On the benefit of collective norms for autonomous vehicles

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ABSTRACT

This paper considers the (intelligent) vehicle domain from the perspective of situational awareness, but based on knowledge, rather than data, attempting to model the context of the (human) driver rather than that of an auto-pilot. We set out a (driver) simulation framework, in which some vehicles are operated by a collection of norm-aware BDI agents and connect this with the SUMO traffic simulation environment, which provides the background traffic. While the driver collective retains autonomy with respect to road conditions and actions, it receives guidance from several institutional models that implement social reasoning about the context in which the vehicle is currently situated. We demonstrate the benefit of rapid visualization of simulation metrics and use a range of domain-relevant metrics to show how it is possible to assess both collective (e.g. traffic flow) and individual impact (fuel consumption) arising from individual vs. institutional decision making.

Keywords

multiagent systems, intelligent transportation systems, autonomous vehicles

1. INTRODUCTION

The ability of autonomous agents to operate in pursuit of both their own goals, as well as comply with obligations from a collective view, presents numerous challenges but a significant number of potential benefits. In order to explore what may be possible, a simulation framework has been established with a number of vehicle specific scenarios to assess both the suitability of the framework for such investigations, and to capture individual and global measurements of the effect of institutional governance in these scenarios.

An underlying assumption in the various scenario themes is that of knowledge exchange, both for the derivation of understanding about the environment, and the approach to how this data is shared between distributed components. The concept of Situational Awareness is adopted as a means to categorise information 'levels', considering Endsley's [13] concepts of perception, comprehension and projection as a transition from 'low' level information (e.g. a geographic xy location of another vehicle) to 'high' level information (e.g. given current speed and heading, there may be a collision based on the other vehicle's xy). We explore this theme and related concepts in Section 2.

The mechanism used to exchange these various information levels also needs consideration. A publish-subscribe mechanism has been adopted based on the Extensible Messaging and Presence Protocol (XMPP) [28] framework. Within this, information is packaged according to the Resource Description Framework (RDF), to add semantic annotation to the information exchanged, or JSON, where semantic information is not required. Coupled with a XMPP messaging server, this represents the nucleus of the simulation environment and is referred to as the Bath Sensor Framework (BSF). Supplemental tools have been built around this in order to assess data flow, from low level metrics (e.g. messages per second) through to a 3D representation of the environment and inferred 'high level' knowledge (e.g. collision volumes, upcoming traffic lights). More details about this aspect appear in Section 3.

The Belief-Desire-Intention (BDI) [10] model is adopted as the agent architecture in this work and specifically the Jason [9] platform, providing a multiagent system where agents store beliefs and available plans in order to pursue goals. In the context of the BSF framework, Jason is extended to process RDF data and pass it on to agents, who react accordingly, and can trigger actions back to the environment through creation of suitable RDF requests. The BDI model has been demonstrated in vehicle convoy scenarios (e.g. [24] and [3]) and that work is built upon further here.

In order to augment the capability of these agents to operate collectively and to be able to function in new situations about which they have no prior knowledge, the use of an institutional framework has been integrated into the BSF simulation. As an agent senses its world view via received RDF data triples, so does (each instance of) an institution, and whereas an agent may not have a suitable plan or belief handling for a given situation (e.g. socially complex or ambiguous cases) an institution, embodying situation-specific knowledge, can issue appropriate obligations to participants in order to achieve common goals. Furthermore, the institution is able to act as a situational governance mechanism, issuing obligations to individuals which might be contrary to the maximum satisfaction of their current desires, but of benefit to the wider collective (e.g. one vehicle being told to move out of the way to allow a queue to pass). We discuss the institutional aspect in more detail in Section 4

The opportunity to integrate such technology with real world vehicles increases as autonomous vehicles step ever closer to the mainstream. With Google's driverless car [22] and the Volkswagen based 'MadeInGermany' [15] vehicles both gaining mileage over the last few years, as well as more recent announcements such as Nissan's [16] there are autonomous vehicles across America, Europe, and Japan.

Adopting vehicle scenarios as the chosen context provides an appropriate challenge for the simulation framework (i.e. high message rates and timeliness of message delivery) as well as a rich information context (i.e. higher level knowledge vs low level sensor feeds) with which to assess the application of both BDI agents and institutional frameworks.

Following the construction of a suitable simulation framework, and with the autonomous vehicle context in mind, two scenarios are put forward in Section 5 to explore the use of norms in the vehicle domain. The first investigates the use of an institution to transform a visual cue of a vehicle behind flashing its lights (requesting that the vehicle ahead moves to another motorway lane) to an obligation to change lane. The second explores the use of upcoming traffic light data based on a vehicle's current route and speed, and the use of an obligation to adjust speed in order to arrive at that light whilst it is green. Clearly, both such behaviours could be pre-loaded into the agent: the institution appears superfluous; our point is that such an argument can be made for *every* such scenario, which would lead to agents carrying a lot of plan baggage which may be rarely used and which, being embedded in the agent, is not readily revisable, furthermore, there will also always be scenarios not foreseen when the agent was constructed. Our position therefore, and what this paper seeks to demonstrate, is that institutions provide through the delivery of obligations, a mechanism for out-sourcing agent knowledge of conventional and regulated situations, while permitting ready update and the provision of new knowledge on an as-need basis [19]. Subsequently, we analyse some of the metrics collected from these scenarios in Section 6, which indicate a positive impact on fuel consumption. There is also some early indication that traffic flow can be improved, however further work is needed to establish and quantify this benefit.

2. RESEARCH BACKGROUND

Whilst this work draws on a number of different research areas, the core theme is that of Situational Awareness. Formally, Endsley [13] defines this as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future" and this forms the basis of three levels of SA: perception, comprehension and projection. These levels are drawn on as knowledge representation levels within the framework and experimentation of work presented here. 'Low level' information is considered as the perception level (e.g. a traffic light x-y location), and as reasoning and data fusion is performed the information rises through the levels, firstly comprehension (e.g. distance to that traffic light from current position), through to projection (e.g. affect that light will have on vehicle given current speed and state of light).

With vehicles containing increasing technology in terms of driver aids and safety systems work has also been taking place to consider how cooperation between vehicles, based on V2V communication, could be beneficial. Coordination in terms of vehicle platooning or convoy behaviour has been receiving attention. The SAfe Road TRains for the Environment (SARTRE) study [6] demonstrated the ability of vehicles to form an effective convoy when following a designated lead vehicle, identifying benefits (e.g. time, fuel) and considering the real world implications of such message exchange. Given the physical limits encountered when using real networks in V2V communication [7] this provides motivation to explore whether we can communicate less via exchange of higher level information, and still provide acceptable knowledge transfer and performance. Such an approach is explored in the second scenario presented in this paper, which relates to the 'projection' aspect of SA based on traffic light state to future vehicle state. Particularly relevant to the first scenario put forward in this paper, Bilstrup [8] considers emergency vehicle routing, where V2V messaging is used to coordinate clearing a path for emergency vehicles.

Regarding vehicle coordination in relation to traffic lights, work has been undertaken [17] to implement communication between traffic lights and vehicles, in order to improve fuel consumption and reduce emissions. Similarly, a recent news announcement [27] provided details of Audi vehicles retrofitted with new technology interacting with traffic lights, in order to improve traffic flow. CO2 emission reductions of up to 15 percent are claimed, along with a potential 900 million litre fuel saving per year if the system were implemented throughout Germany, but no precise details of the simulation or the methodology are given, so it is not clear how the figures might be verified.

The use of institutions as a mechanism to provide norms in the absence of a clear individual choice, or as an enforcement mechanism contrary to the individual's choice, has been explored in contexts where an individual gains at the expense of peers [4], a scenario which can be easily applied to the vehicle domain. Furthermore, the possibility for multiple institutions to interact [11] (e.g obeying a traffic light vs. moving out of the way of an emergency vehicle) characterises scenarios where human drivers may struggle to resolve the situation. Indeed, the topic of human drivers interacting with autonomous vehicles will create even more challenges, and whilst thought has gone into what such hybrid interactions may look like (e.g. traffic light systems [12]) we believe there is a role for institutions in facilitating this integration as externally verifiable repositories of normative (conventional and regulatory) knowledge.

Considering specifically traffic situations, we have identified several future scenarios where the use of institutions could be of benefit. One such use could be to enforce variable speed limits, a technique currently implemented through the use of road signs with speed cameras as the enforcement mechanism. The benefits of such approaches have been assessed, for example on the M42 [23] and M25 [26] motorways in the UK, with findings [26] that whilst some objectives have been met (smoother traffic flow, journey time reliability) others have not (no increase in peak throughput, unable to suppress shockwaves).As traffic conditions are difficult to replicate (e.g. day of the week, weather) it becomes challenging to perform like-for-like comparisons in the real world, and therefore hard to infer a direct benefit for a specific scenario. However, it seems generally accepted that such traffic control measures have benefits in smoothing traffic flows post accidents, and reducing recurrent occurrences of congestion. This raises two points of interest specific to the simulation framework adopted in this paper. Firstly, that as the work is simulation based, like-for-like comparisons are feasible, as the same simulation conditions can be recreated many times. Secondly, that the unpredictability of human reaction and compliance is removed. Although institution obligations do not necessarily have to be obeyed, for variable speed limit compliance this could be more rigidly enforced, and thus identify what degree of compliance is required for the mechanism to achieve the intended effect, for example. In this case, the question of whether assessment of real world flow results is based on drivers complying with the speed limit is removed, and instead we see a more true (or arguably, idealized) view of what the impact would be.

Whilst the obligation received from the institution may not necessarily be obeyed, they can be considered as guidance for what to do in a given set of circumstances[2, 5, 20]. As such, this work also has a relationship with the field of collaborative behaviour between agents. Earlier scenarios focussed on convoy management using vehicle proximity data: we now considered this as an institutionally managed activity, in contrast to other coordination approaches (e.g. [24]). There is the aspiration that similar benefits can be demonstrated by self-organising vehicle collectives [14] for improved traffic flow and fuel savings via the institutional approach.

Having introduced the context and motivation for this work, the simulation framework which has been constructed to investigate the vehicle scenarios is now presented.

3. SIMULATION FRAMEWORK

The simulation framework has been designed with distribution and a de-coupled approach to system component interoperability in mind. The Extensible Messaging and Presence Protocol (XMPP) includes support for a publish-subscribe mechanism, allowing simulation members to publish without an overhead of managing consumers. Combined with the Resource Description Framework (RDF) specification, this data then includes a level of semantic annotation, providing subscribers with both the data and a definition along with it. Built around this, the Bath Sensor Framework (BSF) provides an 'out of the box' capability (opensource at http://code.google.com/p/bsf/) with various components based on the publish-subscribe approach. Some of these are fairly generic in nature (a database logger for RDFs, a replay tool to recreate events from database logs, performance testing tools), whereas others are more specific to the vehicle scenarios explored here (a 3D world view tool based on OpenStreetMap data, the Jason BDI engine).

Earlier work based on the BSF [3] presented a number of scenarios exploring communication between vehicles when acting as a convoy, investigating acceptable convoy performance while reducing the inter-vehicle communication, based on varying strategies. Discussion of new scenarios presented here follow in the next section, but there have been substantial developments specific to the simulation framework.

Vehicle simulation is now performed by the 'Simulation of Urban MObility' (SUMO) [18] package, whereas previously the simulation was limited in terms of individual vehicle simulation, adherence to road networks and their rules, as well as general traffic representation. Through the use of a Java API, vehicle information is extracted and published to BSF subscribers, and a number of vehicle control commands have been implemented such that Jason agents are able to interact with and control SUMO vehicles. Furthermore, the richer simulation information provided by SUMO has allowed more investigations around the concepts of Situational Awareness discussed earlier.

One specific scenario based on this involves reasoning about traffic light data and how light states might impact the future state of the vehicle. Drawing fro Endsleys 'projection' component, the consideration around how future events will effect an individual vehicle requires far greater computation. For this reason, a new simulation component referred to as the 'Area Of Interest (AOI)' module has been created. This can be considered as a data fusion engine, subscribing to data published by SUMO, calculating a vehicles AOI volume (based on current location and speed), and then publishing AOI RDF data back to the framework. Furthermore, as SUMO is handling vehicle routes, additional reasoning can be done based on what will be encountered in this AOI volume based on the current route, for example publishing upcoming traffic lights not just in the AOI in general, but that control lanes along the vehicle's route. This allows Jason agents to be able to react to both low level percepts (e.g. `+info(PosX, PosY, PosZ, Health, Heading)`) as well as much higher level (e.g. `+upcomingTrafficLight(Colour, Distance)`).

However, this improvement in simulation richness also introduces new challenges for the simulation framework itself. It was discussed in previous work [3] that there were performance differences dependent on the message volume, although scenarios at that point were quite lightweight in terms of data demand (four vehicles with one second update rate; four RDF messages per second). It was also found that when additional (agent mind state) data was broadcast from Jason, the resulting increase up to approx forty messages per second caused system instability. The introduction of SUMO leads to the possibility of simulating background traffic with potentially a hundred times increase in message volume from the four vehicle scenarios used earlier. There is further complexity, as vehicles now need to exchange route information, and convey their light state (e.g. indicating, flashing lights, braking) and their performance metrics (e.g. fuel consumption, CO2 emission). There is also environmental information to be exchanged, such as traffic light states and flow detectors.

Consequently, there was a significant reworking of the simulation framework, to ensure that it is capable of meeting this requirement. An alternative XMPP message server (ejabberd) has been adopted, which yields significantly improved message throughput. Coupled with general code improvements, the system is comfortably handling 800 messages a second (over a wireless network). Due to the importance of message delivery in this framework, part of the build test now performs checks for message loss and message rates in order to ensure the deployed hardware and network configuration performance is acceptable.

Ameliorating the bottleneck in message delivery now reveals costs in the data serialization task. As previously mentioned, clients transform data into RDF triples before publishing, but this is relatively expensive. Where semantic annotation is not needed JSON provides an efficient alternative format, that has been measured as significantly quicker than RDF due to the improved serialization performance (along with a wider range of benchmarks [25]). This bears relevance to the knowledge transfer theme, as it suggests the possibility to transfer high volume-rate but with little semantic description (i.e. JSON), or low volume-rate but with additional semantic definitions and analysis possible (i.e. RDF). In general we consider this a problem of impedance matching; that publishers and subscribers need to be matched not just in terms of data rates but also knowledge richness. For example, it has been found that there are issues if publishing at high rates to the Jason BDI engine, and that lower rates of richer data is more suitable. Conversely, the 3D viewer is better suited to high rate of low level information (e.g. position updates) and not so well placed to display high level information (at least, in a raw format).

4. INSTITUTIONS

We are motivated to incorporate institutional reasoning into the simulation framework for two immediate reasons: (i) the breadth of possible situations requiring resolution between vehicles is too great to encode prior to runtime, and (ii) to be able to constrain a vehicle's sole pursuit of its own goals in order to consider the greater society of vehicles, through the enforcement of some form of global obligations.

In the first case, a scenario based on a somewhat ambiguous situation has been chosen: a vehicle becomes obstructed by a slower moving vehicle and wishes to get past. To indicate this, the vehicle flashes its front lights, and if this cue is interpreted correctly by the leading vehicle, it would change lanes in order to yield to the other vehicle's desire. With the simulation framework outlined in Section 3, the Jason agent is able to refer its requirement to the institution, updating the institution manager with the event `flashLights(Agent)` which in turn generates the institutional event `iniOblChangeLane(Agent)`. This in turn generates the obligation `obl(changeLane(Agent)` which the institution manager packages as an RDF triple and transmits to the BSF. As Jason agents are subscribed to the institution node, they receive this obligation, resulting in that agent's belief base being updated with the percept `+changeLane`, for which the agent can then decide to issue a command to its SUMO vehicle to move to different lane.

In the second case, an institution was defined to handle information regarding upcoming traffic lights, and issuing appropriate obligations to ensure the vehicle arrives at that light when it is green, rather than being held at a red light[1]. In this scenario, traffic light information is received via RDFs from the Area of Interest module, and where the distance to an upcoming light is between 100m to 300m and that light is red, the institution is updated with the event `upcomingRedLight(Agent)`. This then generates the institutional event `iniOblSlowDown(Agent)`, resulting in the obligation `obl(reduceSpeed(Agent)`, which the Jason agent receives and resolves by reducing its speed for a specified (35 second) period. We demonstrate the impact of such institutional obligations in the experiments that follow.

As noted earlier, such behaviours could easily be encoded directly, if they were considered as part of the requirements, but this necessitates both fore-knowledge of the requirement and that it is fixed. We regard the mixed driving scenario as one example of the rich variety of socio-cognitive systems, populated by humans and software, mediated by technological artefacts, that are now emerging, where new requirements arise over time and old requirements change, rendering conventional software engineering approaches obsolete. Institutions are one way to provide a form of late binding of behaviour in order to address this issue. As also noted elsewhere, multiple institutions, while inevitably risking the creation of conflicting obligations [21], further enrich the environment, while keeping knowledge separated but linked [11].

[1]Inspired by the earlier cited Audi news item [27]

5. EXPERIMENTAL SCENARIOS

Initial work using this framework focussed on information exchange in vehicle convoys, and explored the impact of various communication strategies on convoy performance. However, as discussed in the previous section, there were some limitations on what was simulated in those scenarios. Now with the improved vehicle and traffic simulation, coupled with improved message transfer capability, more advanced scenarios have been constructed.

The current focus of these is in the use of a normative framework to control aspects of the vehicles, motivated by two factors. Firstly, while the BDI approach has been found to be robust in the vehicle domain, a combination with an institutional framework provides greater flexibility. The BDI agents are able to perform plan selection based on their belief state, with the added layer of the institution acting as a late binding mechanism, able to influence the agents ultimate approach. Secondly, the BDI agents are vehicle-centric in their view of goal achievement (i.e. pursuing their individual goals without concern regarding benefits for the society of vehicles), and the use of the institution model allows us to introduce a more society-centric consideration. For example, the institution can issue obligations to slow down to vehicles, in order to improve traffic flow for the greater population of vehicles, a method already in use via variable speed limits, as discussed earlier in Section 2.

Due to this shift in scenario focus, results need no longer focus purely on underlying message metrics and convoy cohesion. Instead, there are now measurements of individual vehicle performance metrics (e.g. fuel consumption, emissions), as well as global metrics (e.g. flow volume, average speeds). Videos of scenario runs are also made available.

Two scenarios have been constructed to explore the impact of the introduction of the institution framework, which are now discussed in more depth.

5.1 Scenario 1: 'Move out of way' obligation

This scenario explores the ability of the institution to issue obligations based on the needs of other users in the road system, which may be contrary to the desire of individual vehicles. Currently, this is demonstrated through the use of two vehicles along a section of the M25 motorway in the UK. Flow traffic has been populated in SUMO, based on data from the UK Highways Agency Traffic Flow Database System (TRADS [1]), for this road section in order to provide a representation of background traffic flow. A snapshot of the scenario can be seen in Figure 1 where background traffic is yellow vehicles, and Jason controlled vehicles are red.

In the scenario context shown in Figure 1, a leading vehicle (V1) is travelling slightly slower than a trailing vehicle (V2), and as V2 wishes to maintain its speed without changing course (i.e. moving to another lane to overtake) it gains on V1. As the vehicles near each other, the Area Of Interest (AOI) module informs vehicles of other vehicle locations in their AOI volume. The Jason agents then perform a finer granularity check using their perceived collision volume space (directly in front), and determine whether another vehicle is in this space, along with distance to that vehicle. As V2 gains on V1, this behaviour is triggered, and if V1 is between 60m to 40m ahead, V2 will flash its lights at V1. With the institution running, V1 is issued an obligation to change lane, and perform this request. Without

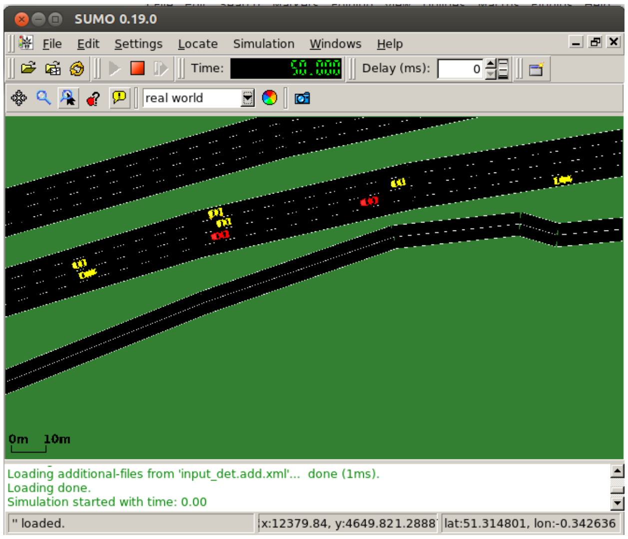


Figure 1: Scenario 1 M25 Motorway

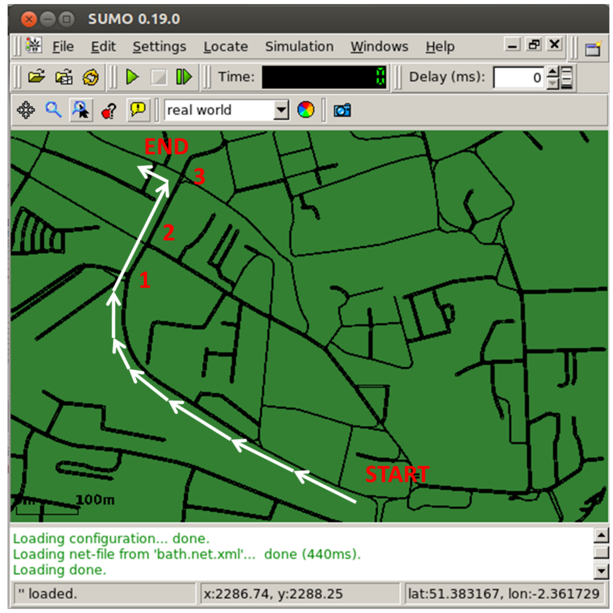


Figure 2: Scenario 2 Bath City Centre

the institution, V2 will continue to gain on V1, and below 40m V2 will brake hard in order to avoid a collision. In this case, once V1 is detected as leaving the collision volume, V2 increases speed again, and a cyclical catch up – slow down behaviour is expected.

Such a scenario has applications elsewhere in the road domain, for example an emergency vehicle can create a similar requirement to move past.

5.2 Scenario 2: React to likely future events

This scenario explores the ability of agents to reason about future states of the environment in which they operate. Specifically, given a current route, what bearing the future state of traffic lights will have on that agent.

In this case, similarly to the previous scenario, the AOI module detects any traffic lights within the AOI volume. Upon detection, a route analysis determines whether any of these traffic lights control a lane on that route. If so, then the institution is informed about the traffic lights current colour state, and the distance to that light. Based on this, the institution is able to issue an obligation to reduce speed, so as to arrive at that light when it is green rather than red.

As discussed earlier, there are some similarities to the system produced by Audi [27]. However, in the scenario implemented here, the speed modification is enforced in order to assess the impact on the larger vehicle population, as well as the individual vehicle. Parallels can be seen with mechanisms such as variable speed limits on motorways discussed previously.

The route taken in this scenario is shown in Figure 2, with some annotation added to explain key areas. The 'START' and 'END' locations correspond to the area on the map where the vehicle is inserted, and location when the simulation is finished. The numerical labels refer to the three junctions controlled by traffic lights located along this route.

The results of these scenarios are now presented.

6. RESULTS

This section presents results for the two scenarios discussed in the previous section, comprising of a baseline without institution involvement, and with institution issued obligations.

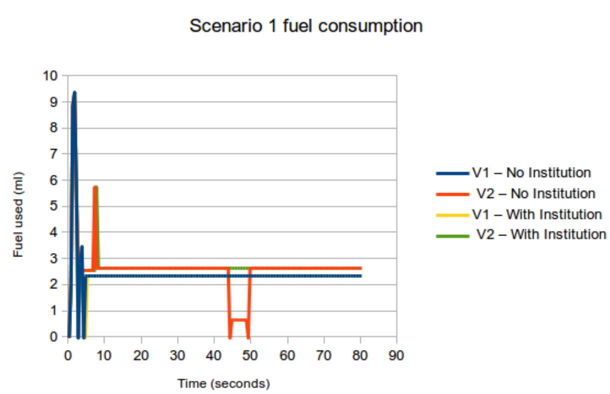


Figure 3: Scenario 1 Fuel consumption comparison

6.1 Scenario 1

In this scenario, there were two configurations for the experiments. The first, with the institution not active, involves vehicle 2 approaching vehicle 1 until a distance threshold triggers a hard brake (in order to avoid a collision). Once vehicle 1 has left the collision volume, vehicle 2 returns to the previous speed and so begins to gain on vehicle 1 again. The second, is with the institution active, which issues an obligation the vehicle 1 to change lane before the need for a sudden brake occurs.

In Figure 3 we can see the fuel consumption profiles of the two Jason controlled vehicles in this scenario, with the two variations of having the institution running or not. To clarify, V1 produces the same result with and without the in-

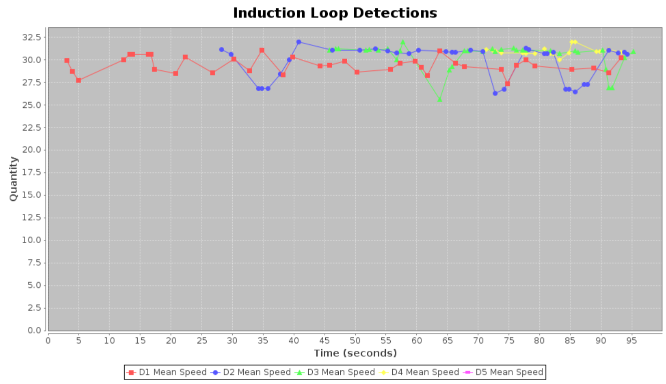


Figure 4: Scenario 1 detector values, no institution, http://people.bath.ac.uk/vb216/S1NoInst.mp4

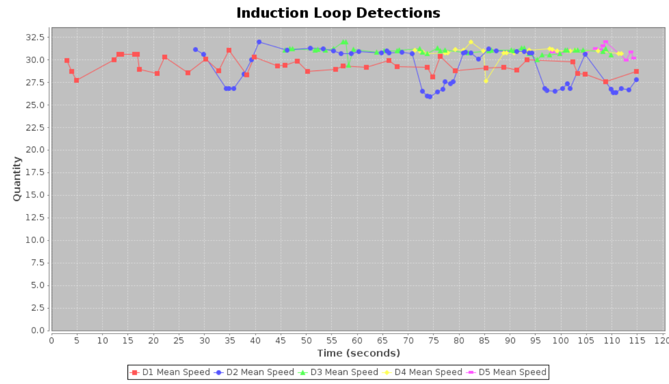


Figure 5: Scenario 1 detector values, with institution, http://people.bath.ac.uk/vb216/S1WithInst.mp4

stitution, V2 only shows variation between 45 to 50 seconds. In both cases, Vehicle 2 has a slightly higher fuel consumption rate, as it is travelling at a higher speed than Vehicle 1. Ignoring initial fluctuations as the simulation moves to steady state, we can see the main, and only, perturbation occurs in V2 at approximately 45 seconds. This is the point where it has got too close to the vehicle ahead (as there is no response to flashing its headlights) and has to brake. After about 5 seconds the vehicle ahead has moved out of its collision zone, and it resumes its previous speed.

By comparison, with the institution issuing the obligation to change lane, the need to reduce speed is removed, and as such the fuel consumption profile remains constant. Fuel consumption is currently implemented in SUMO based on the Handbook Emission Factors for Road Transport (HBEFA) model, and with the motorway scenario is has been found there is largely linear correlation between speed and fuel consumption. As such, the impact of excessive braking and acceleration is not captured in the fuel metric, however there is development effort under way to implement an alternative model in SUMO, which would result in more realistic – and, for the institutionally governed experiment, improved – figures for this scenario.

With the background traffic flow present, there is the desire to measure a more global metric rather than focussing on individual vehicles, in order to ascertain the impact of the behaviour of V1 and V2 on the general population. In order to achieve this, five detectors have been placed along the route that measure average vehicle speed and time since the vehicle was last detected.

The results reported by these sensors can be seen in Figures 4 and 5, respectively without and with institution. As traffic enters the simulation, it takes a while until there is traffic flowing at each detector site, hence the first detector (D1) reports speeds earlier than the next (D2) and so on. It can be seen that across these detection sites (approximately spaced at 800m gaps) there is an approximate speed variation of 5 m/s, and there is no conclusive impact of the institution control. There does appear to be a decrease in speed observed at D3 recorded at 64 seconds, which could match with a short bottle neck created by V2 (which Figure 3 shows returning to normal speed at 50 seconds). Visually there does appear to be some slight congestion in the SUMO GUI, and so further investigation is planned with improved metrics (e.g. gap between vehicles) and reduced variability (e.g. SUMO vehicles prevented from changing lanes).

6.2 Scenario 2

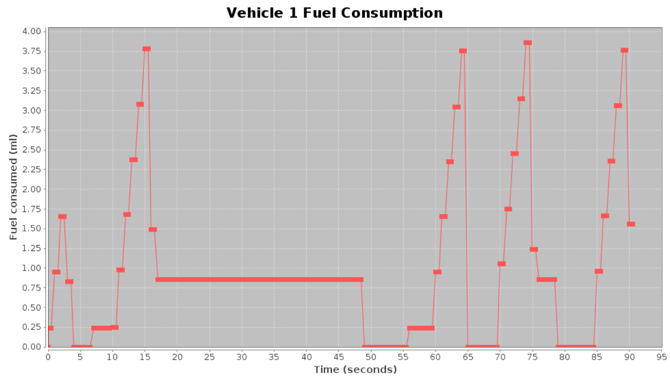
In this scenario, two experimental variations are reported. Firstly, a baseline where the vehicle is given its route, and SUMO handles speed control. In this case, the vehicle will obey the appropriate speed restriction for that road, and slow down, if required to, for events such as turns at junctions.

It can be seen in the baseline results of Figure 6 that there is some significant variation in fuel consumption usage. The vehicle initially accelerates up to appropriate speed for that road, with its fuel use remaining constant until it arrives at junction 1, which is on a red light. The vehicle comes to a stop at this light and idles for five seconds, until the light turns green. The vehicle then accelerates and arrives at the second junction which is also on a red light. This light changes to green before the vehicle starts to idle, at which point the vehicle accelerates again and arrives at the third junction. The vehicle slows as this is a left hand turn, before reaching the 'END' location at approximately ninety seconds.

The institution scenario results can be seen in Figure 7, where some immediate visual differences can be seen compared to Figure 6, due to the different chain of events caused by the institution involvement. In this case, at 15 seconds the institution issues the obligation `obl(reduceSpeed(Agent))`, resulting in the vehicles speed being reduced for 35 seconds. At 55 seconds this action is completed, and so the vehicle increases its speed back to the road limit. However, the vehicle arrives at junction 1 while the light is green, and so does not waste fuel idling or having to perform acceleration from stationary. The vehicle then passes through junction 2 as well, and at 85 seconds reduces speed for the turning at junction 3. This is followed by a spike in fuel consumption to increase speed, and approximately 95 seconds the vehicle arrives at the 'END' location.

Whilst the individual fuel consumption profiles are useful to explore in relation to events in each scenario, a more substantial result can be found when taking the cumulative fuel consumptions for non institution and institution variants of this scenario. The results of this are shown in Figure 8.

Here a direct comparison of the results presented in Figures 6 and 7 can more easily be made, and there are some



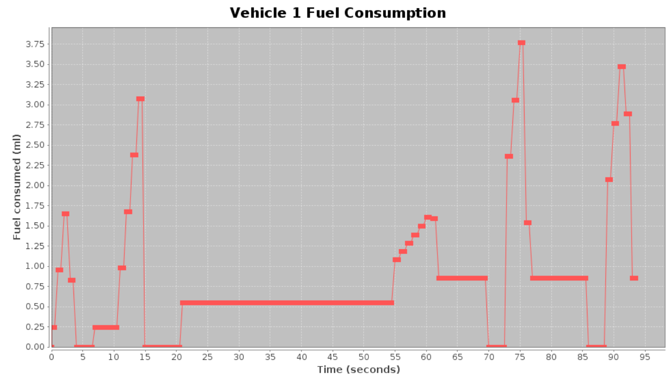


Figure 6: Scenario 2 fuel consumption, no institution http://people.bath.ac.uk/vb216/S2NoInst.mp4

Figure 7: Scenario 2 fuel consumption, with institution http://people.bath.ac.uk/vb216/S2WithInst.mp4

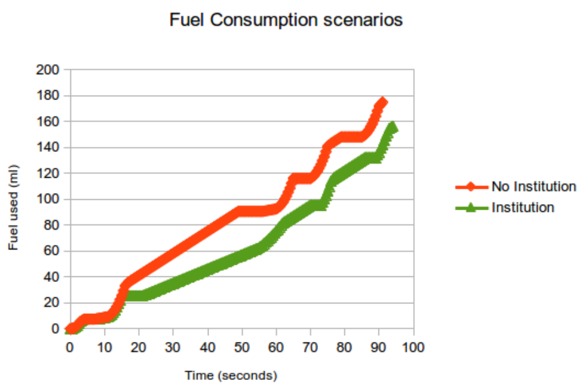


Figure 8: Cumulative fuel consumption

key findings to draw out. Firstly, despite the fact that the institution has enforced a slower speed on the vehicle for a significant duration of the scenario, the vehicles arrive at almost the same time (3 seconds difference). However, in the institution variant of the scenario, there is almost 20ml less fuel used, approximately 10 percent less. As there is a correlation between emissions and fuel consumption, this also signifies that there is a significant reduction in CO_2.

7. SUMMARY

In essence this work is an investigation into knowledge representation and transmission across a distributed platform, set in the context of intelligent vehicle systems. By performing elements of data fusion, and allowing components within the system to subscribe to their desired information source, we explore the question of whether it becomes possible to understand more, but communicate less. This ethos carries through the various system components, for example the 3D viewer ability to represent both environment spatial information through to agent mind state beliefs and plans.

Specific to the use of norms, the aspiration is to reduce the burden of coding for every eventuality, by aggregating data to suitable levels and triggering more powerful plans and actions based on this. Rather than Jason agents having to reason about their physical spatial conditions in relation to upcoming traffic lights, they receive more appropriate belief updates at a higher level. Similarly the institution does not have to micro-manage the vehicle's speed, instead it issues a higher level obligation to slow down, and leaves this to the vehicle to resolve appropriately.

To explore the benefits of such functionality, the two scenarios demonstrate areas where human drivers struggle with uncertainty of appropriate action selection, both for their own benefit, and (with even more difficulty) what to do for the greater collective benefit. In these cases, a single institution has been shown in each scenario as being capable of resolving, and improving, the situation.

Results from the first scenario of a vehicle moving out of the way of another vehicle show a clear variation in fuel consumption, though a less clear overall impact of this to the wider vehicle population. Results from the traffic flow measurements are not conclusive, but with further improvements may prove a suitable metric to capture such aspects. Further work is planned on this component, firstly, in validating the detectors by checking against the original traffic flow data used. Furthermore, the new fuel consumption model planned for SUMO will be used to reassess the fuel consumption expectations of the excessive brake-accelerate behaviour in this scenario.

Results from the second scenario show a benefit to the individual vehicle adopting the institutions obligations. By reducing that vehicles speed (to the detriment of the apparent benefit of arriving at its destination faster) both fuel consumption and emissions are reduced. This scenario will also be expanded to include background traffic, as well as the complexity of how to manage multiple traffic lights, which may then become a minimisation problem (also suitable for resolution by some software component).

Having produced results which indicate there is a useful role as well as quantifiable benefit for institutions in governing a future of autonomous vehicles, further experimentation is planned. Scenarios involving the use of multiple institutions to resolve conflicting cases will be implemented in order to further explore the use of norms in the vehicle domain. Further metric development and validation is also planned, in order to better capture and represent the impact of institutions across the community of vehicles.

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