Mycomobility

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Mycomobility: Analysis of human transport through a mycorrhizal analogy

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ABSTRACT

The field of transportation research addresses the complexities of a particular sociotechnical system. Its usual focus is on human transportation systems, but non-human systems that effect transportation are also abundant in nature. This paper draws an analogy between modern human transportation systems and mycorrhizal networks (MN), the underground networks formed by fungi and plants for resource transportation. By examining MN, the study aims to extract insights applicable to human transport and to explore potential reciprocal learnings about natural systems. The research emphasizes an interdisciplinary approach that acknowledges both the technical and social dimensions of transport. The primary focus is to propose improvements to human transportation by learning from the natural efficiency of MN, thereby fostering a more holistic understanding and implementation of transport solutions.

1. Introduction

The field of transportation research deals with an ever-expanding and ever-actualizing sociotechnical system. The system of modern transport is also the result of an inherently historical process necessitated and inextricably intertwined with what we refer to as civilization. The system is by all means complex, not yielding itself to being understood reductively through deconstruction into parts. Over the ages, the means of transport and the resulting infrastructure have shaped the very face of the Earth, and they continue to determine the future possibilities of individual becomings. To understand this huge beast, we turn to nature, hypothesizing that evolution might already have provided hints as to how best effect transport. However, aware of the already existing work and considering man as a part of nature, we hope that discoveries made in transportation research might also contribute to our understanding of nature.

Drawing analogies between humanity's techniques and nature is not new and has been done for transport and mold (Tero et al., 2010), and for cities and circulatory systems (Cooley, 1894), or metabolism (Swyngedouw, 2013; Capel-Timms et al., 2024), to name a few examples. These analogies have been shown to have significant potential in improving human-made systems (Helbing et al., 2009). We continue in this tradition and propose an analogy between mycorrhizal networks (MN)[1] and human transport systems. The aim of this analogy will be twofold.

1. What can we learn about transport if we look to nature?
2. What can we learn about nature if we look to transport?

The first question is easier to answer directly and we will make it the main focus of this work. The second question is more challenging, and we will allude to it and identify potential directions of further research regarding it. However, we will not give a full answer to either one. Instead, the aim of this work is to approach these questions using a concrete example of MN. Our work is intended to spark more interest in these lines of thought and propose specific improvements to human transportation systems based on the analogy with MN.

2. Transport

Definition 1. Transport is the directional displacement of matter.

Fundamentally, transport is the procedure that displaces material objects from one location to another. However, this procedure has become increasingly complex and, in the context of human beings, inextricably linked to the social sphere. Nevertheless, transport phenomena, as defined above, can be understood to be initiated by non-humans as well (ants, bees, trees, etc.). Furthermore, transport may occur across a variety of scales, as much on the human scale as on the cellular scale (transport of blood, nutrients, neurotransmitters and so on across the body).

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[1] Mycorrhizal networks are networks where fungi and plants form a joint underground network which is used to transport resources.

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By directional, we mean that transport is a displacement that has a direction, a spatial goal determined *a priori*. This is in contrast to displacement that occurs without a goal of reaching a given point in space.[2] Thus, transport as simple displacement must be inherently teleological in that it only exists in terms of its goal and does not arise at all without it. It is worth pointing out that transport predates humans and is a fundamental property of life (cellular pumps, etc.). Transport of humans specifically is not interchangeable, meaning that the aim of one specific human being is to get from one place to another, and this particular human cannot be replaced with another human, even if their destination is the same. This differs from the transport of goods, where a given good, if identical, can be replaced by another.

Furthermore, in the context of human endeavors, transport becomes a social phenomenon. Habitual behavior, social norms, and individual preferences affect the structure and development of the transport system. While the created transport systems are certainly shaped by society, it is becoming more and more apparent that these systems also shape the society itself (Lyons, 2004). The simplest metrics by which transport can be judged are speed and cheapness (Cooley, 1894), but its social effects and numerous externalities escape encapsulation in such simple measures.

We choose to define transport in such a manner as to restrict and focus our considerations. We do admit that alternative definitions are certainly possible and it can be useful to consider them at different times. By referring to directionality and through it introducing an implicit assumption of agency, our definition consciously excludes ay physical processes such as, for instance, chemical reactions, where ions are exchanged. Similarly, by referring specifically to matter, our definition excludes the transfer of immaterial objects, for instance, abstract information. That is not to say that these processes could never be considered in the same categories as human transport. It is simply that, we believe, a more restrictive definition empowers our analogy.

In this work, when we refer to transport we will mean one of two things (which we hope will be clear from context). One meaning is the abstract concept of transport as defined in this section, and more concretely a grounding of that abstract concept to a particular socio-historical system. In the second meaning, we will distinguish two distinct systems: the modern human transportation system and the modern plant-fungi transportation system.

2.1. Two questions of transport

Thus, in order to understand what transport is, we propose two questions that are implied by the definition.

1. What is being transported? (matter)
2. How is it being transported? (modalities)

Regarding the first question, the things that can be transported do not constitute a closed list — it can always be expanded. However, for the purpose of this work, we will specify two objects of transport of key relevance in the modern society — humans and resources.

The second question investigates the particular technique through which a given object is transported. In the human context, there are several modalities of transport that serve different purposes and have different specifications. They can be loosely introduced in a historical progression: walking, animal-powered modes (carts, chariots, horse riding, etc.), human-powered (bikes, skateboards, etc.) and engine-powered (e.g. cars, trains, airplanes). The evolution of transport modalities is clearly associated with the increase in the distances traveled in time – speed.

[2] In many modes of physical activity humans engage in displacement without the intention of reaching a certain point in space. A surfer displaces themselves along the wave, an aimless wanderer throughout the landscape but their goal is not to go anywhere in particular (Debord, 1998).

2.2. Challenges

Being a complex system that involves both questions of technical and social nature, transport is notoriously challenging to research and design. The social aspects of transport can be best understood and addressed by the social sciences. On the other hand, the technical aspects fall into the domain of engineering and physics. Thus, an interdisciplinary approach is necessary in order to study transport at its full breadth.

Technical approaches can gravitate towards proposing solutions that seek to optimize certain metrics (common metrics to be optimized in traffic engineering include travel times, emissions, wait times (Korecki, 2022, 2023)). Although such an approach is admissible in many cases when dealing with abstract models, it often fails (and/or leads to unforeseen externalities (Korecki et al., 2023a)) in the context of complex social systems (Carissimo and Korecki, 2024). Therefore, it is up to the social sciences to scrutinize these methods and ensure that the human component and perspective are included in the technical process that seeks to improve or design certain transport solutions.

It is the aim of this work to investigate another system that effects similar functions as the human transport system. By indicating the analogies between the two systems, we hope to provide foundations for imagining and actualizing a more holistic system that accounts for the inherent complexity of the transport problem in ways that satisfy both the technical as well as social circumstances.

3. Human transport system

3.1. Mobility

A good conceptual starting point for understanding transport is the circle suggested by Wegener (2004). It shows that the location of housing and settlements is closely related to the need for transport. People want to travel to their work and to visit other people. Within transport, the four-step model, dating back to the 1950s, is most common to describe the actions of people (McNally, 2007). The steps include: (1) trip generation (how many will travel), (2) trip distribution (where will they travel), (3) mode choice (that is, choice for car, public transport, bicycle), and (4) traffic assignment (routes). Note that steps 1 and 2 indicate a so-called origin destination matrix, or OD matrix, where, based on the non-interchangability of people, the terms in different directions do not cancel out. There could be feedback effects from later stages to earlier stages. So, if routes become congested (Step 4), that might lead to a different choice of mode in Step 3, or a different destination choice in step 2, or even the choice not to travel in step 1.

Networks are designed and developed to accommodate traffic. Note that we typically have hierarchical networks. This holds for roads (e.g., highways, national roads, local roads), as well as for public transport systems (e.g., trains, metro, bus). The study of the structural properties and functional performance of road networks is one of the key interests in transportation science (Reza et al., 2024). The same interest has been shown for metro networks (Derrible and Kennedy, 2010) and even air networks (Wandelt et al., 2025).

Connecting from and to various network levels could result in multi-modal trips (e.g. a car to a train station). In multi-modal traffic hubs might play a role. Where previously a mode was chosen for a full trip, now car parks can be created near train stations or near highway entrances, so that drivers can change mode (from their own car to a train or carpooling with someone else). In public transport, and especially in aviation, these hubs are even more common, with passengers flowing to a larger station where they change to another vehicle.

3.2. Supply chains

Supply chains can be understood as networks of organizations connected both downstream and upstream that engage in different processes that generate value in the form of products (Christopher, 2022). Since their formalization in the early twentieth century and subsequent research into them, supply chains have been evolving and adapting, taking various forms and incorporating different transport systems in their management (Shukla et al., 2011). Although research into supply chains involves the study of both production processes and the transportation processes involved in delivering the products to customers, in this work, we will focus on the latter topic.

The structure of the supply chain influences the transport capabilities, which can be categorized as time compression, reliability, standardization, just-in-time delivery, support for information systems, flexibility and customization (Morash and Clinton, 1997). The potential disruption of transportation networks has significant effects on supply chains and increasing the resilience of transportation networks and thus supply chains continues to be a topic of great interest (Wilson, 2007; Korecki et al., 2023b). The supply chains, much like mobility systems, also rely on hubs and might engage a variety of transport modalities.

4. Plant-fungi transport system

According to the definition of transport we have proposed, it is a phenomenon that is not strictly limited to humans. In fact, other organisms also engage in transport. Social insects like bees and ants are clear examples, transporting food back to their colonies. But perhaps surprisingly transport can also be found in plants and fungi, organisms that traditionally are perceived as immobile. This transport can occur at different scales and is made possible in a variety of ways. We will first discuss the transport that occurs within vascular plants and then extend it to include transport between distinct plants.

4.1. Land plants

Xylem and Phloem are the two types of transport tissue that are present in vascular plants:

- xylem – mostly composed of dead cells, passive transport of sap – mainly water and inorganic ions but also possibly organic chemicals. The difficulty of passively transporting water upwards might be a limiting factor for how tall trees can grow. Xylem transports material from roots to leaves and throughout the plant. Movement in the xylem is only possible upwards (McElrone et al., 2013).
- phloem — living cells, transports sap rich in photosynthesized sugars (also amino acids, phytohormones and mRNA), transported to non-photosynthetic parts of plant roots or bulbs and tubers. Movement is multidirectional. Sugars are transported from sources to sinks. Source to phloem and phloem to sink are effected by active transport (though the movement through the phloem is passive). The flow pattern changes as the plant develops as the translocation is usually attempted from the source to the closest sink (Boundless, 2021).

4.2. Mycorrhizal networks (MN)

A mycorrhizal network is formed by fungi and plants. The basic infrastructure of the network is the connection between the hyphae of a fungi and the roots of a plant. The inter-species relation thus established is predominantly a form of mutualism, where both parties benefit. A given plant can connect to multiple fungi and a given fungus can connect to multiple plants (in both cases, distinct species may be involved).

The mycorrhizal networks can be classified based on the way in which the contact between the fungi and plants occurs:

- Ectomycorrhiza – do not penetrate cell wall but form intercellular interface – Hartig net.
- Endomycorrhiza — penetrate the cell wall and invaginate the cell membrane.
  - Orchid mycorrhiza — critically important during orchid germination, as an orchid seed has virtually no energy reserve and obtains its carbon from the fungal symbiont.
  - Ericoid mycorrhiza — penetrate the cell wall but not the plasma membrane.
  - Arbuscular mycorrhiza (AMF) - penetrates the cortical cells of the roots, are characterized by the formation of unique tree-like structures, the arbuscules. Found in 80% of vascular plant families in existence.

The underground mycorrhizal networks are highways through which plants and fungi exchange elements and carbon complexes. Well-functioning and healthy networks have been associated with increased resilience of the forest environment, and they seemingly allow for an emergence of a diverse inter-species economy-like system (Simard and Durall, 2004; Simard et al., 2012).

Certain species of plants that are related to specific AMF taxa can affect the composition of the AMF community (Montesinos-Navarro et al., 2012). Similarly, AMFs can have a bottom-up influence on the diversity of the plant community (Montesinos-Navarro et al., 2012).

Let us start by applying the two questions posed for transport (Section 2.1) to mycorrhizal networks. What is being transported in the networks is, among others, carbon (Graves et al., 1997), nitrogen (He et al., 2003), and phosphorus (Whiteside et al., 2019). Moreover, networks have been suggested to also facilitate the transport of plant signaling compounds that can, for example, facilitate a defense response (Gilbert and Johnson, 2017). The transport is effected by the given fungus that constitutes the particular network. A given plant can be in a relationship with more than one fungus, thus connecting it to more than one network.

4.2.1. Ecological network theory

In recent years, network theory has been employed by biologists to better understand the emergent structure of the MN. Typically, plants and fungi are represented as nodes in the network, while connections represent interactions between them. Two metrics have been of particular interest: nestedness and modularity. Nestedness is a measure of the structure in the system and of the character of species-species interactions. Nestedness is high, for instance, in cases where a specialist interacts with a subset of partners that a generalist would interact with. Modularity, on the other hand, measures the strength of division of the network into partitions. A network with high modularity would have dense connections within partitions, but sparse connections between the partitions themselves.

Modularity is expected and found to be high in MN, as during the community emergence the MN associated to different plant species may differentiate over time, resulting in a network with distinct modules (Davison et al., 2011; Chagnon et al., 2012). Furthermore, some fungi taxa specialize only for a few plant species and thus create modules by default (Chagnon et al., 2012).

Nestedness, on the other hand, in the context of MN is less clear. The level of nestedness is expected to be high in mutalistic networks (Fontaine et al., 2011). And indeed some studies do detect some level of nestedness in the plant-fungal interactions (Öpik, 2012). Moreover, MNs have been shown to be scale-free networks (Simard et al., 2012).

However, another study detects strong anti-nested architecture in many (not all) MN in forest environments. The authors hypothesize that the anti-nestedness might highlight the diversity of the network.

Table 1
Systematic comparison of the components of the human and the plant-fungi transport system.

	Human transport system	Mycorrhizal transport system
Transported Object	Humans, Commodities	Elements, Compounds, Hormones
Medium (infrastructure)	Roads, Train-tracks, Paths	Fungi, Plant Cells
Modalities	Land, Maritime, Aviation	Xylem, Phloem, Fungi-facilitated (MN)
Interface	Hubs (e.g. Train stations, Airports)	Arbuscule

They also claim that competition for host plants could decrease nestedness (Toju et al., 2014, 2018a). Moreover, some of the plant-fungus interactions are found to have not only positive but also negative effects. The diversity of interaction can be responsible for increasing the stability of communities. This is due to the fact that a moderate mixture of antagonistic and mutalistic interactions may have a stabilizing effect on population dynamics (Mougi and Kondoh, 2012). The high nestedness can negatively affect the stability (Allesina and Tang, 2012).

5. Analogies

As we have already stated, plant-fungi and human transportation systems are analogous on multiple levels. First and foremost, both systems are involved in displacing matter over distance. This is the essential similarity — the proper functioning of both of these systems fulfills the same general aim. Beyond this functional affinity, there are further parallels in how this shared aim is achieved. In this section, we will elucidate and discuss the specific analogies between these two systems (see Table 1).

5.1. Origin — Destination

A common way to study both the traffic and the supply chains is to consider origin–destination matrices, which specify the origin and destination of each vehicle or commodity in the system. The same reasoning can be applied to MN, where, for example, carbon originating in a particular tree can travel from that tree, via the body of the fungi forming MN, to another tree (Deslippe and Simard, 2011).

In the case of supply chains, the origin and destination of certain commodities will be determined by factors such as resource distribution as certain resources are only present in specific locations. If a given commodity is in demand in locations where it is lacking, we can reasonably expect that it will be moved from the origin that is rich in it to that destination. This hints at the inseparability of transport and factors of geography, economy, and society that we will discuss in more detail further on. Interestingly, similar patterns of transport between rich origins and poor destinations have been identified within MN (Whiteside et al., 2019).

5.2. Character affected by physical conditions

While the dynamics of transport through the MN might be affected by factors such as resource inequality, the species of organisms that constitute the network seems to be affected by conditions such as soil and landscape gradients (Jansa et al., 2014). This corresponds to the physical factors that affect the human transport networks. It is enough to compare the shape of a mountain road and one that goes through flatlands to notice the impact of geography on the topology of the transport network. Some terrains make it impossible to build roads, and at the very least most need to be significantly transformed to allow for construction (forests need to be cut, hills flattened). Similar factors influence MN, as certain fungi will not grow in certain types of soil and terrain (Jansa et al., 2014). Moreover, at least some transport networks are, much like the MN, scale-free (Wu et al., 2004).

5.3. Modalities

In the modern transportation system, there is a multiplicity of distinct modalities. Both people and goods are moved via a variety of modes, each with its own dedicated infrastructure. The most common modalities are land (road, train, cycling, walking), maritime, and aviation. Especially in urban areas, it is common for an individual or a certain commodity to switch between a few modalities. For example, cycling to a train station, taking a train to another city and then taking a bus to reach one's final destination.

In the context of the transportation systems of the land plants, distinct modalities can also be identified. The phloem and xylem serve as the internal transportation systems within a given plant, whereas the MN connects multiple plants together. In addition, a plant is also capable of releasing elements directly into the soil, which can then potentially reach other plants. As such, xylem and phloem could be compared to urban transport systems that connect the neighborhoods of a given city. The MN, on the other hand, could be compared to intercity transport (e.g. trains). The direct release of elements into the soil, being very rudimentary and having little guarantee that the elements reach their destination (Kaiser et al., 2015), could perhaps be linked to walking — the most basic way of transport available to humans.

Comparing the two modes of inter-plant transport we note that the MN provides a way of transferring resources that is less prone to disruptions (e.g. competition with soil microbes, fauna, physical disturbances of the soil) when compared to the direct release into the soil (Deslippe and Simard, 2011). As such, from the perspective of plants, the ability to transport elements over large distances in a targeted way is enabled by engaging in a symbiotic relationship with another species. Furthermore, the mutualistic relationship increases the resilience of the said transport.

5.4. Terminals and hubs

The presence of a variety of modalities necessitates the emergence of terminals and hubs, where people or goods traveling in one mode are able to switch to another mode. Many central stations and airports all over the world are such hubs, where trains, roads, and air modalities meet.

The interface between the given plant's roots and fungi acts like a terminal, where the transport modalities serving within the plant (phloem, xylem) connect with the MN — the inter-plant modality.

From the perspective of fungi, such organisms that connect to many plants (including different species) will serve as a hub, transferring a range of elements to a high number of destinations (Toju et al., 2018b). Alternatively, from the perspective of the plants, such plants that connect to many fungi will serve as hubs. Large and mature trees have been shown to act as network hubs with a significantly higher degree of nodes compared to younger trees (Beiler et al., 2015). This appears analogous to the older and larger cities serving as hubs for their countries.

5.5. Competition

Much of the current transportation system has been developed within capitalist economies. Thus, it has been shaped and continues to be shaped by market forces such as competition. This dimension of the transportation system (hinting again at the inseparability of transport and economy) has rarely been captured by biological analogies. The unique characteristic of the MN system, as we view it here, is that it involves a variety of distinct organisms, unlike some previous similar work that usually focused on single species (Tero et al., 2010). Different species of fungi connect to different trees and compete with each other for resources and space. These different species could be seen as mirroring different providers of transport solutions (e.g. car manufacturers or airlines) that might compete for customers, just as the fungi compete for access to particular plants.

5.6. Economy of transport

As we have already hinted, it appears that transport is inseparable from a certain notion of economy. In human societies, supply chains are predominantly driven by economic considerations. Similarly, transport networks are built and developed in relation to the economic development of the region where they are located.

The same is true for biological networks such as the MN. Indeed, the mutualistic interactions between plants and fungi appear to be established using mechanisms similar to those known in the economy, leading to a research direction known as the biological market theory (Wyatt et al., 2014). It has been shown that both plants and fungi can modulate the amount of elements that are exchanged (Wipf et al., 2019). A bidirectional control mechanism is established and used to maintain fair levels of exchange for both parties (Kiers et al., 2011). Moreover, fungi can also control the value of phosphorus based on its availability (Van't Padje et al., 2021).

6. Differences

In the previous section, we have established the analogies between human and plant transportation systems. The similarities are multi-dimensional and go beyond the simple sharing of function. Both systems move objects from origin to destination according to gradients that usually go from higher to lower concentration. We can also identify distinct modalities that can be switched between via terminals and hubs. Finally, both systems are inextricably linked with an economic system that is to a significant extent driven by competition.

We believe that the similarity between these systems is high enough to allow us to use one to understand the other. However, since at their core these systems share so much, any differences between them become especially meaningful. By identifying the areas in which the characters of these systems diverge, we can learn more about their potential and perhaps inspire novel design ideas. Let us then highlight the most striking differences between the plant and human transportation systems.

6.1. Autopoietic infrastructure

A significant difference between the two systems is the nature of the infrastructure that enables transport. The MN, which we identified as the main infrastructure for inter-plant transport, is itself a living organism. As a living organism, the MN is autopoietic, that is, it is able to produce itself and maintain its own structure. This might be seen as contrasting with the infrastructure that makes up human transport systems. Roads, train tracks, walking and cycling paths are all designed and maintained externally by humans.[3] This perspective would make the human infrastructure more similar to that of the MN. Nevertheless, even then one would need to consider that the human transport itself would not occur within a living body. They have no agency of their own, no ability to repair themselves or maintain their structure. In fact, they are extremely prone to entropy and deterioration necessitating constant expenditure of energy for their maintenance.

6.2. (De)centralization and self-organization

Most of the infrastructure that constitutes the human transport system is designed and planned in a centralized manner. Since building roads, tracks, and paths is often a costly endeavor that requires foresight and research it is usually conducted in a top-down manner. In many places in the world different levels of governance (more and less direct) are also involved in the planning and design process. On the other hand, in the case of the plant transport system, the MN emerges spontaneously and self-organizes into connecting plants and forming hubs. The process is not planned, as the fungi are unlikely to have prior knowledge of the location of the plants and soil conditions in the entire area that it will eventually cover.

6.3. Mutualism

The MN is based on the principles of symbiosis and mutalism. Thus, the plant transport infrastructure serves not only more than one species of plant but also organisms spanning more than one kingdom. It is beneficial for the fungi to form MN that then provides useful services for the plants. The human transport, however, serves only humans and not all of them at that (transport-related social exclusion). As a matter of fact much of human transport is actively detrimental to other life forms. Moreover, the MN develops through natural selection, while human infrastructure is developed through an iterative engineering process. These two processes occur at different time scales, allowing humans to modify their infrastructure frequently and draw inspiration from natural processes.

6.4. Impact

While the infrastructure formed by MN is an integral, mutually beneficial part of the natural environment, human infrastructure more often than not has a significantly negative impact on natural environments. In order to build roads and tracks, forests are cut and natural landscapes are modified, removing habitats and leading to species die-offs. The emissions of mechanized forms of transport are also actively harmful to biological life, human and animal alike. The growing urbanization driven by the development of transport infrastructure further threatens natural environments.

Such antagonistic relationships or imbalances dangerous to the local environment are also found in natural systems. Nevertheless, the MN proves that a different mutualistic way is also possible. A question emerges here, namely: which of these two contrasting modes of interaction should the human transport system embody in its design?

7. Discussion

In this work, we have established and argued for an analogy between the transport systems that are designed by humans and those that have evolved in nature with a specific focus on the interactions between plants and fungi. The similarities between the systems allow us to employ the same reasoning to both of them, and the conclusions drawn about one may readily apply to the other. Beyond the analogies, we have also pointed out the differences between these systems with an interest to identify areas in which the human transportation system could be improved by learning from the way transport is organized in nature. Here, we wish to indicate specific directions for improvement inspired by the MN.

[3] On the other hand, it is also conceivable to see humans as integral, living part of the infrastructure in as much as they maintain it and ensure its proper functioning (similarly to how the spider produces and maintains its web).

7.1. Recommendations

One potential direction for improving the transportation system based on inspiration from nature would be to revolutionize the way infrastructure is developed and maintained. While creating an *autopoietic infrastructure* seems, at the current point in time, highly unlikely, it is still possible to work towards making it less difficult to maintain and less detrimental to the environment. The already present notions of ecologically friendly solutions (e.g. bridges under highways allowing animals to migrate) could be seen as part of the effort of making the infrastructure more attuned with the ecosystem. The recent advances in material science and the introduction of self-healing materials (Tabaković and Schlangen, 2016), which can be used for bitumen (Shu et al., 2019), could result in roads that are more resilient, ecological, and less prone to deterioration (Rodríguez-Alloza et al., 2019). Another novel material offers to sequester carbon dioxide through inclusion of photosynthetic organism colonies in its structure (Dranseike et al., 2025). Moreover, self-powered sensors may soon replace centrally powered sensors in applications such as traffic signal control and other civil infrastructure (Salehi et al., 2021). All of these advances could be seen as steps towards autopoietic infrastructure.

Another direction could be developing more decentralized and democratic decision-making solutions with respect to transportation policies (Helbing et al., 2023). For instance, one could argue that people who are more affected by the noise and pollution generated by given modalities (e.g., people living next to a hub) should have a direct say in how the transport system is managed in their neighborhood (Korecki et al., 2024). On the other hand, democratization might come at a premium as it risks increasing the complexity of the decision-making process. Similarly, decentralization might introduce the risk of inefficiencies between separately managed parts of the transport system. Thus, introducing these principles into the present infrastructure requires a thorough analysis. Gradual approaches are likely to be less risky.

Since MN works for a variety of distinct species and organisms from more than one kingdom, one could argue that the human transport system could also be designed with other beings in mind. This would be consistent with modern ecologically oriented approaches. A historical precedent for a transport system that includes both humans and other species could be animal-based transport, such as horse riding and animal-powered carriages. However, in these cases, the relationship between the two species appears more parasitic than symbiotic since the benefit to the work animals is questionable at best. Nevertheless, one could perhaps imagine a similar transport system that relies on animals but does not overburden them and benefits them via food and shelter. Such a system would necessitate novel ethical frameworks that would be capable of ensuring that the involved species are treated fairly, that the relationship is mutually beneficial and does not devolve towards parasitism.

Furthermore, more attention could be given to accounting for and minimizing the disruptive effects transport infrastructure might have on non-human animals. Train tracks and highways might split habitats and disrupt migration routes. Moreover, accidents involving animals are a problem for both the animals themselves and the efficient functioning of transport systems. Existing methods aimed at developing transport systems that take into account other non-human animals involve building passages for animals and deploying devices that can deter them from approaching dangerous areas (Kossak, 2005; Babińska-Werka et al., 2015).

We noted that the plant and MN transport is often based on naturally occurring concentration or pressure gradients (as in the case of the passive transport in xylem for instance). This approach, of using the already existing natural forces for effecting transport, could also be used to improve human transport.[4] Historically, these types of passive approach were highly popular and included wind-powered sailing ships and timber rafting. Nowadays, however, the focus is on mechanized transport that expands large amounts of energy and emissions. Perhaps, the transport system of the future could be oriented to incorporate more passive modes. In order not to decrease the efficiency of the transport system as a whole, passive modes could be introduced first as parallel alternatives and not replacement. This would increase the number of available modalities and reduce the overcrowding of existing ones. Since these modes would likely be slower than the active, energy-consuming modes, they would not be able to serve all purposes. In practice, such ‘passivization’ might involve an increased focus on walkability in urban contexts (common in e.g. Europe but less so in the USA). In addition, in certain regions (e.g. the Netherlands), the existing water infrastructure is vast and could allow efficient and relatively passive transport to occur that could serve as an alternative to terrestrial modes.

MN-based transport, which is based on a mutualistic relationship, leads to a setting with high levels of perceived altruism (richer patches moving resources to poorer ones (Whiteside et al., 2019)). Thus, perhaps an insight for the human transport system could also be along the lines of increasing its ‘altruism’. A concrete example of that could be the introduction of free public transport policies in densely populated areas (Cats et al., 2017) for the entire population or specific groups. Such a move necessarily carries with it economic consequences. For one, the financing of public transport needs to transition from a fare-based model to an alternative one (e.g. one based on the parking and/or road use fees paid by private vehicle users). This can cause both political and economic disruption as the local government struggles to maintain the quality of service at a drastically reduced budget. Nevertheless, certain case studies suggest that such projects can be at least partially successful (Tuisk and Prause, 2018). A gradual introduction of such an approach or a less costly form could extend free transport to specific groups only (students, less privileged members of society, etc.).

8. Conclusions

Our discussion has indicated ways in which the human transport system can be made more alike the MNs. This involves deepening the similarities between these two systems as well as diminishing the differences. At the same time it remains the case that effecting a fundamental change to a system as complex as human transport is fraught with many difficulties. The sheer inertia of this socio-technical system and the scale of its infrastructure tempers wishfully thoughtful attempts at revolution. Thus, we have presented our recommendations considerate of ways in which they could be gradually introduced (evolved rather than revolutionized). Our work has also served to highlight the potential value of re-contextualizing biological concepts such as mutualism, symbiosis and altruism in the domain of transport.

Lastly, we have also suggested that the insights from human transport research could be applied to better understand MN and plant transport. We hypothesize that knowledge of road networks could perhaps be used to predict the topology and characteristics of the MNs, which are notoriously hard to map. The first step towards this goal would be first a quantitative comparison between road networks and known MNs to establish if there are indeed similarities in the networks’ structure. Furthermore, transportation research has been highly successful in applying and integrating modeling and simulation technologies (e.g. multi-agent simulations of urban traffic (Korecki, 2023)). These same approaches could prove highly valuable in the context of MN studies.

[4] Similarly, some roads in America (e.g., in Southern Appalachia) were laid out following natural trails established by cattle or other animals. Especially in the context of mountain roads, following the footsteps of animals helped to select optimal paths.

CRediT authorship contribution statement

Marcin Korecki: Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization. **Victor L. Knoop:** Writing – original draft. **Serge Hoogendoorn:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition.

Declaration of Generative AI and AI-assisted technologies in the writing process

No AI was used for any part of the work related to this manuscript.

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Declaration of competing interest

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Data availability

No data was used for the research described in the article.

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