_{ij}^k \right\} \ge 0 \qquad (i,j) \in A \tag{11}$$

$$0 \le \bar{x}_{ij}^k \perp \left(\bar{t}_j^k + \bar{t}_{ij}(X) + \bar{x}_{ij}.\partial \bar{t}_{ij}(X)/\partial \bar{x}_{ij} - \bar{t}_i^k \right) \ge 0 \qquad (i,j) \in A,\ k \in D \tag{12}$$

$$0 \le \bar{t}_i^k \perp \left\{ \sum_{j|(i,j)\in A} \bar{x}_{ij}^k - \sum_{j|(j,i)\in A} \bar{x}_{ji}^k - \bar{q}_i^k \right\} \ge 0 \qquad i \in N,\ k \in D \tag{13}$$

$$0 \le \bar{x}_{ij} \perp \left\{ \bar{x}_{ij} - \sum_k \bar{x}_{ij}^k \right\} \ge 0 \qquad (i,j) \in A \tag{14}$$

In the above NCP formulation, SO and UE traffic flows are represented by Eqs. (9)–(11) and Eqs. (12–14), respectively.

3.2. Numerical analysis

For a numerical analysis, we use the dataset of the Sioux-Falls network, which has 76 links and 24 intersections (or nodes). As for a delay function, we use the following function:

$$t_{ij}(X) = \alpha_{ij} + \beta_{ij}.\left(x_{ij} + \bar{x}_{ij}\right)/C_{ij}\big)^4 \tag{15}$$

where $\alpha_{ij}$and β_{ij} are parameters to be calibrated based on a field survey (by measuring actual delay and traffic flow). The total travel demand (UE and SO combined) is $\sum_{i,k} Q_i^k$ =594.66. To cap the UE demand, we introduce a parameter denoted bypvvarying from 0 to 1 which indicates the penetration rate of the private vehicles (UE) of the total demand, that is $q_i^k = pv\,.\,Q_i^k$ and $\bar{q}_i^k = (1 - pv)\,.\,Q_i^k$. The NCP-UE-SO is coded using GAMS, one of the leading optimization software programs. The GAMS code, which also contains the details of the Sioux Falls network and its travel demand matrix, is provided in Appendix 1.

We run the GAMS code for various UE penetration rates whose results are reported in Table 1, which illustrates the total travel time as well as average travel time pertaining to the UE and SO modes. Fig. 4 demonstrates the topography of the Sioux-Falls network, and traffic volume for the resulting traffic pattern. To better comprehend the information of the Table, let us visualize it.

Fig. 5 depicts the variation of the total travel time over various UE penetration rates. As can be seen, three distinct segments can be spotted on the graph: (i) the segment between the UE penetration rate of 0 and 30 which exhibits the maximum decrease of the total travel time, (ii) the segment between the rate of 30 and 80 which demonstrates a monotone and relatively stable and constant total travel time, and (iii) the segment between 80 and 100 which shows a significant change of the value of the total travel time.

Since the less UE penetration rate is associated with more investments into the public transport, perhaps going for zero UE (an all-out SO, or public transport) is very costly and unlikely. Therefore, a wise choice is the third segment, which is to reduce the percentage of private vehicles from 100 to 80. Any more investment would be economically less viable since it falls within the second segment in which no significant gain can be achieved until over a long-stretched segment.

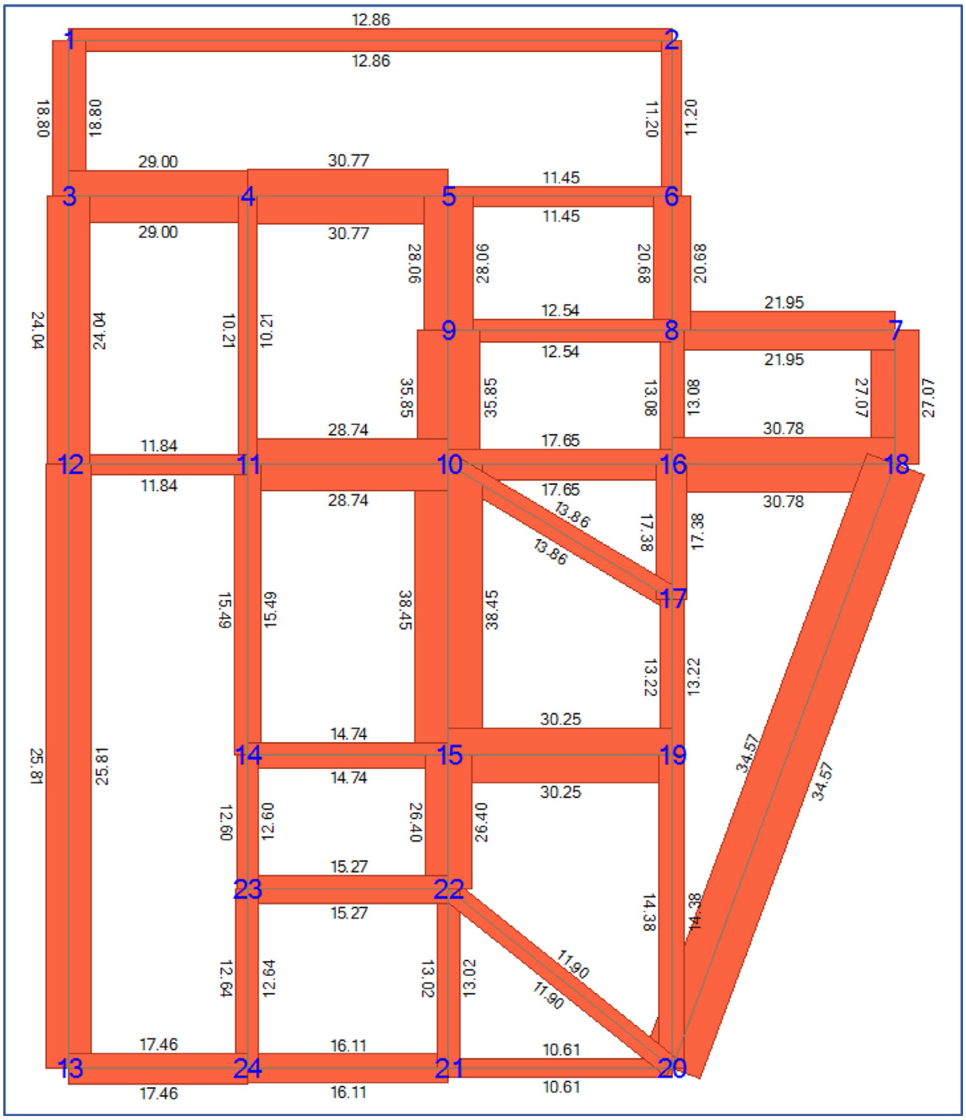

Fig. 4. Sioux Falls, UE traffic flow.

It is important to investigate the average travel time that a typical UE user or SO user experiences under different UE penetration scenario; this is shown in Fig. 6 (derived from Table 1). Obviously, for a clear majority of the penetration rates (10 to 70), everyone (be it a UE or SO user) shares almost the same burden equally (say 84 units of time). It is evident that the UE penetration of 80% is an outlier, in the sense that by reducing 20% out of the private cars (UE) and pushing them to the public transport (SO), the remaining private vehicles reap the most benefit (significant reduction in their average travel time), at the expense of the public transport users being worse off abruptly. It is important to note that (according to Table 1 or Fig. 5) the total travel time of both the UE penetration of 80% is identical to that of 70%. Hence, one resolution to the fairness issue of the rate of 80% is to shift 10% more toward the SO modes (i.e., the rate of 70%).

Nevertheless, the sudden change or diversion seen at the UE penetration rate of 80% exhibits an unexpected chaotic behavior in the traffic flow, which has been observed and extensively studied in the literature [19,40,52]. This would highlight the complexity as well as the sensitivity of the traffic flow with respect to even minor twists.

4. An application of Ethereum Blockchain and smart contract in transportation

As noted above, limited mobility permits (say equivalent to the UE penetration rate of 70%) can be issued to the market tradable via a Blockchain platform and they can be exchanged and traded as well. The tradable mobility permits (TMPs) can

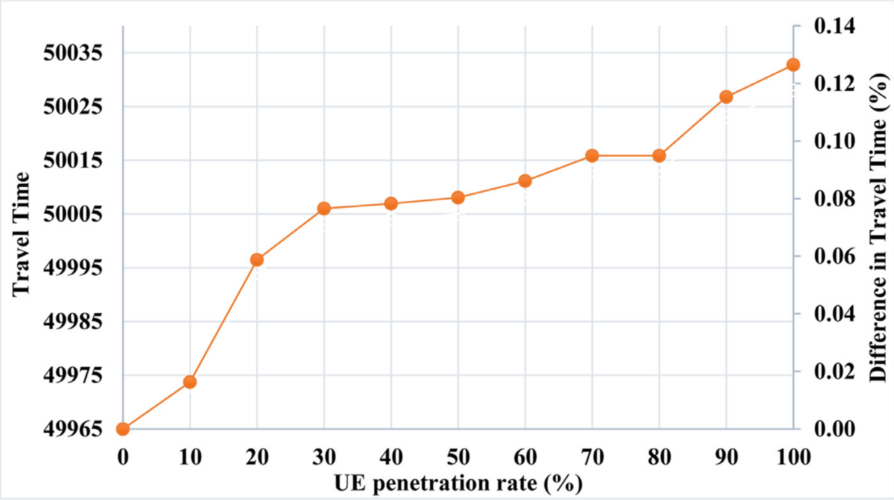

Fig. 5. Total travel time over various UE penetration rates.

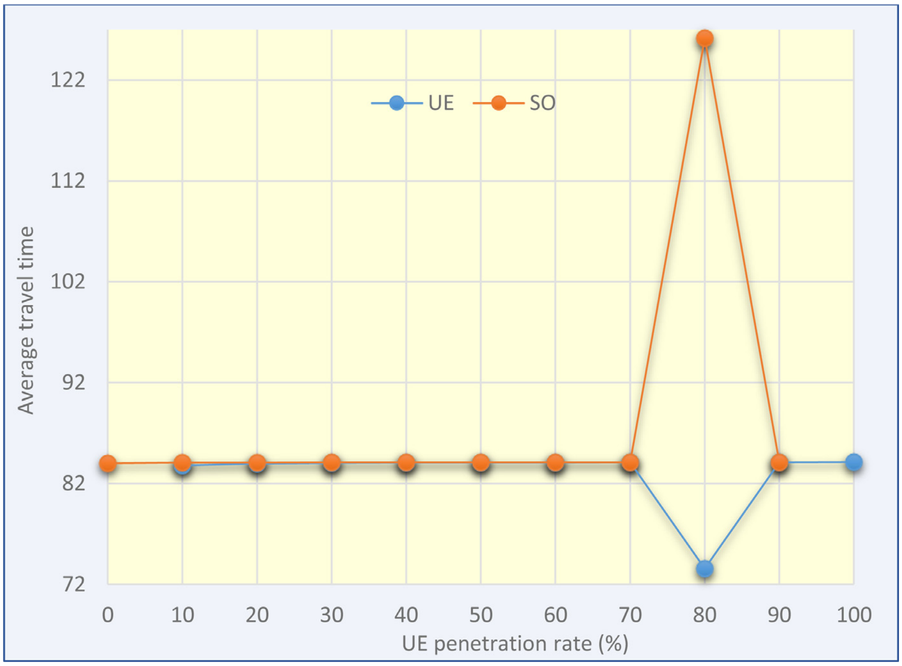

Fig. 6. Total travel time over various UE penetration rates.

also be regarded as credits to be used by both drivers and passengers for a variety of transport-related payments such as toll payment, parking fee, public transport ticket, car registration fee etc.

Pieces of such technologies already exist. For example, cash-less or mobile payment (making payment by cell phones) is becoming a norm, led by supermarket chains, shopping malls etc. [13,51,56]. In some jurisdictions, public transport passengers can pay using their mobile phone [56]. The Electric Toll Collection (ETC) is a well-established technology eliminating the delay on toll roads, by collecting tolls without cash and without requiring cars to stop [11].

Drivers and public transport passengers can save and spend their mobility credits on their mobile phones. Their credits can be programmed by an Ethereum-like Blockchain as a “smart contract” to be traded in the market and to be spent against their mileages and other payments. The concept of “smart contract” and “programming” as explained in the bidding example above, will put drivers and passenger at ease such that they do not need to bother about exchanging their credits or spending them. This will open the door to a variety of opportunities aiming to improve transport and traffic congestion.

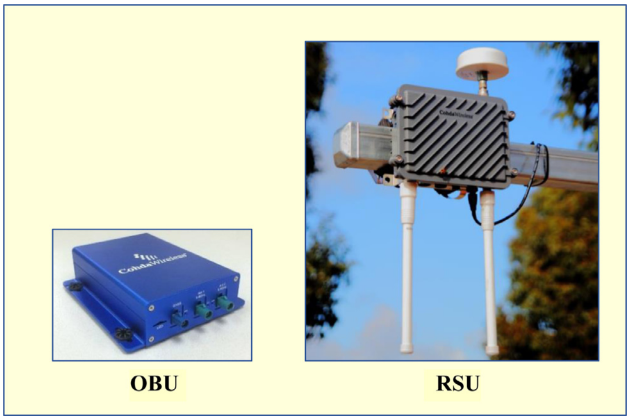

Fig. 7. Vehicles' on-board unit (OBU) and road-side unit (RSU) [24,67].

For instance, a dynamic toll-road system will become attainable, such that the toll prices can vary across the time to trim off the sharpness of the traffic congestion at the peak hour times.

Moreover, the mobility permits can also be traded en route, that is, cars can communicate with one another and place their bids for a faster route. This invokes the concept of the connected vehicle (CV) which is no longer a distant idea, as it is currently becoming a new norm and reality. It's estimated that more than 380 million connected cars will hit the roads by 2021 globally, which is a figure two time larger than that of the year 2017 [42]. The key component of a CV deployment is a small gadget called On-Board Unit (OBU) to be installed in vehicles which will not cost more than a few hundred dollars and the cost is projected to decrease in coming years [33]. The OBU makes vehicle-to-vehicle communication possible, based on which en route exchange of mobility permits will be conceivable. It is worth mentioning that everything about the en route permit exchanges can be done by already programmed smart contracts on an Ethereum-like Blockchain, without distracting drivers. This new opportunity unwinds a new toolbox in the hand of traffic authorities. For example, priority can be bestowed upon emergency vehicles by assigning a highly expensive price on the respective paths, that is, the other vehicles will instantly choose other alternative routes and leave the space empty to the emergency vehicles.

Moreover, the concept of the connected vehicle combined with the Blockchain technology can spur other revolutionary schemes. One example is to encourage or enforce platooning of the heavy-duty trucks, that is to line up several moving vehicles in tandem at the same speed to maintain traffic flow and reduce the chances of crashes [6,61,63]. Some studies have shown that saturation flow rates, and hence intersection capacity, can be doubled or tripled by platooning [32,36,37]. Platooning can result in reducing air drag or resistance and hence less fuel consumption [9,30,59] as high as 20%. Hence, this is a big opportunity for academia, governments, as well as freight companies and truck manufacturers to reduce fuel consumption [6,7,60]. To encourage the platooning, it is plausible to consider a positive credit associated with the leading truck to the extent the subsequent trucks will join the platoon to reap the credit. To detect the leading truck, like the OBU, the Road-Side Unit (RSU) installed at traffic signals, roadsides etc., enable the vehicles to communicate with the infrastructure as well (see Fig. 7). Hence, a constant stream of real-time data such as vehicles' position, speed, brake, acceleration, trajectory etc. can be collected.

The Blockchain technology can, in fact, facilitate the communication between vehicles and the infrastructure. Data being exchanged between connected vehicles and with the infrastructure can be regarded as transactions to be stored and retrieved from a Blockchain database.

One of the main concerns related to the safety of the traffic is the safety of the communication of the connected vehicle. There are several reports of researchers of people that managed to remotely access and hijack running vehicles through their connected applications [26,57,68]. To this end, the Blockchain as a tamper-proof database can be regarded as a solution [15].

Moreover, the Blockchain can offer a decentralized personal data management system that ensures that users own and control their data. It can be made possible via implementation of a protocol that turns a Blockchain into an automated access-control manager with no need of trusting in a third party [27,69]. This is an important property of Blockchain that can divert much of the monetary benefit of the data of the connected vehicles to the drivers. A snapshot of the applications of Blockchain in transportation and logistics is shown in Fig. 8.

5. Conclusion and future research directions

In this paper, we first provided an overview of the cryptocurrencies and the underlying technology (Blockchain) and its features, followed by Ethereum and the concept of the "smart contract". The widespread implications of Blockchain for soci-

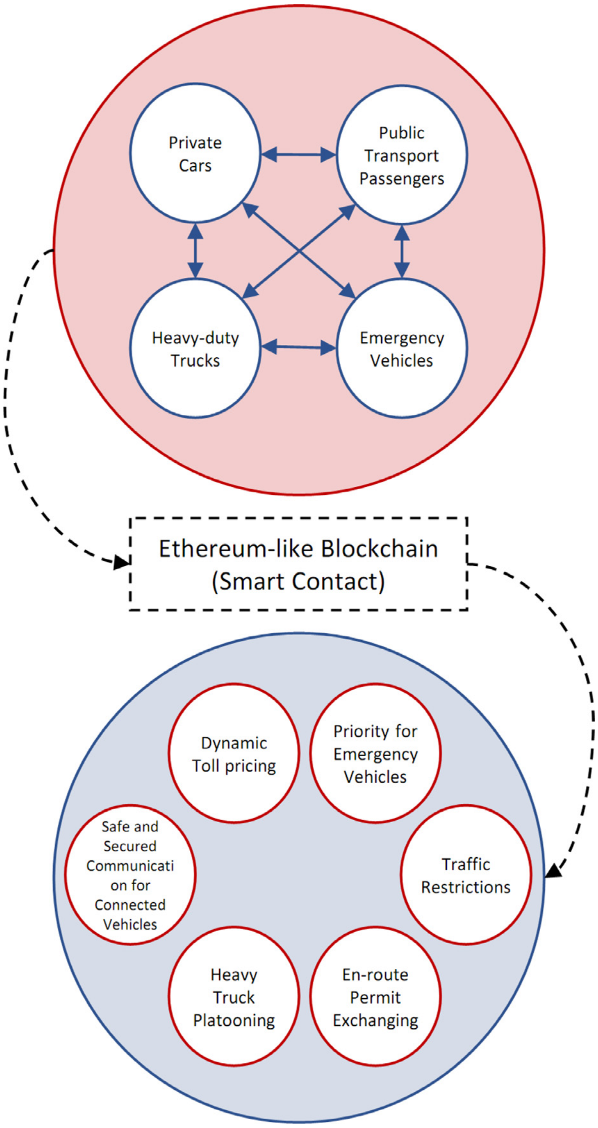

Fig. 8. An outline of Blockchain in transportation and logistics.

ety and economy were seen to be profound so that the paper's overall review of the topography of the Blockchain technology should be of interest to authorities, technologists, entrepreneurs, and economists seeking to gain a decent understanding of the cryptocurrency and Blockchain.

Equally, though within such a broad framework, it may be important to see how the potential and significance work out in specific cases. Within such a broad framework, it may be equally important to see the potential and significance of the technology in specific cases. To this end, the paper provides a mathematical model for a congestion pricing scheme, namely the "tradable mobility permit (TMP)" aiming to address traffic congestion in urban areas. Numerical analysis vindicates the effectiveness of the TMP to sand off the sharpness of the traffic congestion. We proposed a Blockchain-framework to deploy the TMP scheme based on the concept of the Ethereum's smart contract, which results in a smart transportation system. We then discussed the perks of such a smart system in applications such as dynamic toll pricing, priority for emergency vehicles, heavy truck platooning, as well as connected vehicles.

In collaboration with universities, tech companies, car manufacturers and governments several pilot studies dedicated for the connected vehicles are underway. This would provide a fertile ground to corroborate the applications of Blockchain in transportation and logistics. Further studies deem warranted to investigate possible technical challenges of Blockchain in the transport sector. One such hindrance is the size of the data and hence growing size of the Blockchain database, which could be of serious concerns in terms of both software and hardware to save, retrieve and process the data.

The Blockchain's promising features can be summarized as follows: (i) it can eradicate third party role in the transactions, (ii) no need for central authorities, (iii) it can address the data transparency issues, (iv) it would bring the cost of transactions down, (v) it would speed up the speed of transactions, and (vi) it can be a good solution for data security and privacy. On the other hand, the following challenges raise concerns: (i) data storage might be of concern, given the fact that the size of the ledger and data consistently would increase exponentially; (ii) Blockchain is a democracy-based technology in the sense that it is primarily made based on the consensus of users. Hence, it may be divided based on their preferences or opinion and result in many different versions of the original Blockchain, a phenomenon called forking. Therefore, forking can jeopardize integrity of the Blockchain, and (iii) to address the data storage issue, resorting to some sorts of centralization seems inevitable which goes against the very fabric of the Blockchain.

There are a number of threads for further research. The operational challenges of the tradable mobility permit (TMP) are unknown and it is a worthy subject for future research. A laboratory pilot study can be considered for investigating. Data storage of the TMP via Blockchain needs to be further scrutinized. It is important to highlight the fact that data associated with the TMP will be live (real-time). The trading part of the TMP is a complicated process, especially, considering fairness feature of the trading to include less-privileged people in the market. Given the size of the data, applications of the Big Data Analytic and machine learning [1] are deemed to be inevitable in future transport.

The main contributions of this paper can be summarized as follows: (i) the concept of the tradable mobility permit is formulated as "smart contract" to address traffic congestion; (ii) a numerical analysis of the proposed formulation is provided; and (iii) applications of smart contract and TMP have been discussed (e.g. dynamic toll pricing, priority for emergency vehicles, heavy truck platooning, as well as connected vehicles).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

GAMS code for UE-SO traffic flow - Sioux Falls network

```
$Title traffic Equilibrium
Scalar  PV/0.1/;
SET n NODE /1*24/;
ALIAS (i,n),(j,n),(K,n),(L,n);

SET
Dest1(j), Dest2(j) IDENTIFICATION OF DESTINATION NODES
Active1 (i,j,k), Active2 (i,j,k)  identifies the set of Active arcs
A1(n,n), A2(n,n) ARCS
PARAM/A, B, K/;

TABLE RoadDelay(i,j,PARAM) road delay data
               A        B         K
1.2            6       .90      25.9002
2.6            5       .75       4.9582
3.12           4       .60      23.4035
4.11           6       .90       4.9088
5.9            5       .75      10.0000
7.8            3       .45       7.8418
8.9           10      1.50       5.0502
9.10           3       .45      13.9158
10.15          6       .90      13.5120
10.17          8      1.20       4.9935
11.14          4       .60       4.8765
13.24          4       .60       5.0913
14.23          4       .60       4.9248
15.22          4       .60      10.3150
16.18          3       .45      19.6799
18.20          4       .60      23.4035
20.21          6       .90       5.0599
21.22          2       .30       5.2299
22.23          4       .60       5.0000
1.3            4       .60      23.4035
3.4            4       .60      17.1105
4.5            2       .30      17.7828
5.6            4       .60       4.9480
6.8            2       .30       4.8986
7.18           2       .30      23.4035
8.16           5       .75       5.0458
10.11          5       .75      10.0000
10.16          5       .75       5.1335
11.12          6       .90       4.9088
12.13          3       .45      25.9002
14.15          5       .75       5.1275
15.19          4       .60      15.6508
16.17          2       .30       5.2299
17.19          2       .30       4.8240
19.20          4       .60       5.0026
20.22          5       .75       5.0757
21.24          3       .45       4.8854
23.24          2       .30       5.0785;
RoadDelay(i,j,PARAM)$RoadDelay(j,i,PARAM) = RoadDelay(j,i,PARAM);

TABLE qfix(i, j) Trip matrix
      1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
1     0  1  1  5  2  3  5  8  5 13  5  2  5  3  5  5  4  1  3  3  1  4  3  1
2     1  0  1  2  1  4  2  4  2  6  2  1  3  1  1  4  2  0  1  1  0  1  0  0
3     1  1  0  2  1  3  1  2  1  3  3  2  1  1  1  2  1  0  0  0  0  1  1  0
4     5  2  2  0  5  4  4  7  7 12 14  6  6  5  5  8  5  1  2  3  2  4  5  2
5     2  1  1  5  0  2  2  5  8 10  5  2  2  1  2  5  2  0  1  1  1  2  1  0
6     3  4  3  4  2  0  4  8  4  8  4  2  2  1  2  9  5  1  2  3  1  2  1  1
7     5  2  1  4  2  4  0 10  6 19  5  7  4  2  5 14 10  2  4  5  2  5  2  1
8     8  4  2  7  5  8 10  0  8 16  8  6  6  4  6 22 14  3  7  9  4  5  3  2
9     5  2  1  7  8  4  6  8  0 28 14  6  6  6  9 14  9  2  4  6  3  7  5  2
10   13  6  3 12 10  8 19 16 28  0 40 20 19 21 40 44 39  7 18 25 12 26 18  8
11    5  2  3 14  5  4  5  8 14 40  0 14 10 16 14 14 10  1  4  6  4 11 13  6
12    2  1  2  6  2  2  7  6  6 20 14  0 13  7  7  7  6  2  3  4  3  7  7  5
13    5  3  1  6  2  2  4  6  6 19 10 13  0  6  7  6  5  1  3  6  6 13  8  8
14    3  1  1  5  1  1  2  4  6 21 16  7  6  0 13  7  7  1  3  5  4 12 11  4
15    5  1  1  5  2  2  5  6  9 40 14  7  7 13  0 12 15  2  8 11  8 26 10  4
16    5  4  2  8  5  9 14 22 14 44 14  7  6  7 12  0 28  5 13 16  6 12  5  3
17    4  2  1  5  2  5 10 14  9 39 10  6  5  7 15 28  0  6 17 17  6 17  6  3
18    1  0  0  1  0  1  2  3  2  7  1  2  1  1  2  5  6  0  3  4  1  3  1  0
19    3  1  0  2  1  2  4  7  4 18  4  3  3  3  8 13 17  3  0 12  4 12  3  1
20    3  1  0  3  1  3  5  9  6 25  6  4  6  5 11 16 17  4 12  0 12 24  7  4
21    1  0  0  2  1  1  2  4  3 12  4  3  6  4  8  6  6  1  4 12  0 18  7  5
22    4  1  1  4  2  2  5  5  7 26 11  7 13 12 26 12 17  3 12 24 18  0 21 11
23    3  0  1  5  1  1  2  3  5 18 13  7  8 11 10  5  6  1  3  7  7 21  0  7
24    1  0  0  2  0  1  1  2  2  8  6  5  8  4  4  3  3  0  1  4  5 11  7  0;
```

```
qfix(i,j)=qfix(i,j)*0.11*1.5;

PARAMETER cA(i,j),cB(i,j),cK(i,j);
cA(i,j)=RoadDelay(i,j,"A"); cB(i,j)=RoadDelay(i,j,"B"); cK(i,j)=RoadDelay(i,j,"K");

VARIABLES
Y1(i,j,K), Y2(i,j,K) FLOW TO K ALONG i-j
X1(i,j), X2(i,j) AGGREGATE FLOW ON ARC i-j
T1(i,j), T2(i,j) time to get from i to j;


* Identify roads using delay parameter:
A1(i,j)=YES$cA(i,j); A2(i,j)=YES$cA(i,j);

* Identify destination nodes using the trip table:
Dest1(j)=YES$SUM(i,qfix(i,j)); Dest2(j)=YES$SUM(i,qfix(i,j));

Active1(A1,k)=YES$Dest1(k); Active2(A2,k)=YES$Dest2(k);
Active1(i,j,i)=NO; Active2(i,j,i)=NO; Active1(i,i,j)=NO; Active2(i,i,j)=NO;

EQUATION
FlowBalance1(i,j), FlowBalance2(i,j) MATERIAL FlowBalance
Xdef1(i,j), Xdef2(i,j)  AGGREGATE FLOW DEFINITION
Rational1(i,j,k), Rational2(i,j,k) COST;

* Minimum travel time is set up here
Rational1(i,j,k)$Active1(i,j,k)..
cA(i,j)+cB(i,j)*POWER((X1(i,j)+X2(i,j))/cK(i,j),4)+T1(j,k)=G=T1(i,k);

Rational2(i,j,k)$Active2(i,j,k)..
cA(i,j)+cB(i,j)*POWER((X1(i,j)+X2(i,j))/cK(i,j),4)
+4*cB(i,j)*X2(i,j)/POWER(cK(i,j),4)*POWER((X1(i,j)+X2(i,j)),3)+T2(j,k)=G=T2(i,k);

* what goes into a node equals what goes out:
FlowBalance1(i,j)$T1.UP(i,j)..
SUM(K$Active1(i,k,j),Y1(i,k,j))=G=SUM(K$Active1(k,i,j),Y1(k,i,j))+qfix(i,j)*PV;
FlowBalance2(i,j)$T2.UP(i,j)..
SUM(K$Active2(i,k,j),Y2(i,k,j))=G=SUM(K$Active2(k,i,j),Y2(k,i,j))+qfix(i,j)*(1-PV);

* Flow on a given road constitutes flows to all destinations K:
Xdef1(A1)..X1(A1)=E=SUM(K$Active1(A1,K),Y1(A1,K));
Xdef2(A2)..X2(A2)=E=SUM(K$Active2(A2,K),Y2(A2,K));

* Initial levels for roads flows are needed so that we can properly evaluate
X1.L(A1)=cK(A1);X2.L(A2)=cK(A2);

* Lower bounds are zero for flows , positive for times :
Y1.LO(A1,K)=0; Y2.LO(A2,K)=0;
T1.L(i,j) =cA(i,j)$A1(i,j)+SMIN(K$A1(i,k),cA(i,k))$(NOT A1(i,j));
T2.L(i,j) =cA(i,j)$A2(i,j)+SMIN(K$A2(i,k),cA(i,k))$(NOT A2(i,j));

* Fixing values causes corresponding equilibrium conditions to be dropped:
T1.LO(i,j)=0; T2.LO(i,j)=0; T1.FX(i,i)=0; T2.FX(i,i)=0;
X1.FX(i,j)$(NOT A1(i,j))=0; X2.FX(i,j)$(NOT A2(i,j))=0;

MODEL TRAFFICMCP1 /Rational1.Y1, FlowBalance1.T1, Xdef1.X1,
                   Rational2.Y2, FlowBalance2.T2, Xdef2.X2/;

Option Domlim=999999;
Option solver=PATH;
*Option solver=MILES;
*$onecho > miles.opt
*itlimt = 1000
*$offecho
TRAFFICMCP1.optfile=1;
TRAFFICMCP1.ITERLIM=999999;
SOLVE TRAFFICMCP1 USING mcp;

parameter rep(i,j,*) summary report;
rep(i,j,'A ') =  cA(i,j);
rep(i,j,'B ') =  cB(i,j);
rep(i,j,'vol-UE ') =  X1.L(i,j);
rep(i,j,'vol-SO ') =  X2.L(i,j);
rep(i,j,'vol-Total ') = X1.L(i,j)+X2.L(i,j);
rep(i,j,'Cap ') =  cK(i,j);
display rep;
```

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