Formalizing traffic rules for uncontrolled intersections

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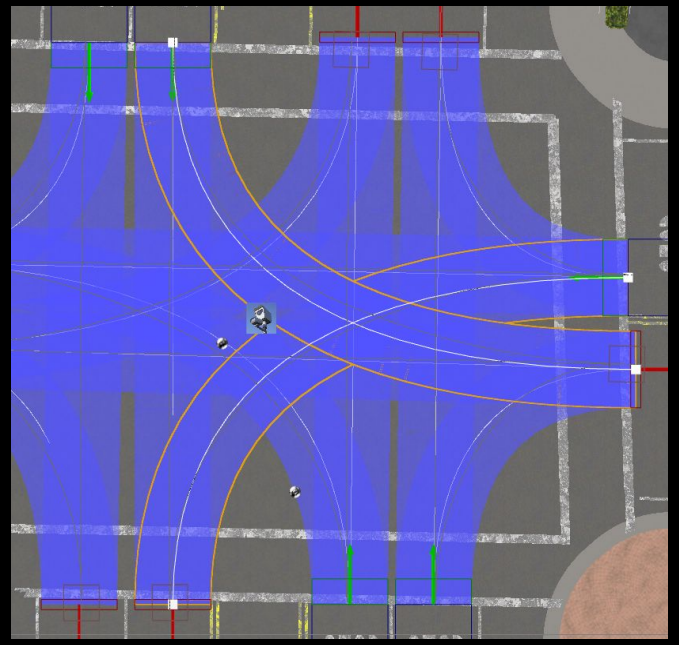
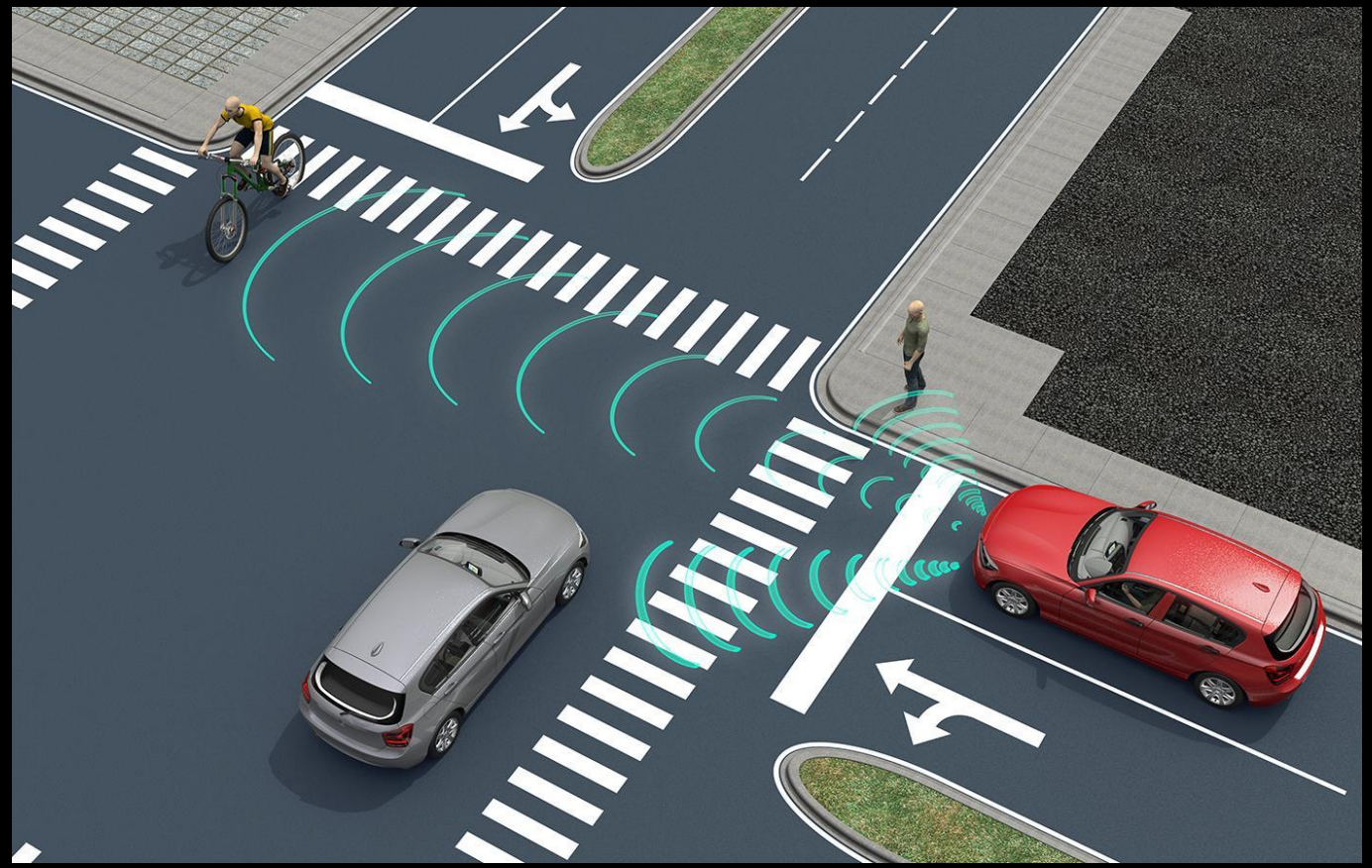
Motivation

- 47% of accidents in US in 2015 were intersection related
- 89% of AV accidents in California in 2014-2017 happened at intersections
- Intersection traffic is inherently prone to conflicts, due to lane overlaps



The requirement

Common set of traffic rules for humans and AVs



https://www.ADASLegal-IssuesAndLiabilities.com/en/

The problem

Natural Language

Translate

Formal Language

LAWS AND RULES OF THE ROAD

RIGHT-OF-WAY RULES

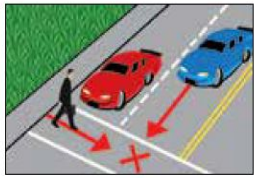
General Information

Never assume other drivers will give you the right-of-way. Respecting the right-of-way of others is not limited to situations such as yielding to pedestrians in crosswalks, or watching carefully to ensure the right-of-way of bicyclists and motorcyclists. Yield your right-of-way when it helps to prevent collisions.

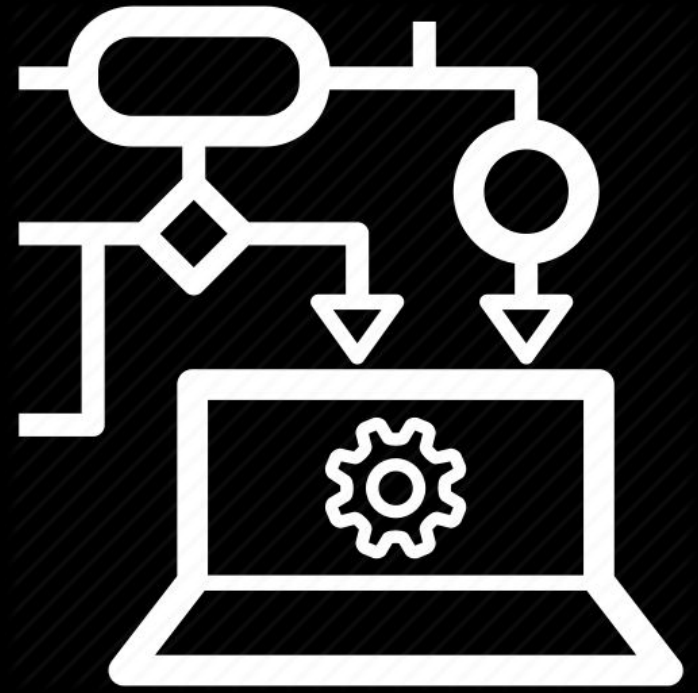
Pedestrians

A pedestrian is a person on foot or who uses a conveyance such as roller skates, skateboard, etc., other than a bicycle. A pedestrian can also be a person with a disability using a tricycle, quadricycle, or wheelchair for transportation.

- If you approach a pedestrian crossing at a corner or other crosswalk, even if the crosswalk is in the middle of the block, at a corner with or without traffic signal lights, whether or not the crosswalk is marked by painted lines, you are required to exercise caution and reduce your speed, or stop if necessary, to ensure the safety of the pedestrian.
- Do not pass a vehicle stopped at a crosswalk. A pedestrian you cannot see may be crossing the street. Stop and proceed when all pedestrians have crossed the street.



- Do not drive on a sidewalk, except to cross it to enter or exit a driveway or alley. When crossing, yield to all pedestrians.



Applications

- Automated vehicles
  - Development and testing
  - Certification
- Traffic
  - Monitoring
  - Simulation

Traffic generation in CARLA

The translation challenge

- Formal language:
  - Computable
  - Intuitive syntax and semantics
- Translation:
  - Preserve meaning

Previous approaches (ICTAC 2016):

Urban Multi-Lane Spatial Logic

- Prove safety (collision-freedom) of controllers
- Technical syntax and semantics
- Decidable (on a bounded view)

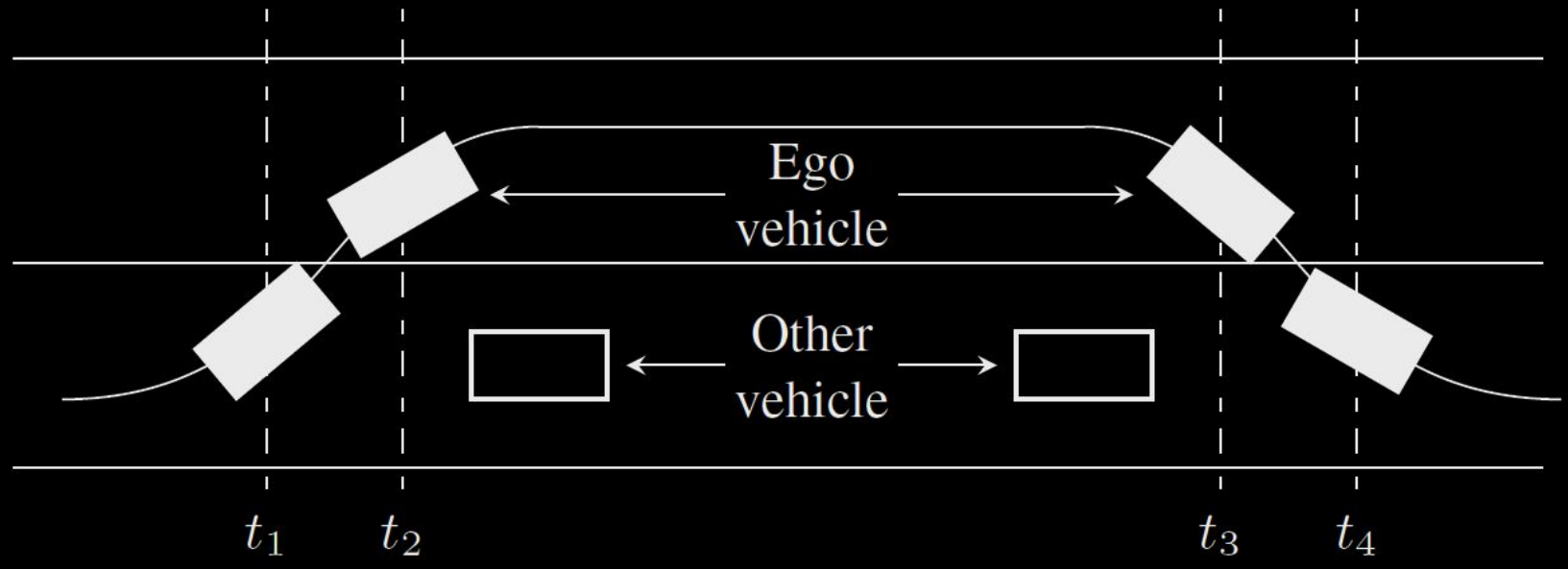
Previous approaches (IFM 2017):

Linear Temporal Logic (LTL), Higher-Order Logic (HOL)

1. “Codify” the logical form into LTL
2. “Concretize” the atomic propositions in HOL

- Applied to highway traffic

…using LTL, HOL



"During overtaking, the driver has to change from the fast lane to the right lane as soon as possible."

codify ⟹ G (merging ⟷ safe-to-return)

Our approach

- Syntax: first-order logic
- Semantics: denotational
  - Terms denote:
    - traffic objects (conceptual or physical),
    - timestamps (of discrete events)
  - Predicates denote:
    - mathematical relations

Example

"At intersections without 'STOP' or 'YIELD' signs,
yield to the vehicle or bicycle on your right
if it reaches the intersection at the same time as you.

More explicit

If vehicles V1,V2 are at the intersection,
V1 arrived at the same time as V2, and V1 is on the right of V2,
then V2 must yield to V1.

Codify in FOL

$$mustYieldToForRule(V2, V1, yieldToRight)$$
$$\leftrightarrow \begin{pmatrix} atTheIntersection(V1) \wedge atTheIntersection(V2) \wedge \\ arrivedSameTime(V1, V2) \wedge isOnRightOf(V1, V2) \end{pmatrix}$$

Codify further to atomic predicates

$$atTheIntersection(V) \leftrightarrow \big(arrived(V) \wedge \neg entered(V)\big)$$

$$arrived(V) \leftrightarrow (\exists F)(\exists T)arrivedAtForkAtTime(V, F, T)$$

$$entered(V) \leftrightarrow (\exists F)(\exists T)enteredForkAtTime(V, F, T)$$

$$arrivedSameTime(V1, V2) \leftrightarrow$$
$$(\exists T)(arrivedAtTime(V1, T) \wedge arrivedAtTime(V2, T))$$

$$arrivedAtTime(V, T) \leftrightarrow (\exists F)(arrivedAtForkAtTime(V, F, T))$$

…codify further to atomic predicates

$$isOnRightOf(V1, V2) \leftrightarrow (\exists F1)(\exists F2)(\exists T1)(\exists T2)($$
$$arrivedAtForkAtTime(V1, F1, T1) \wedge$$
$$arrivedAtForkAtTime(V2, F2, T2) \wedge$$
$$isOnRightOf(F1, F2))$$

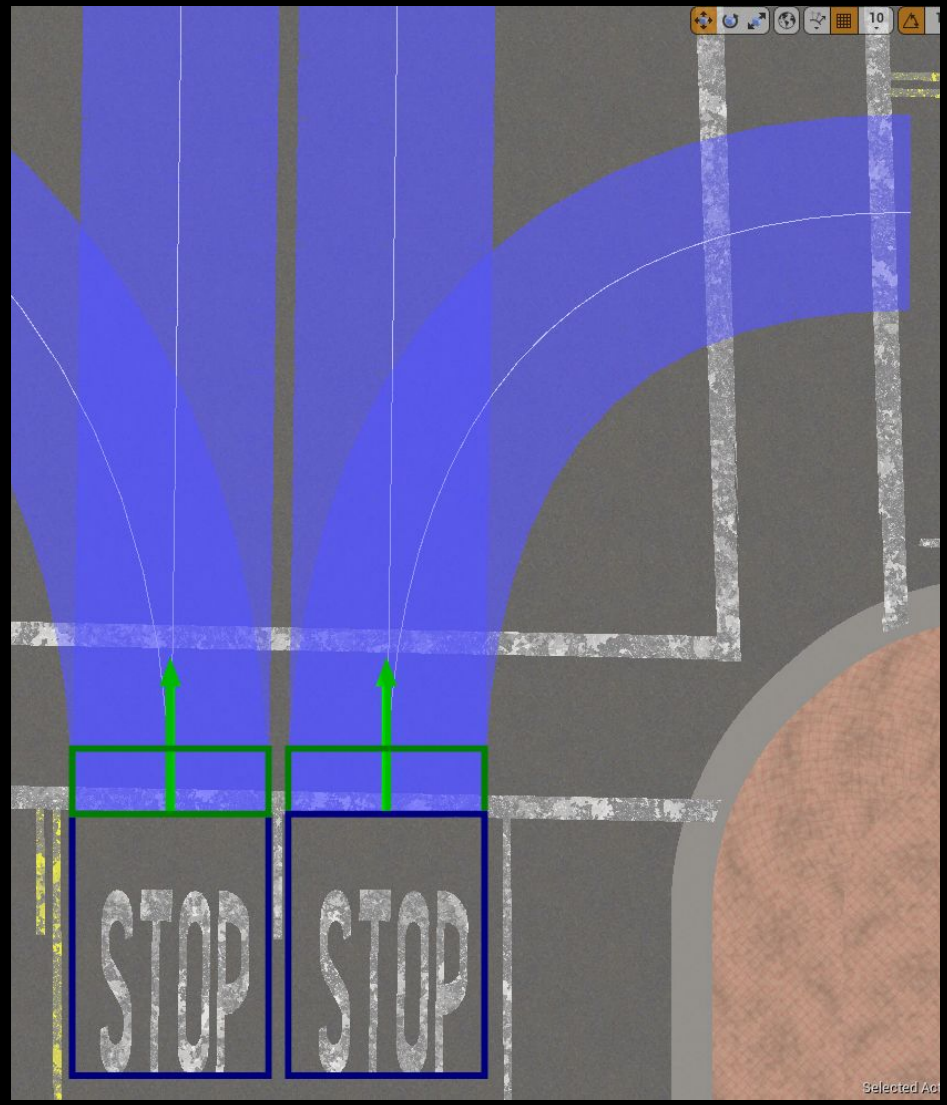
Define atomic predicates

$arrivedAtForkAtTime(V, F, T)$:

Vehicle V started overlapping with fork F's arrival box at time T

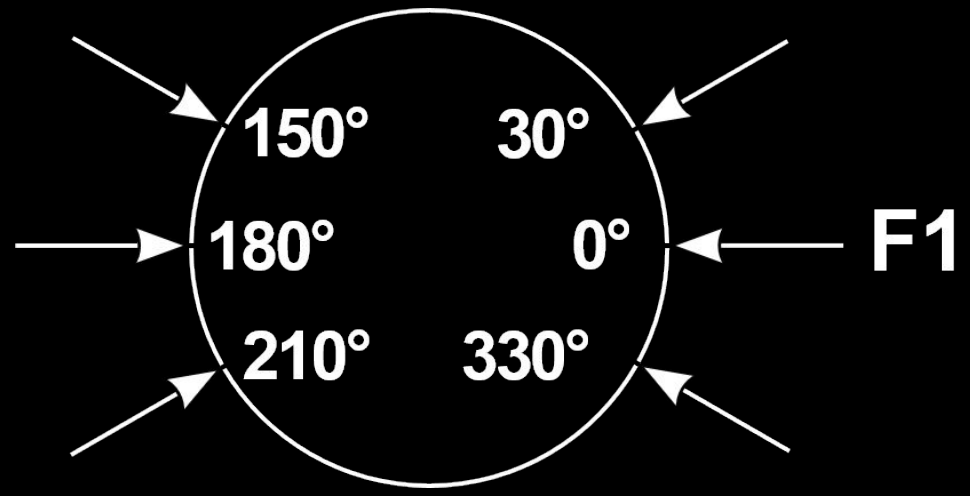
$enteredForkAtTime(V, F, T)$:

Vehicle V started overlapping with fork F's entrance box at time T



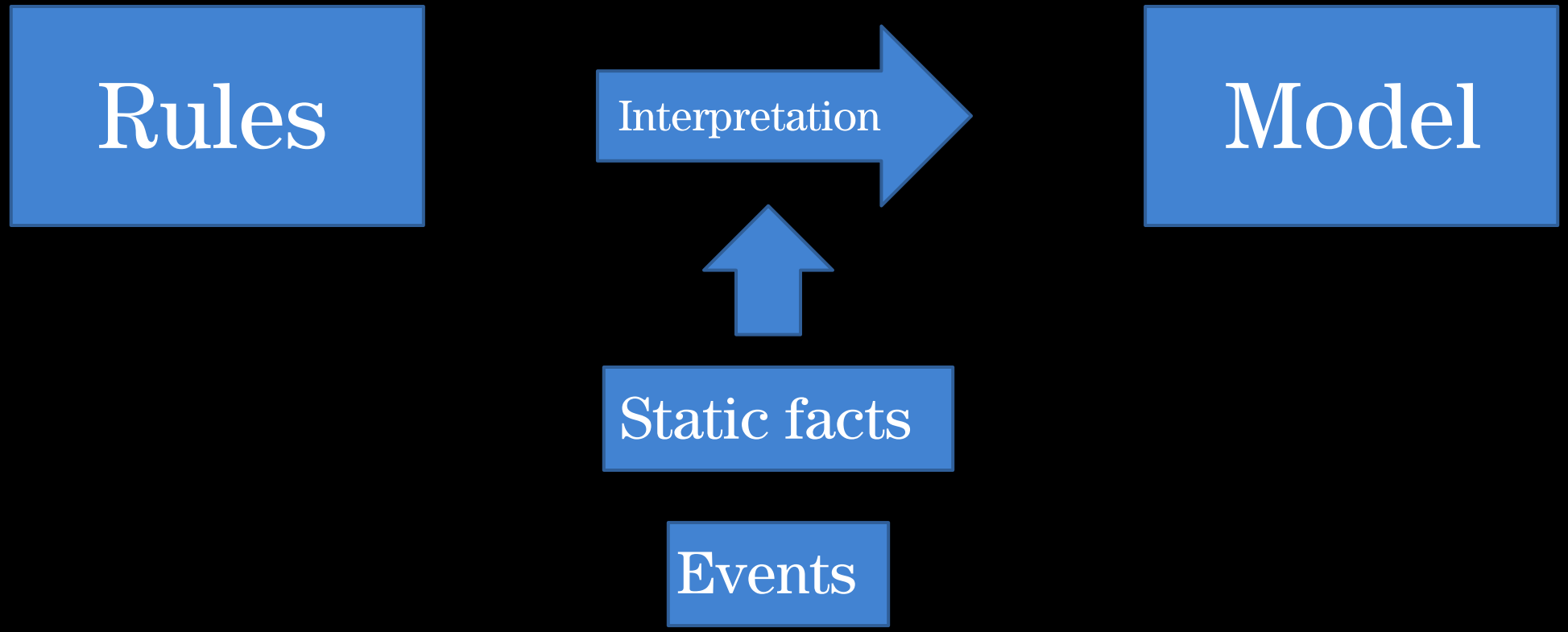
…define atomic predicates

$isOnRightOf(F2, F1)$



If the angle of F2 relative to F1
measured counterclockwise,
is more than 30 and less than 150 degrees.

Herbrand semantics



Example

$$mustYieldToForRule(V1, V2, yieldToRight) \leftrightarrow \begin{pmatrix} atTheIntersection(V1) \wedge \\ atTheIntersection(V2) \wedge \\ arrivedSameTime(V1, V2) \wedge \\ isOnRightOf(V2, V1) \end{pmatrix}$$

Interpretation

```
mustYieldToForRule(
v_BP_ChevroletImpala_C_74,
v_BP_ChevroletImpala_C_12,
yieldToRight)
```

```
isOnRightOf(f_Fork_8, f_Fork_6)
```

```
arrivesAtForkAtTime(v_BP_ChevroletImpala_C_12, f_Fork_8, 28)
arrivesAtForkAtTime(v_BP_ChevroletImpala_C_74, f_Fork_6, 28)
```

A list of implemented rules

1. “At intersections without `STOP' or `YIELD' signs, yield to traffic and pedestrians already in the intersection or just entering the intersection.”
2. “At intersections without “STOP” or “YIELD” signs, yield to the vehicle or bicycle that arrived first.”
3. “At intersections without “STOP” or “YIELD” signs, yield to the vehicle or bicycle on your right if it reaches the intersection at the same time as you.”
4. “When you turn left, give the right-of-way to all vehicles approaching that are close enough to be dangerous.”
5. “At “T” intersections without “STOP” or “YIELD” signs, yield to traffic and pedestrians on the through road. They have the right-of-way.”

Examples of predicates

Atomic	Auxiliary
arrivedAtForkAtTime(V, F, T)	inTheIntersection(V)
enteredForkAtTime(V, F, T)	atTheIntersection(V)
exitedFromAtTime(V, E, T)	isAtFork(V, F)
signaledAtForkAtTime(V, S, F, T)	isOnLane(V, L)
enteredLaneAtTime(V, L, T)	arrivedEarlierThan(V1, V2)
leftLaneAtTime(V, L, T)	arrivedSameTime(V1, V2)
isOnRightOf(F1, F2)	isOnRightOf(V1, V2)
laneFromTo(L, F, E)	branchOf(L, F)
laneCorrectSignal(L, S)	requestedLane(V, L)
overlaps(L1, L2)	reservedLane(V, L)
T1 < T2	vehicleOnThroughRoad(V)
…	…

V: Vehicle
F: Fork
T: Timestamp
E: Exit
S: turn-Signal
L: Lane

Conclusion

- Intuitive translation
- One-to-one correspondence
- Auditability

Future work

- Ground truth of traffic rules
  - DMV, police, insurance data?
- Many-valued logic
  - three-valued
  - Fuzzy logic
- Scenario generation

References

1. "Traffic Safety Facts 2015," NHTSA, 2017.

2. "Examining accident reports involving autonomous vehicles in California."

   Favarò, Francesca M., et al., 2017.

3. "An abstract model for proving safety of autonomous urban traffic."

   Hilscher, Martin, and Maike Schwammberger, ICTAC 2016.

4. "Formalising and monitoring traffic rules for autonomous vehicles in Isabelle/HOL."

   Rizaldi, Albert, et al, IFM 2017.

Thank you!