but) due to the availability of V2V communication. Availability of communication in SUMO provides an advantage to the EVA since in real traffic scenarios sirens may not always be heard or drivers may not always know the lane to clear until the EVA is in sight. Also, the SUMO strategy includes the simulator's state of the art lane change model which has been shown to compare favorably against other competing models described in [3]. Hence, the SUMO strategy we use for bench-marking is expected to be favorable to the EVA in terms of travel time.

2.2 The Fixed Lane Strategy (FLS)

FLS is a baseline strategy that is based on the following idea: the EVA identifies the lane, that is fastest on an average, based on prior information and picks that as the fixed lane for its entire journey. Assuming a right handed driving system, in most cases leftmost lane is the fastest, as faster vehicles tend to move on the left lanes while the slower ones move on the right lanes (the vice-verse typically holds true for left handed driving systems). When using FLS the EVA therefore moves to the leftmost lane from its current position and then tries to clear out the vehicles from that lane.

2.3 The Best Lane Strategy (BLS)

In BLS, the EVA calculates the utilities of the current lane and the other lanes using the utility computation function described below and then takes a decision to switch if it is beneficial to do so. Similar to FLS the EVA tries to clear out vehicles from the lane it currently is in. Also, the EVA can get the information about the speed and position of vehicles upto the **communication distance** (c_d).

We envision utility u_l, of a lane l, to be a function of the following factors: (a) Normalized speed of the slowest vehicle, calculated as (speed/maximum possible speed) and denoted by $\frac{a}{m}$ (since traffic on a lane eventually moves at speed of the slowest vehicle). (b) Normalized average speed (many times a vehicle(s) might be temporarily slow since it is just about to change a lane or near an intersection i.e., give some weight to average rather than decide entirely on temporary phenomenon), $\frac{b}{m}$, calculated as (average speed/maximum possible speed), and (c) Normalized free space (since not all vehicles may be able to switch lanes immediately after a clear lane message is received), an approximation computed as $\frac{n-c}{n}$, where c is the number of vehicles present on the lane l upto distance c_d, and n is the maximum number of vehicles that can be on the lane upto c_d. To compute n we assume an average length for vehicles which makes the computation an approximation. Here, m , maximum possible speed, is the speed limit of the road (different lanes can have additional speed restrictions). Combining the terms:

$$u_l = w_a * \frac{a}{m} + w_b * \frac{b}{m} + w_c * \frac{n-c}{n} \quad (1)$$

where w_a, w_b, w_c are the weights of each of the terms. At the beginning of the simulation an EVA starts on the lane with maximum value of u_l. Utilities are recomputed every t seconds and lane changes happen when the utility of the best lane u_b, exceeds the utility of the current lane u_c, by at least δ to compensate for lane switching overheads:

$$u_b - u_c > \delta \ (\mathit{Condition\ for\ lane\ change} \ )$$

In addition to the above described strategies, we also model the **Empty road baseline (ERB)** strategy. The ERB strategy acts as a lower bound on the EVA traversal time and captures the time taken by the EVA when there are 0 vehicles on the road apart from the EVA.

3. EXPERIMENTAL RESULTS

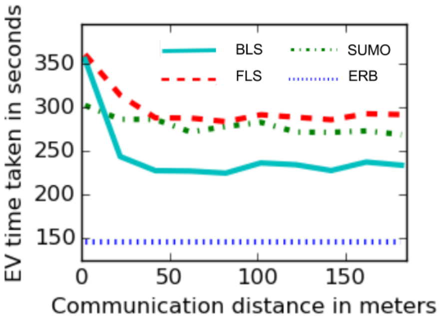

Figure 1: Variation with communication distance, c_d

For purposes of this experiment, we modeled an urban traffic environment corresponding to a densely populated city namely New York City. We tested on a wide range of lane speeds, calibrated using data from a data set providing us with actual traffic speeds of a comprehensive set of roads in New York city available from the City of New York Department of Transportation [2]. Our results in Figure 1 are an average of our simulations for a 2 km representative stretch of a road. The experiment shows how the four different strategies ERB, SUMO, FLS and BLS perform when c_d changes. The figure shows the different values picked for the parameter c_d on the x-axis (in meters) and the time taken by the EVA on the y-axis (in seconds).

FLS, BLS and SUMO strategies gain advantage from an increase in c_d as the EVA can send lane change requests to farther vehicles. BLS gains additional advantage as it also uses the information about speed and position of other vehicles present in different lanes upto distance c_d, to compute better lanes. However, increasing the distance to greater than say 75 meters, does not lead to much better computation of utilities since additional vehicles may not add much to the existing information. Overall we can conclude that, for realistic distances involving single hop communication, BLS performs significantly better than FLS and SUMO strategies (e.g., 18.90% and 16.42% improvement at $c_d = 100$ meters).

REFERENCES

[1] D. Krajzewicz, J. Erdmann, M. Behrisch, and L. Bieker. Recent development and applications of sumo–simulation of urban mobility. *International Journal On Advances in Systems and Measurements*, 5(3&4), 2012.

[2] City of New York Department of Transportation. Real-time traffic speed data. `https://data.cityofnewyork.us/Transportation/Real-Time-Traffic-Speed-Data/xsat-x5sa`, Oct. 2015.

[3] M. Rahman, M. Chowdhury, Y. Xie, and Y. He. Review of microscopic lane-changing models and future research opportunities. *Intelligent Transportation Systems, IEEE Transactions on*, 14(4):1942–1956, 2013.