1 Lane-Changing Model in SUMO

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1.1 Abstract

SUMO is an open source microscopic traffic simulation. A major component of modelling microscopic vehicle behavior is the lane-changing behavior on multi-lane roads. We describe a new model which uses a 4-layered hierarchy of motivations to determine the vehicle behavior during every simulation step and motivate in which ways it improves the current lane-changing model.

Keywords: microscopic simulation, lane changing.

1.2 Introduction

The SUMO application suite [1, 2] provides tools for the **S**imulation **O**f Urban **MO**bility. It consists of a microscopic simulator for multimodal road traffic and a host of applications for preparing simulation input data (network import and modification, traffic import, routing) and for working with simulation outputs. The microscopic driving dynamics of road vehicles are determined by the interplay of several models briefly listed below:

- **Car-following model:** determines the speed of a vehicle in relation to the vehicle ahead of it.
- **Intersection model:** determines the behavior of vehicles at different types of intersections in regard to right-of-way rules, gap acceptance and avoiding junction blockage.
- **Lane-changing model:** determines lane choice on multi-lane roads and speed adjustments related to lane changing.

When simulating traffic on complex road networks with multi-lane roads, most routes which a vehicle might use require changing lanes. Even where there are no such hard necessities, lane-changing behavior is often a major determinant for traffic efficiency which underscores the importance of the respective model.

The lane-changing model in SUMO has been under continuous development since the start of the project in 2001 and will certainly undergo changes in the future. Due to a large number of improvements in 2013 we see the need to report on the current state of the model. These changes were prompted by problems and visibly implausible behavior in some of our simulation scenarios.

- Motorway traffic which requires many vehicles to change lanes at a point where the motorway splits exhibited heavy jamming contrary to real-world measurements (*A92* scenario).

- Heavy jamming where motorway traffic in the main direction came to a stop because of vehicles merging at on-ramps (*Braunschweig* scenario).
- Jamming because vehicles did not change to their respective turn lanes in time and thus blocked the flow (*Braunschweig* scenario).
- Jamming because vehicles only used the outer lanes of a two-lane roundabout (*ACOSTA* scenario)

The model changes which were undertaken to alleviate these problems are tightly interwoven with the previous model which makes it impractical to discuss them in isolation. Instead we will describe the new model fully in the following sections and then describe areas of improvement relating to the above scenarios in section 1.10. Where the new model differs significantly from the previous model this is indicated by the flag **(new)** within the descriptions.

The lane-changing model described herein fulfills two main purposes: It computes the change decision of a vehicle for a single simulation step based on the route of the vehicle and the current and historical traffic conditions in the vehicles surroundings. Furthermore, it computes changes in the velocity for the vehicle itself and for obstructing vehicles which promote the successful execution of the desired lane change maneuver.

In comparison to other microscopic lane-changing models, this model explicitly discriminates between four different motivations for lane-changing. After discussing the general architecture of lane-changing within the simulation, the handling of these four motivations will be discussed in detail. The complete formulas and decision trees used in the implementation cannot be given due to lack of space. For those wishing to re-implement or modify these models, this paper should serve as a useful guide when reading the source files of the implementation in SUMO [3].

1.3 Architecture

Road traffic simulation in SUMO represents the road network in terms of **edges** which are unidirectional street segments between intersections and remain constant in their number of lanes, and their maximum speed (among other attributes). An edge consists of one or more parallel **lanes** which correspond to the (mostly marked) lanes found in European road networks. These lanes are **indexed** from right to left starting at 0. The route of a vehicle is stated in terms of the edges it needs to follow but during the simulation it moves along the lanes with mostly free choice of lane usage (except where lane usage restrictions are explicitly defined). Connectivity in the road network is defined on the level of lanes, with each lane having 0 or more successor lanes. If the lane on which a vehicle drives does not have a successor lane which belongs to the next edge along this vehicles route, the vehicles must change its lane in order to continue.

The speed of a vehicle is mainly determined by the next vehicle in front of it called the **leader**, which may be on the same lane or on the preferred successor lane after the current lane. This preference is discussed in section 1.4.1. The speed for following the leader is defined by the car-following model which is not discussed in this paper [5]. A vehicle may only change its lane if there is enough physical space on the **target lane** and if it neither comes to too close to the leader on the target lane nor to its immediate **follower** on the target lane (*too close* being defined by the car-following model). If either of these conditions is not met, the vehicle is said to have a **blocking leader** or a **blocking follower**. To distinguish the vehicle currently under consideration from its leaders and followers we will refer to it as the **ego** vehicle. A

vehicle that advances to a lane on the next edge is said to **advance** the lane, whereas a vehicle that changes to a parallel lane on the same edge is said to **change** lane.

During each simulation step, the following sub-steps are executed in order for every vehicle:

1) Computation of preferred successor lanes (called **bestLanes)**
2) Computation of safe velocities under the assumption of staying on the current lane and integration with lane-changing related speed requests from the previous simulation step
3) Lane-changing model computes change request (left, right, stay)
4) Either execute lane-changing maneuver or compute speed request for the next simulation step (involves planning ahead for multiple steps). Whether speed changes are requested depends on the urgency of the lane-changing request.

The sub-steps 3 and 4 are handled by a customizable software component the *laneChangingModel*. This gives a high amount of configurability within the bounds of the architecture. The *laneChangingModel* described in this paper is can be swapped against the previous model by setting user-configurable parameters. In the following, the four motivations for lane-changing are discussed in the order of their priority beginning with the most important. In section 1.9 we explain how conflicts between these motivations are resolved.

1.4 Strategic lane changing

Whenever a vehicle must change its lane in order to be able to reach the next edge on its route, we call this type of lane changing *strategic.* This happens whenever the current lane of the vehicle has no connection to the next edge of the route. In this case we say that the vehicle is on a **dead** lane. Note that such a lane does not have to be a dead-end in the common sense. A left-only turn lane is dead from the perspective of a vehicle that wants to go straight. A vehicle may perform a strategically motivated lane change well in advance before reaching the dead lane if no other motivation prevents it. This topic is discussed in the next two sections.

1.4.1 Evaluating subsequent lanes

Vehicles (or rather their assumed drivers) need to decide a sequence of lanes to follow along their route of edges. In this they have some degree of restriction (because some lanes are dead-ends) and they have some degree of freedom because there are multiple lane sequences available. In SUMO a data structure is computed which allows retrieving the following information necessary for subsequent computations:

a) For every lane on the current edge, a sequence of lanes that can be followed without lane changing up to the next dead-end or to a maximum distance (**bestLanes**).
b) For every lane on the current edge, the traffic density along the bestLanes (**occupation**)
c) For every lane on the current edge, the offset in lane index to the lane which is strategically advisable (**bestLaneOffset**)

Note, that multiple lanes may have a bestLaneOffset of zero. In this case, the bestLaneOffset of other lanes points to the closest best lane. Most parts of this data-structure are only updated whenever the vehicle advances to the next lane. The algorithm for computing this data structure is discussed in [3]. The strategically advisable direction is not part of the

customizable architecture because it is rather unambiguous (being based on maximizing the drivable distance and minimizing the number of necessary lane changes). Nevertheless, improvements in this part of the lane-changing model were made by fixing long-standing implementation bugs during the work on improving the lane-changing model in SUMO.

1.4.2 Determining Urgency

While approaching a dead-end lane, a vehicle has some amount of freedom to pursue the strategically advisable lane (which may involve changing or staying) or to follow conflicting motivations. The urgency for following the strategic necessities (i.e. changing to the left if bestLaneOffset < 0 and changing right if bestLaneOffset > 0) correlates with the following factors:

a) remaining distance to the dead-end
b) the presumed speed while approaching the end of the dead lane (**lookAheadSpeed**)
c) magnitude of the bestLaneOffset
d) occupation on the ultimate target lane (lane with bestLaneOffset = 0)
e) occupation of the intermediate target lane (next target in direction of the bestLaneOffset

A strategic change is deemed urgent if the following relation holds true:

$$d - o \; < \; lookAheadSpeed \; \times \; abs(bestLaneOffset) \times f \quad (1)$$

Where d is the distance to the end of the dead lane, o is a discount due to occupation and f is a factor that encodes the time typically needed to perform a successful change maneuver set to 10 for changing to the left and 20 for changing to the right.

Notably, if there are multiple lanes in between the current lane and the ultimate target lane, all their occupations should also matter, but are not currently evaluated. The lookAheadSpeed depends on the current and historical speed of the vehicle. This is necessary to avoid vehicles which temporarily have to slow down from losing all sense of urgency (new). The expected number of seconds until reaching the end of the dead lane (**remainingSeconds**) is used in subsequent computations. Currently, urgency is only considered for strategic lane changes but we discuss how it could apply to other motivations in section 1.11.

1.4.3 Speed adjustment to support lane-changing

Whenever a desired lane change cannot be executed due to blocking vehicles, a vehicle may adjust its speed to allow the lane change to succeed in later steps. Furthermore a vehicle may exert an influence on the speed of blocking vehicles (in reality this typically happens as a reaction to observing the turn signals of the ego vehicle). Due to the importance of completing strategic lane changes, it is assumed that the ego vehicle will take careful adjustments to enable the change. Basically, vehicles are assumed to drive at the maximum safe speed, so speeds can only ever adjusted downwards. However, as a part of the car-following model, vehicles may have a stochastic component which prevents them from using their maximum possible acceleration. Preventing this stochasticity (called **dawdling**) is a way of increasing vehicle speeds somewhat.

To compute the desirable speed adjustments, the following hierarchy of situations is distinguished by comparing ego speed, blocker speed, gaps and remainingSeconds (new):

(1) Has blocking leader
   a. **Will be able to overtake leader:** request leader to refrain from speeding up, prevent dawdling, (prevent overtaking on the right where forbidden by law)

> **b. needs to stay behind the leader**
>> **i.** slow down to stay behind the leader
>> **ii.** keep speed since the leader is faster anyway
> **(2) leader is not blocking:** set a maximum speed to ensure that the distance to the leader remains sufficiently high
> **(3) there is no leader:** drive with the maximum safe speed

The above decision tree results in a **plannedSpeed** with regard to a blocking leader. Using this value,

> **(4) has blocking follower**
>> **a. will be able to cut in before follower**
>>> **i. fast enough to do so with current speeds:** request follower to refrain from speeding up, prevent dawdling
>>> **ii. follower decelerating once is sufficient to open a gap:** request follower to decelerate as much as needed, prevent dawdling
>> **b. needs to be overtaken by follower**
>>> **i. follower should slow down a bit to increase the chance that subsequent followers will be slow enough:** request follower to decelerate a bit, slow down to be overtaken fast enough
>>> **ii. follower should overtake quickly:** prevent follower from dawdling, slow down to be overtaken fast enough

Speeds, computed in this way are integrated with the maximum safe speed (**vSafe**) as computed by the car-following model by using the minimum of vSafe and all requested speeds.

The distinction between cases (4)b.i and (4)b.ii warrants further explanation. Whenever a vehicle tries to change from an on-ramp onto the motorway it has to yield to vehicles already on the motorway. These vehicles may slow down slightly to help merging vehicles, but they must not cause the flow on the motorway to break down. For this reason, vehicles that try to change to the left only cause blocking followers to slow down if their own speed exceeds a threshold value (currently 27m/s).

1.4.4 Preventing deadlock

If a vehicle needs to stop on a dead lane because changing to a continuing lane did not succeed it creates an undesirable impediment to traffic flow. The measures in the previous section help to prevent this situation from occurring too often (and it does occur in reality as well). However, if two vehicles on adjacent lanes both need to change to the lane occupied by the other vehicle (**counterLaneChange**) and both vehicles reach the end of a dead lane, a deadlock occurs. Neither vehicle has the option of driving any further nor can either vehicle get the space it needs to execute the strategic lane change (vehicles in SUMO cannot go backwards). This situation blocks the flow of traffic on both lanes and is highly undesirable. Currently, it can only be resolved by moving vehicles in a non-standard way (teleporting) after a time threshold is elapsed.

To prevent this type of deadlock, special care is taken whenever two vehicles are in a counterLaneChange relation. We refer to the vehicle which is closer to the end of the dead lane as the **blocking leader** and the other vehicle as **the blocking follower**. Note that this relation may change from one simulation step to the next. Generally, the blocking follower slows down when approaching the dead-end to ensure that the blocking leader has enough

space to complete its lane change. In some cases the blocking follower is too fast or the blocking leader is too long. In this case the blocking leader must slow down to leave enough space for the follower before the dead-end (new).

Unfortunately, dead-lock situations can still arise if vehicles need to perform strategic lane changes across multiple lanes. In this case, a counterLaneChange situation can arise at a time where both vehicles have already reached the dead-end and are unable to move. To prevent this, vehicles reserve additional space in front of the dead-end whenever they have to change across more than one lane (new). Currently, additional space of 20m is reserved for vehicles which need to change to the right across and 40m for vehicles which need to change to the left. The asymmetry is necessary to prevent yet another type of deadlock. The values were selected because they were found to perform well in preventing deadlock. Eventually they should be made configurable and be subject to rigorous calibration.

1.5 Cooperative lane-changing

In some real-world situations vehicles (or rather their drivers) perform lane-changing maneuvers with the sole purpose of helping another vehicle with lane-changing towards their lane. In the current model, vehicles are informed by other vehicles about being a blocking follower (the reason being that the turn-signals of the vehicle being blocked are always visible to the follower, whereas being a blocking leader is less obvious). If there are no strategic reasons against changing the lane, the ego vehicle may change in either possible direction to clear a gap for the blocked vehicle. Contrary to expectation, this was found to have a beneficial impact on traffic flow in some scenarios even if the ego vehicle attempts to change towards the blocked vehicle. This effect is not yet understood and warrants further investigation.

Vehicles which cannot perform a cooperative lane change adjust their own speeds slightly to increase the success probability for subsequent simulation steps. However, they do not request speed changes if they are blocked.

A special case for cooperative behavior arises at multi-lane roundabouts. Typically, all vehicles enter the roundabout at the outermost lane and also need to leave again at the outermost lane. Due to the short distances involved, this means they should always remain on the outermost lane for strategic reasons. However, this effectively turns all multi-lane roundabouts into one-lane roundabouts and thus degrades throughput. For this reason, the lane-changing model compels vehicles which are not yet on their final roundabout edge to change towards the inner lane (new). While this ignorance of strategic motivations sometimes results in stranded vehicles it has a beneficial impact on roundabout performance (see results for the *ACOSTA* scenario).

1.6 Tactical lane-changing

Tactical lane-changing refers to maneuvers where a vehicle attempts to avoid following a slow leader. It requires balancing the expected speed gains from lane changing against the effort of lane-changing (which is arguably a very driver-subjective value). The expected speed gains must also be balanced against the obligation for keeping the overtaking lane free. Failure to do so results in situations where slow vehicles with minor speed differences become major impediments to traffic flow. This part of the model is left unchanged from the old model [4]. Each vehicle maintains a signed variable **speedGainProbability** which by its sign indicates the beneficial change direction and by its magnitude the expected benefit. If the magnitude exceeds a threshold value, a tactical lane change is attempted. The variable

speedGainProbability is modified incrementally during each simulation step and reset upon lane changing to prevent oscillations. If the lane to the left is faster than the current lane the value is updated according to the following formula:

$$speedGainProbability := speedGainProbability + \frac{v - u}{v} \quad (2)$$

Where v is the expected speed on the left lane and u is the expected speed on the current lane. If the left lane is slower, speedGainProbability is divided by 2 instead. If the right lane is faster than the current lane by at least 5 km/h the value is updated as:

$$speedGainProbability := speedGainProbability - \frac{v - u}{v} \quad (3)$$

Where v is the expected speed on the right lane and u is the expected speed on the current lane. If the right lane is slower, speedGainProbability is again divided by 2 instead. The asymmetry in handling changes to the left and to the right and the size of the thresholds (-2.0 for changing to the right, 0.2 for changing to the left) serve to prevent oscillations in lane usage.

Currently, whenever a slower vehicle cannot be overtaken because the ego vehicle is on the right side of it (and overtaking on the right is prevented in SUMO in accordance with German driving regulations), an impulse to move towards the left lane is generated. This should allow the blocking vehicle to move to the right and be overtaken on the left. This prohibition and the resulting behavior can be disabled by setting the simulation option **--lanechange.overtake-right[1]**.

1.7 Obligation to clear the overtaking lane

The compulsion to clear the overtaking lane could be framed as cooperative behavior because it helps other faster moving vehicles. However, contrary to the cooperative lane-changing behavior described in section 1.5 which is optional, the behavior described in this section is mandated by traffic laws. In the current lane-changing model, each vehicle maintains a variable **keepRightProbability** which is decremented over time and triggers a lane change to the right once a lower threshold value of -2 is exceeded (negative values are used in allusion to the variable speedGainProbability).

In reality, (German) drivers are obliged to change to the right unless they plan to overtake another vehicle. This anticipation of future behavior is modeled in the following way (new): If the current lane is not faster than the right lane by at least 5 km/h the ego vehicle determines the time t it could expect to drive with its desired maximum speed on the right lane before having to perform an overtaking maneuver depending on the gap and speed difference to the lead vehicle on the right. This is used to update the value of keepRightProbability p:

$$p := p - \frac{t * L}{V * v * T} \quad (4)$$

Where L is the legal speed limit on the current road, V is the maximum desired speed of the ego vehicle, v is its current speed and T is a calibration parameter currently set to 5. Thus, vehicles only change to the right if the expectation that they may stay there for some time is confirmed repeatedly. Vehicles which desire a lower speed are more eager to change to the right.

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[1] Available in the current source repository and in version 0.21.0 which is expected to be released at the time of this publication.

1.8 Remote controlled lane changing (TraCI)

Running SUMO simulations can be controlled by external programs using an interface called TraCI (**Tra**ffic **C**ontrol **I**nterface). Among the things that can be controlled is the lane usage of the vehicles. Remote requests to change to a target lane or keep the current lane must be integrated with the "intrinsic" requests computed by the lane-changing model. This is accomplished by letting the user determine the urgency and the priority of remote requests by setting appropriate flags (new).

As an example, the interface allows the remote program to specify that a given vehicle should try to change to the left lane with urgency (i.e. with speed adjustments to itself and to blockers), unless there are urgent strategic reason against changing to the left and that the vehicle should ignore all other requests by the lane-changing model.

1.9 A hierarchy of lane changing motivations

The four motivations discussed above are considered in a hierarchical fashion as described by the following decision schema. The first statement which applies determines the vehicles change request. In every simulation step, each vehicle first considers changing to the right, and if no change to the right is performed, a change to the left is considered as well. Accordingly, the currently considered direction d is either right (-1) or left (1) according to resulting offset in lane index.

1. **Urgent strategic change to d needed:** change
2. **Change to d would create an urgent situation:** stay
3. **Vehicle is a blocking follower for another vehicle with urgent strategic change request:** change
4. **speedGainProbability above threshold and its sign matches d:** change
5. **non-urgent strategic change to d needed:** change (new)

An important aspect of preventing stopping at a dead lane is avoiding detrimental lane changes. Generally speaking, the fewer lane change maneuvers vehicles have to perform, the less chance they have to become stuck. One change that was found to be quite beneficial was the avoidance of changing to a dead lane which continues elsewhere. This is most often the case for turn-lanes at an intersection. A vehicle which intends to go straight should not use the left-only turn lane to get ahead because it will find it difficult to go back onto the required lane (new). In reality these turn-lanes often have directional markings at their start and there are rules which prohibit their use by vehicles which follow another direction.

1.10 Improvements over earlier Model

For a quantitative evaluation of the improvements, the following metrics were computed for a selection of benchmarking scenarios.

- **avgWaitingTime:** the average time each vehicle spent with speed below 0.1m/s
- **wrongLaneTeleports:** the count of vehicles which had to be moved artificially (teleported) because they could not complete a strategic lane change (after a threshold time t)
- **jamTeleports:** the count of vehicles which had to be moved artificially (teleported) because the successor lane was occupied (after a threshold time t)

The scenario *Braunschweig* contains the urban area of the German city Braunschweig (Brunswick) and the surrounding area with sections of motorway. The scenario spans one day and contains 650000 vehicle movements. The threshold time for teleporting was set to 120 seconds.

The scenario *A92* consists of a motorway section in southern Germany with a length of 20km. It contains 63000 vehicle movements over the course of one day. The threshold time for teleporting was set to 300 seconds.

The scenario *ACOSTA* is comprised of a section of the Italian city of Bologna and contains 9000 vehicles over the course of 1 hour. It is notable for containing a 2-lane roundabout. The threshold time for teleporting was set to 300 seconds.

The algorithms *old* and *new* correspond to the SUMO vType parameters laneChangeModel="DK2008" and laneChangeModel="JE2013". As can be seen in Table 1, the new algorithm brings a significant improvement in all considered scenarios. Additional topics for future improvement are discussed in the next section.

Scenario/Algorithm	avgWaitingTime	wrongLaneTeleports	jamTeleports
Braunschweig/old	89.73	845	464
Braunschweig/new	46.66	7	9
A92/old	17.16	21	1
A92/new	0.02	0	0
ACOSTA/old	144.59	0	7
ACOSTA/new	76.69	0	0

Table 1 Performance metrics for old and new lane-changing model and different scenarios.

Compared to the old lane-changing model described in [4], the new model shows improvements in the following areas:

- Fine grained control over speed adjustments to ego vehicle and blockers lead to higher fulfillment rate of change request. In the old model, vehicles always reacted to blocking leaders by slowing down and they always slowed down when being a blocking follower (improved all metrics and all scenarios).
- Extrapolation of dynamics over multiple steps allows better choices between overtaking blockers and allowing to be overtaken (also improves the success rate and thus improves all metrics).
- Improved checking for deadlock-prone situations avoids deadlocks in more cases. In the old model, some cases of deadlock were avoided by allowing neighboring vehicles with opposite change requests to swap their positions instantly. This oversimplification is no longer necessary (primary impact on wrongLaneTeleports but secondary effect for the other metrics).
- Asymmetrical behavior when helping other vehicles with lane-changing (depending on the direction of change) prevents the main flow from breaking down at busy highway on-ramps (improved avgWaitingTime especially in *Braunschweig*).
- Special behavior within multi-lane roundabouts ensures that all lanes are used whereas in the earlier model only the outer lane was ever used (improved avgWaitingTime and jamTeleports, only *ACOSTA*).
- The explicit discrimination between the 4 different motivations for lane changing allows fine grained control for integrating model dynamics with external change

requests (TraCI). This was necessary to successfully complete a project which simulated automated platooning (not discussed here).

Note, that a large number of model changes were tested in isolation using the above metrics. To simplify the presentation of our results we only show the effect of all combined model changes. It can be seen that all metrics improved for all scenarios except for the few cases where they had the best possible value to begin with, thus validating the useful ness of the new lane changing model. The *A92* scenario is based on fine grained detector measurements which showed no jamming in the real world data. Also, the *Braunschweig* scenario exhibited deadlocks and jamming with a frequency that was utterly implausible for the demand model of a normal working day. Although improved traffic flow is not generally a sign of a more realistic model (after all, jams are a fact of life), for the above scenarios an increase in realism can be posited.

1.11 Outlook

The focus of the recent improvements of the lane-changing model was on deadlock-prevention and success rate of lane-changing. Since these dynamics are qualitative rather than quantitative and the failure cases a visibly obvious, simulation behavior could be tuned by inspection. The next goal is to calibrate the model to reproduce empiric lane-usage data.

Current measurements are promising but indicate room for improvement. Figure 1 and figure 2 show the evolution of simulated traffic measurements with the leftmost data points being taken directly from traffic measurements on the German motorway A3 whereas data points to the right are measured at successive points on an otherwise featureless 3 lane road. It can be seen that vehicles more or less maintain the lane distribution and speeds which were measured in reality. Numbers are averaged over a simulated period of 24 hours.
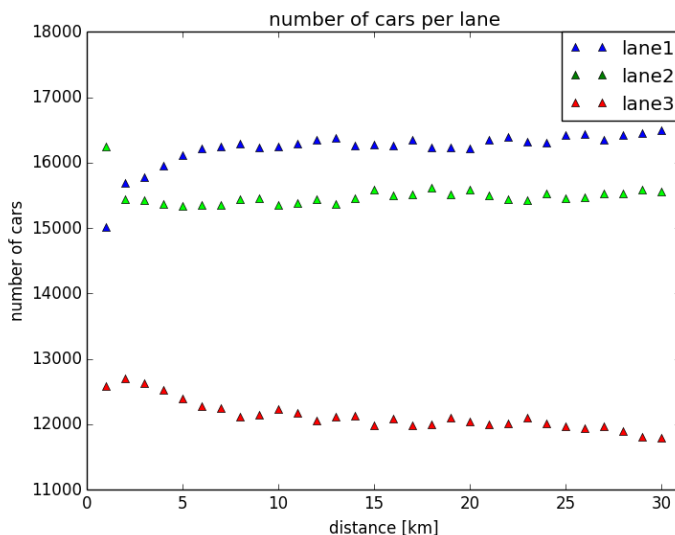

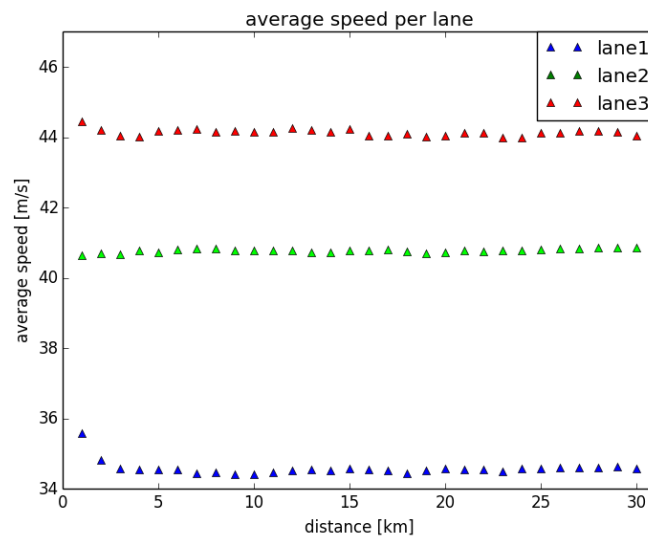Figure 1 Evolution of lane usage over space for a 3-lane motorway section

Figure 2 Figure 3 Evolution of speeds over space for a 3-lane motorway section

To allow model calibration, several hard-coded model parameters shall be exposed to the end user in a future release. There should at the very least be one parameter for each of the four motivations:

- Urgency of strategic changes
- Tradeoff between altruistic and egoistical behavior
- Eagerness to realize speed-gains
- Eagerness to clear the overtaking lane

Using these parameters the model will be calibrated and validated using real world measurements.

Cooperative lane-changing has not been extensively looked at and is a probable candidate for model improvements. Currently, only blocking followers change cooperatively whereas real-world situations are conceivable in which blocking leaders change as well. A typical situation which is not yet considered by the lane-changing model is the coercion to change to the right because a faster vehicle is approaching from the rear on the same lane. Another point is the usage of multi-lane roundabouts where currently, some vehicles become stuck on a dead-end inside lane. Additional checks should be done to prevent these situations from arising. It would also be helpful to know the degree in which inner lanes of roundabouts are used in reality. The curious fact that cooperative lane changes towards the vehicle being benefit simulation performance should also be investigated.

Some of the above issues might be resolved by extending the concept of *urgency* to all four motivations. A cooperative lane change is more urgent if the supported vehicle is about to suffer a bigger speed loss unless it receives help. Likewise a tactical lane change is more urgent if the ego vehicle is about to suffer a bigger speed loss (due to a slow leader on its lane). Changes with the intent of clearing the overtaking lane are more urgent if the follower on this lane is about to suffer a bigger speed loss as well.

1.12 References

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