Dynamic Coordination in Fleet Management Systems: Towards Smart Cyber Fleets [*]

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Abstract. Fleet Management Systems are commonly used to coordinate mobility and delivery services in a broad variety of domains. However, their traditional top-down control architecture becomes a bottleneck in open and dynamic environments, where scalability, proactiveness, and autonomy are becoming key factors for their success. In this paper, we first present an abstract event-based architecture for Fleet Management Systems that supports tailoring dynamic control regimes for coordinating fleet vehicles, and illustrate it for the case of medical emergency management. Then, we go one step ahead in the transition towards automatic or driverless fleets, by conceiving Fleet Management Systems in terms of Cyber-Physical Systems, and putting forward the notion of *Cyber Fleets*. We illustrate the idea in the field of electro mobility, where we expect drivers of smart e-motorbikes (*Cyber Vehicles*), equipped with an intelligent communication device (*Cyber Helmet*), to coordinate in a context-aware manner as part of a decentralised Fleet Management System.

1. Introduction

Fleet Management System (FMS) is a term used for a wide range of solutions for different vehicle fleet-related applications in the fields of transportation, distribution and logistics. It comprises target-based planning, as well as supervision and control of fleet operations based on the available transportation resources and application constraints. FMSs have as objective to reduce risk, increase quality of service, and improve a fleet's operational efficiency while minimizing its costs [21].

A key problem in FMS operations is *fleet route planning*, where different transport orders need to be aggregated into tours of fleet vehicles, so that the resulting schedule is both efficient and robust while meeting the constraints put forward in the customers' requests. The main challenges at tactical level are to support decision-making based on seasonality, trends, changing customer mix and demand. At operational and real-time level, the challenge is to respond to daily dynamics, such as traffic, weather, employee absence, equipment breakdown, new coming orders and order adjustments.

Approaches to fleet planning typically focus on the development of near-optimal plans using various types of effective vehicle routing algorithms, which can be either static or dynamic (e.g., [15, 16, 20]). Fleet schedules designed a priori with *static route planning* assume the following: all relevant data is known before the planning starts, the short and long term decisions have the same importance, and the time available for creation, verification, and implementation of route plans is of minor importance. The use of an initial fleet schedule, although necessary, is by no means sufficient since it may not cope adequately with unexpected events during execution like, e.g., traffic delays, vehicle breakdowns, road works, new customer requests or the cancellation of the preexistent ones, which causes fleet delays, unexpected costs, and poor customer service. *Real-time dynamic FMSs* are needed to handle unexpected events, i.e. to detect deviations from the initial dispatch plan and adjust the schedule accordingly by suggesting effective re-routing immediately. In this context, timely close decisions are more important than the ones more remote in time while the time available for verification, correction and implementation of changed route plans is scarce [8, 18].

Real-time FMSs have been applied to a broad variety of domains including emergency vehicles (fire trucks, ambulances, etc.), police cars, taxis, commercial delivery vehicles, courier fleets, public transport fleets, freight

railcars, etc. (see, e.g., [17, 3, 9, 6, 1]). However, state-of-the-art FMS solutions are *centralized* and require vehicle fleet operators to send low-level commands remotely to fleet's drivers and their vehicles. Even though some dynamics of the environment is accounted for, often certain decisions cannot be reconsidered as that could complicate the assignment procedure and potentially compromise the fleet's response time. In addition, quite frequently changes in the environment are not communicated fast enough to the FMS operators to take decisions in a timely manner. The dependence of the FMS on adequate central operator decisions, therefore, compromises its robustness and hinders effective scalability [13].

The technological advances in sensors, communication and networking technologies, and geographic information systems enables fleet operators to be informed about unexpected changes in fleet operation almost at the time that they occur, and thus allows for increased levels of dynamicity in the operational decisions. Moreover, the increased performance of small scale, energy-efficient computing devices allows for delegating part of the fleet decision making to the fleet's vehicles, enabling a more decentralized architecture of FMS that gives more autonomy to the vehicles and their drivers and, thus, fosters the reactiveness of the system.

In this article we sketch our work in the field of real-time FMS and point to developments that we believe are going to take place in the near future. Section 2 shows how an increased level of dynamicity in FMS can lead to a better quality of service. For this purpose, we first present an event-based architecture for dynamic FMS and then instantiate and evaluate it for the case of ambulance coordination in the city of Madrid (Spain). In section 3 we show how our architecture can be extended to decentralized FMS where the vehicles are equipped with computing power to (partially) process the data provided by their sensors and with advanced interfaces to interact with their drivers. We put forward our vision of conceiving FMS as smart Cyber-Physical Systems [19], and illustrate the idea in the field of electro mobility, where drivers of smart e-motorbikes (*Cyber Vehicles*), equipped with an intelligent communication device (*Cyber Helmet*), are coordinated by means of a next-generation FMS. We conclude the article in section 4.

2.   Dynamic Fleet Management

In this section we present our proposal and experience for dynamic fleet management. We first describe an event-based architecture for FMS. Then, we apply our architecture to coordinate a fleet of ambulances and show experimentally that our proposal outperforms the current approach.

2.1 Event-based FMS architecture

There are two main problems fleet operators are faced with: task allocation and redeployment. The *allocation* problem consists of determining which vehicle should be sent to serve a given task. *Redeployment* consists of relocating vehicles in the region of influence in a way that new tasks can be reached fast and/or with low costs. Both issues are particularly challenging in dynamic environments, as continuously upcoming new tasks may require attendance, and the current situation of the fleet may change due to external influences. In order to maximize vehicle utilization and to improve service quality in such environments, task allocation and vehicle redeployment should as well be accomplished in a dynamic manner, adapting the coordination of the fleet seamlessly to upcoming events and changing demands. In order to adequately capture the real-time requirements in such a scenario, we set out from an event-driven approach [14].

Figure 1 depicts our architecture for dynamic fleet management. It contains three basic layers: the top layer contains the vehicles, modelled as agents; the second layer represents the fleet coordination modules; while the third layer includes other components that are necessary for the normal operation of a fleet operator (e.g., components for monitoring, task management, global fleet control, etc.).

In the fleet coordination layer, a Fleet Tracker follows the operational states and positions of the vehicles[1]. It informs the Event Processing module about any changes in the fleet that would require an adaptation of the task allocations and/or the deployment of idle vehicles. This module analyses the incoming events (state changes of vehicles and new task events) and determines whether or not a re-calculation of task assignments and/or deployment of idle vehicles should be done. If necessary, it triggers the execution of the task allocation and predictive redeployment modules. The task allocation module, when executed, re-calculates the optimal global assignment of all pending tasks (in the current moment) to vehicles, based on a set of assignment criteria (depending on the application domain). The predictive redeployment module, calculates adequate positions for all idle vehicles at the current moment taking into account predictions concerning the appearance of new tasks (based on historical data) and the current state of the fleet.
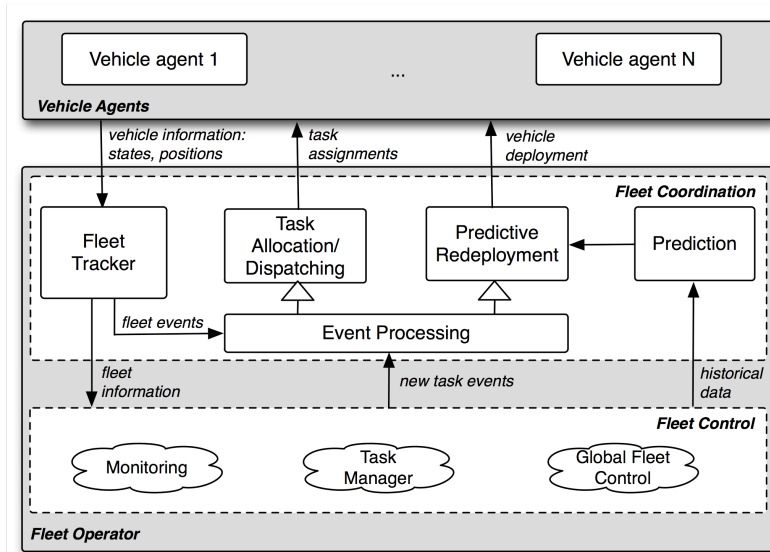

Figure 1: Event-based architecture for dynamic fleet management

2.2 Case study: ambulance coordination in Madrid

We applied the aforementioned architecture in a system for coordinating the fleet of ambulances of the Emergency Medical Assistance Service SUMMA112[2] in the Autonomous Region of Madrid in Spain, a region of about 8000 km^2 with approximately 6 million inhabitants. Among other services, SUMMA112 maintains a fleet of ambulances that provides extra-hospital assistance to patients in cases of emergencies. One of the main goals is to reduce the response time (e.g., the time between a patient calls and the moment an ambulance arrives and the patients location) in cases of life threatening emergencies, since in such cases, shorter response times are directly correlated with less mortality.

SUMMA112 currently employs a static approach to patient allocation and the redeployment of ambulances: Calling

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[1] We assume that vehicles have capabilities to send their current positions on a regular basis and to inform about changes in their operational states.
[2] http://www.madrid.org/cs/Satellite?pagename=SUMMA112/Page/S112_home

patients are classified with a triage system into different severity levels. Patients with the highest level are assigned using the closest method rule based on the first-come/first-served (FCFS) principle. That is, the first patient in the system is assigned first, then the next patient, and so on. In each case, a patient is assigned to the closest available ambulance in that particular moment. After an ambulance has finished a mission, it returns to its base station and waits for a new assignment. The locations of ambulance base stations are fixed and have been chosen based on criteria such as population density and infrastructure.

Based on the architecture presented in Figure 1, we developed a prototype of a dynamic ambulance FMS for emergency medical assistance in Madrid [5], where ambulances and calling patients are the Vehicle Agents and new tasks, respectively, in our architecture. We concentrated only on the most severe emergency cases, those that are assisted with advanced life support units. Regarding the assignment of patients to ambulances (task allocation), we substitute the current static FCFS strategy by a reactive method, where existing assignments can be reconsidered on the fly. As illustrated by Figure 2, any patient who has been assigned previously to an ambulance may be re-assigned to another one if this improves the average response time. In particular, a given assignment is re-calculated if (i) a new patient has appeared (see Figure 2b), or (ii) an ambulance has finished a previous mission (see Figure 2c). For this purpose, we developed an extension of Bertsekas' auction algorithm [4], which assures an assignment that minimises the key performance indicator (average ambulance response time) in a sufficiently fast manner [5].

(a)   (b)   (c)
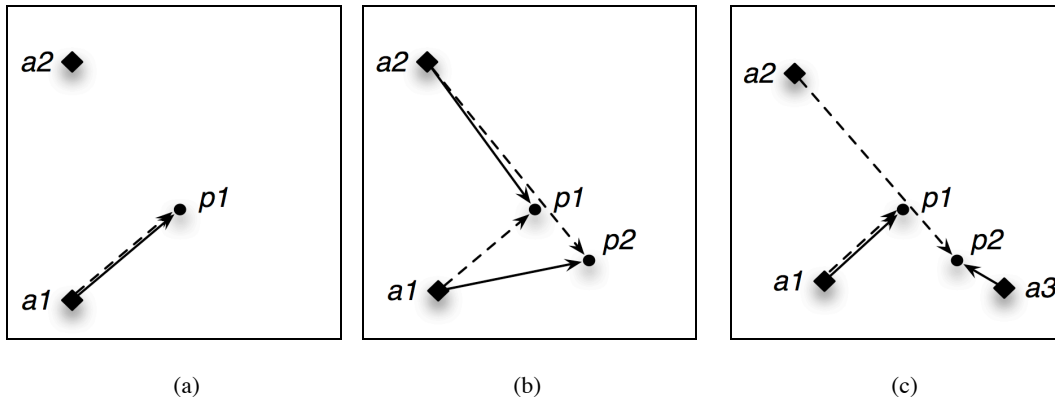
Figure 2. Ambulance assignment strategies: dotted lines show the current (FCFS) approach while solid lines represent our assignment policy: (a) initial assignment; (b) a new patient appears; (c) a previously busy ambulance becomes available

With respect to the redeployment of ambulances, we use historical data to estimate the probability distribution of emergency cases in the region for different days and times of the day (1 hour intervals). Based on this estimation, we calculate adequate waiting positions for all ambulances that are idle in a given moment. The waiting positions are dynamically re-calculated if one of the following events occurs: (i) an ambulance that was previously assigned to a patient becomes idle again (e.g., the mission has been finished or the ambulance has been de-assigned form the patient), (ii) an idle ambulance has been assigned to a patient, or (iii) a different estimation of the probability distribution has to be applied (every hour). The redeployment module has been implemented based on the calculation of centroidal Voronoi tessellations [7].

In order to evaluate the effectiveness of the dynamic approach, as compared to the static approach currently used by SUMMA112, we tested it in a set of experiments, analysing the response times to emergency patients. For this purpose, we have developed a simulation tool for the operation of EMA services (covering the whole assistance process: the emergence of patients, the schedule of an ambulance, the "in situ" attendance and, finally, the transfer of

the patients to hospitals), based on the information obtained from a well-calibrated (external) route service. In the experiments we considered a rectangle of 125 × 133 kilometres that covers the whole area of the Autonomous Region of Madrid. We used 29 hospitals (all located at their real positions) and 29 ambulances with advanced life support (as currently used by SUMMA112). We simulated the operation of the service for 10 different days (24 hour periods) with real patient data from 2009 provided by SUMMA112. The days were chosen to have a representation of high, medium and low workloads.

Figure 3 compares the distribution of the response times (in minutes) over all patients (1609 in total) for both, the current FCFS coordination model (C-SUMMA112) and our dynamic coordination model (DYNAMIC). The results clearly show the benefits of our dynamic approach, which performs better for practically all response time ranges. Furthermore, the most important improvements can be observed in the ranges of higher response times. This is an important advantage because it assures that more patients can be attended within given response time objectives. On average, the response times are 15.8 % better in the DYNAMIC approach (9:54 versus 11:45 minutes). Especially in the case of severe patients, such a reduction of almost 2 minutes can potentially be life saving.
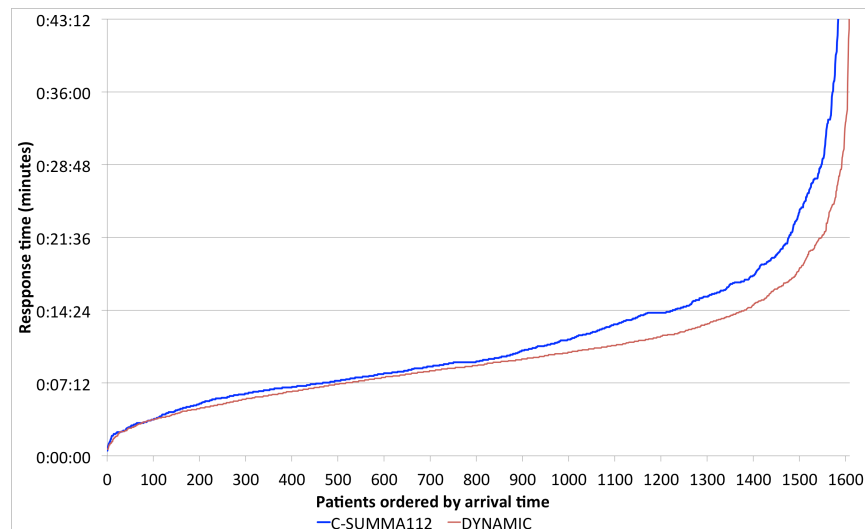

Figure 3. Dynamic versus static fleet management for ambulance coordination in Madrid

3. Towards Cyber Fleets

Today's vehicles are becoming increasingly smart and autonomous. Some prototypes of autonomous vehicles have been designed and tested, and the main challenges related to this new technology are currently being studied in countless realistic and complex scenarios [10, 2]. In the mid term, this poses new challenges to FMS managing fully autonomous vehicles in a decentralised manner. In order to advance in this direction, based on the technologies that are currently available, we are studying the impact of different types of sensors and driver assistance technologies on fleet management. In particular, with the goal of incrementing the efficiency, safety and autonomy of vehicle fleets and their drivers, we propose conceiving FMS as smart Cyber-Physical Systems (*Cyber Fleets*) made of *Cyber Vehicles* and drivers with *Cyber Interfaces*. In such a scenario, FMS decision-making takes place both at vehicle-level (the drivers interact with their own and other Cyber Vehicles through Cyber Interfaces), as well as at system-

level where the fleet operators can focus on more coarse grained management decisions for fleets that are potentially heterogeneous and large-scale.

Figure 4 outlines the proposed structure for FMS based on Cyber Fleets. The fleet coordination cloud is similar to the dynamic FMS outlined in Figure 1, but many low-level events can be coped locally with at the Cyber Vehicles. That is, the management and monitoring tasks are shared between the Fleet Operator and the Cyber Vehicles with their drivers.
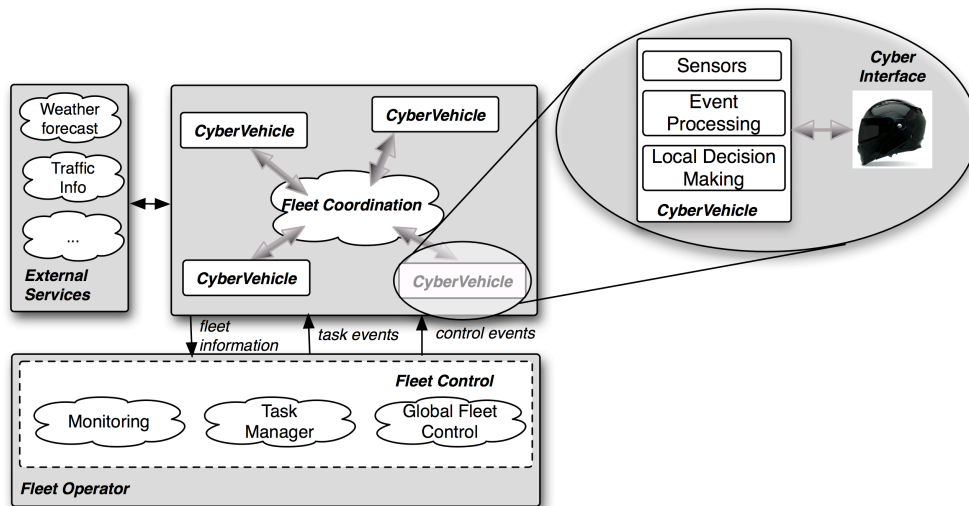

Figure 4. Structure of FMS for Cyber Fleets

In the following, we illustrate the notion of *Cyber Fleets* by means of an example in the field of electro-mobility. More precisely, we set out from a fleet of electric motorbikes. The company *GoingGreen* [11], for instance, is currently deploying fleets of such e-motorbikes in the city of Barcelona for vehicle sharing and home delivery purposes. In line with the abovementioned architecture, the new Cyber Fleet of e-motorbikes that we propose comprises three main components: *Cyber Helmet (CH), Cyber e-Motorbike (CeM)* and *Smart e-Motorbike Fleet Management System (SeM-FMS)*. In the following we will shortly sketch each of these elements.

Smart helmets are currently finding their way into the market (see Figure 5). However, the CH for a Cyber Fleet of e-motorbikes needs to go beyond the state of the art, insofar as it serves as a smart communication bridge between the driver and the vehicle, and between the driver and the SeM-FMS. For this purpose, it is equipped with additional communication outlets, a stereo camera, and a microphone, and is connected to the CeM to take advantage of its computing capacity. Furthermore, the interaction between the CH and the driver has to be grounded in situational awareness, i.e. the former should refrain from communicating with the driver in case of difficult manoeuvring operations or traffic situations, which require the driver's full attention. In particular, a traffic evaluation module ought to take into account traffic images received through the camera, the driver's current maneuvering complexity based on the CeM's GPS coordinates and the actual traffic state, weather conditions, the road infrastructure complexity, and CH sensor readings regarding the CeM's current state (acceleration, velocity dynamics, wheel orientation, etc.). The identification of the traffic situation is possible through image recognition, fusion of data received from different helmet and vehicle sensors, and sensor knowledge extraction. In addition, the CH can determine the mode of communication (audio communication through microphone, video presentation of data on the helmet augmented reality display, or a combination of both) and inform the driver about her tasks, as well as CeM

and traffic conditions (malfunctions, battery, driving performance, security alerts, weather, traffic accidents, traffic jams, alternative routes, etc.)
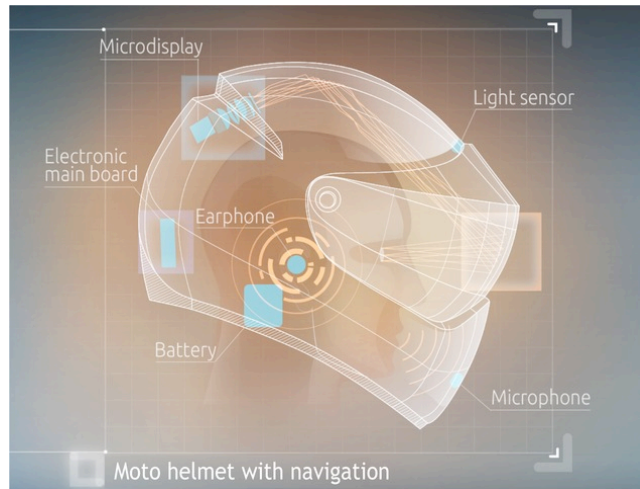

Figure 5. Smart motorbike helmet designed by the Russian company *LiveMap* (from [12])

The e-motorbikes currently deployed by *GoingGreen* (see Figure 6) are already equipped with some simple sensors and basic data processing capacity. We enhance them by additional data sources such as accelerometer, proximity (laser) sensors, stereo-cameras, etc., and will turn them into a CeM by endowing them with additional computing power. With this configuration, the CeM will perform real-time sensor data extraction, fusion, and reasoning, and communicate with the driver through the CH connected to the vehicle's battery and to the SeM-FMS through standard wireless communication. Some of the exemplary vehicle processes are: forecasting the residual battery autonomy with the specific driver profile, maintaining a driver profile based on his/her driving habits, and networking with other vehicles and SeM-FMS in the system for task and work break distribution, contingency coverage, etc. The CeM assists the decision-making of the driver and the fleet operator regarding the mission's execution. It may receive and directly execute commands from the SeM-FMS concerning: maximum speed limit of the CeM, maximum acceleration, engine blocking, etc., so as to enhance energy efficiency or vehicle security. But it can also suggest directly to the driver, e.g., the most adequate charging spots.

Figure 6. E-motorbike belonging to the fleet deployed by the company *GoingGreen* (from [11])

Finally, *SeM-FMS* is the computational platform that orchestrates the vehicle fleet to satisfy fleet objectives. Its level of decentralization in decision-making is tailorable to the fleet owner preferences and constraints; it can vary from a fully *centralized* to the *subsidiary* one (see Figure 7). Subsidiarity is an organizing principle of decentralisation, promoting the delegation of responsibilities to the smallest, lowest, or least centralised authorities capable of addressing an issue effectively (in our case drivers and their CeMs) [22]. On one extreme, in a centralized structure, all the decisions regarding the strategic, tactical and operational level of the fleet related to task allocation, vehicle deployment, battery autonomy, work break and contingency management are controlled by the central fleet operator. By contrast, with fully decentralized control, only the fleet strategy (its mission and related constraints) is given by the fleet operator, while the CeMs manage key parts of the mission execution and related operations at tactical and operative level in real time through lateral interaction. Besides constraints emanating from the concrete organisational environment that the SeM-FMS is embedded in, the fleet's level of decentralization depends, for instance, on the size of the fleet and its dispersion over one or more regions of interest. To facilitate individual accounting for fleet performance, one of the tools for the mission evaluation is tracking of a personal driver profile record. If necessary, the SeM-FMS can undertake corrective actions on the fleet vehicles and drivers and minimize the performance degradation during sudden performance variations.
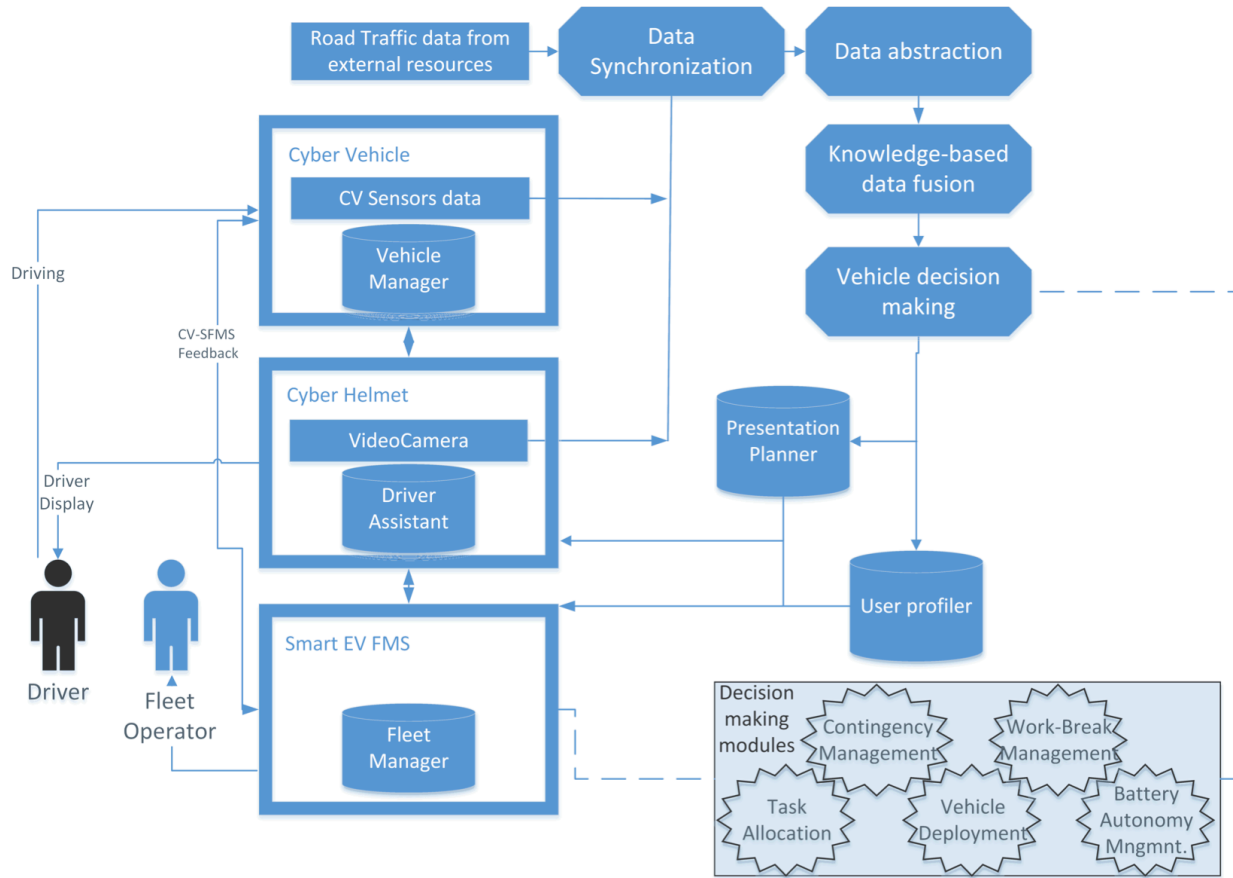
Figure 7. Cyber Fleet tailorable decision-making structure. Depending on the assignment of decision-making modules to the Fleet Manager or Vehicle Fleet, different levels of decentralization can be achieved.

We plan to apply such Cyber Fleets of e-motorbikes in two case studies. In *home delivery*, the task of electric motorcycles is to distribute products in an urban area by assigning CeMs to product pick-up and delivery tasks. The application scenario includes Fast-Food restaurant hot meal delivery. The *vehicle-sharing* scenario refers to a type of vehicle rental for short periods of time, often by hours. The principle of vehicle sharing is that individuals gain the benefits of private transportation without the costs and responsibilities of ownership. Instead, a private user accesses a fleet of vehicles on an as-needed basis. We also plan to integrate both business cases into one business solution where a fleet of CeMs serves both purposes at the same time, and dynamically and seamlessly adapts to user demands in order to maximize vehicle utilization and increase profit gains.

4. Conclusions

In this paper we argued in favour of a more dynamic and decentralised approach to FMS. Based on the case of ambulance coordination in Madrid, we showed that increased levels of dynamicity may lead to a significant increase in performance. Furthermore, we introduced the notion of Cyber Fleets and conjecture that, by integrating advanced sensor and driver assistance technology into vehicles, higher levels of decentralisation can be achieved.

We are currently working in the field of Cyber Fleets for the case of *GoingGreen*'s e-motorbike fleet in Barcelona to confirm the above hypothesis. In future work we intend to extend our approach to mixed Cyber Fleets capable of managing heterogeneous fleets of traditional vehicles, Cyber Vehicles, and fully autonomous vehicles.

References

1. Andersen, Jardar, Teodor Gabriel Crainic, and Marielle Christiansen. "Service network design with management and coordination of multiple fleets." European Journal of Operational Research 193.2 (2009): 377-389.
2. Awasthi, A., Chauhan, S. S., Parent, M., & Proth, J. M. (2011). Centralized fleet management system for cybernetic transportation. Expert Systems with Applications, 38(4), 3710-3717.
3. Belmonte, María-Victoria, José-Luis Pérez-de-la-Cruz, and F. Triguero. "Ontologies and agents for a bus fleet management system." Expert Systems with Applications 34.2 (2008): 1351-1365.
4. Bertsekas, D..The auction algorithm: a distributed relaxation method for the assignment problem, Annals of Operations Research 14 (1) (1988) 105–123.
5. Billhardt, H.; Lujak, M.; Ossowski, S.; Sánchez-Brunete, V., Dynamic coordination of ambulances for emergency medical assistance services. Submitted to: Knowledge-Based Systems.
6. Crainic, Teodor Gabriel, Michel Gendreau, and Jean-Yves Potvin. "Intelligent freight-transportation systems: Assessment and the contribution of operations research." Transportation Research Part C: Emerging Technologies 17.6 (2009): 541-557.
7. Du, Q.; Faber, V.; Gunzburger, M. Centroidal voronoi tessellations: applications and algorithms, SIAM Review 41 (4) (1999) 637–676.
8. Eksioglu, Burak, Arif Volkan Vural, and Reisman, Arnold. "The vehicle routing problem: A taxonomic review." Computers & Industrial Engineering 57.4 (2009): 1472-1483.
9. Goel, Asvin. Fleet Telematics: Real-time management and planning of commercial vehicle operations. Vol. 40. Springer, 2007.
10. http://www.cybercars.org/
11. http://www.goinggreen.es/
12. https://livemap.info/
13. Kurose, James F. and Simha, Rahul. A microeconomic approach to optimal resource allocation in distributed computer systems. Computers, IEEE Transactions on, 38(5):705–717, 1989.
14. Luckham, D. (2002). Power of events. Addison-Wesley.
15. Maden, Will, Richard Eglese, and Dan Black. "Vehicle routing and scheduling with time-varying data: A case study." Journal of the Operational Research Society 61.3 (2010): 515-522.
16. Mardiasmo, Diaswati, et al. "Asset management and governance: Analysing vehicle fleets in asset-intensive organisations." (2008): 1-20.
17. Ossowski, S., J. Z. Hernandez, M.-V. Belmonte, A. Fernandez, A. García-Serrano, J.-L. Pérez-de-la-Cruz, J.M. Serrano, and F. Triguero, "Decision support for traffic management based on organisational and communicative multiagent abstractions", Transportation Research Part C, vol. 13, pp. 272-298, 2005.
18. Pillac, Victor, et al. "A review of dynamic vehicle routing problems." European Journal of Operational Research 225.1 (2013): 1-11.
19. Shi J., Wan., j.; Yan H.; Suo H. A survey of Cyber-Physical Systems. Int. Conf on Wireless Communications and Signal Processing (WCSP), p. 1-6, (2011)
20. Zeimpekis, V., et al. "Dynamic management of a delayed delivery vehicle in a city logistics environment." Dynamic Fleet Management. Springer US, 2007. 197-217.
21. Zeimpekis, Vasileios, George M. Giaglis, and Ioannis Minis. "Development and evaluation of an intelligent fleet management system for city logistics." Hawaii International Conference on System Sciences, Proceedings of the 41st Annual. IEEE, 2008.
22. Paterson, S. L., and David M. Brock. "The development of subsidiary-management research: review and theoretical analysis." International Business Review 11.2 (2002): 139-163.