Packages

In [1]:
```python
import pandas as pd
import matplotlib as mpl
import matplotlib.pyplot as plt
import scipy.stats as stats
import math
import numpy as np
import random

import simpy
```

In [2]:
```python
ε = 0.00001

def isZero(x):
    return abs(x)<ε
```

Entities

In [3]:
```python
# Time tolerance: when at current speed difference a crash might occur within that number of seconds
CRITICAL_TIME_TOLERANCE = 4  # [s]
```

Lanes

In [4]:
```python
def normaliseDirection(d):
    d = d.lower()
    if d=='r' or d=='fast':
        return 'fast'
    elif d=='l' or d=='slow':
        return 'slow'
    else:
        return None
```

In [5]:
```python
LANE_ID = 0

class Lane:

    ## some additional code
    def __init__(self, length, speedLimit):

        global LANE_ID
        self.id = LANE_ID
        LANE_ID += 1

        self.length = length
        self.speedLimit = speedLimit
        self.vehicles = []

        self.next = None
        self.prev = None

        # lane attached to the left/right
        self.left = None
        self.right = None

    # defines generic str() method for Lanes
    # extends the method with list of vehicles on the lane
    def __str__(self):
        l = "" if self.left is None else f" L:{self.left.id:d}"
        r = "" if self.right is None else f" R:{self.right.id:d}"
        vs = "" if len(self.vehicles)==0 else " "
        for v in self.vehicles:
            vs += str(v)
        return f"[{self.id:d} {int(self.length):d}m"+l+r+vs+"]" + \
                    ("-" + str(self.next) if self.next is not None else "")

    def getLane(self, direction):
        if direction=='slow':
            return self.left
        elif direction=='fast':
            return self.right
        else:
            return None

    # adding parallel lane on right side
    def attachRight(self, lane):
        self.right = lane
        lane.left = self

    # adding parallel lane on right side
    def attachLeft(self, lane):
        self.left = lane
        lane.right = self

    # constructs a number of lane segments of the same length
    # and attaches them to the right
    def widenRight(self):
        lane = self
        newLane = Lane(lane.length, lane.speedLimit)
        lane.attachRight(newLane)
        while lane.next is not None:
            lane = lane.next
            newLane = Lane(lane.length, lane.speedLimit)
            lane.attachRight(newLane)
            newLane.prev = lane.prev.right
            newLane.prev.next = newLane
        return self.right

    # constructs a number of lane segments of the same length
    # and attaches them to the right
    def widenLeft(self):
        lane = self
        newLane = Lane(lane.length, lane.speedLimit)
        lane.attachLeft(newLane)
        while lane.next is not None:
            lane = lane.next
            newLane = Lane(lane.length, lane.speedLimit)
            lane.attachLeft(newLane)
            newLane.prev = lane.prev.left
            newLane.prev.next = newLane
        return self.left

    # defines concatenation of lanes
    def extend(self, lane):
        l = self
        while l.next is not None:
            l = l.next
        l.next = lane
        lane.prev = l
        return self

    def totalLength(self):
        total = self.length
        l = self
        while l.next is not None:
            l = l.next
            total += l.length
        return total

    ## additional code
    ## new generalised access method needed to calculate sideway view
    ## returns all vehicles between pos+distFrom and pos+distTo
    def at(self, pos, distFrom=0, distTo=0):
        # make sure that the position of all cars is accurate
        # at this point in time
        for v in self.vehicles:
            v.updateOnly()
                # normally the list should be sorted, but just in case
        self.vehicles.sort(key=lambda v: v.pos)
        res = []
        for v in self.vehicles:
            if pos+distFrom < v.pos and v.pos < pos+distTo:
                res.append(v)
        # if the required distance reaches over the end of the lane segment
        if pos+distTo > self.length and self.next is not None:
            res = res + self.next.at(0, distFrom=0, distTo=distTo-(self.length-pos))
        if pos+distFrom < 0 and self.prev is not None:
            res = self.prev.at(self.prev.length, distFrom=pos+distFrom, distTo=0) + res
        return res

    def inFront(self, pos, far=0):
        # make sure that the position of all cars is accurate
        # at this point in time
        for v in self.vehicles:
            v.updateOnly()
        # normally the list should be sorted, but just in case
        self.vehicles.sort(key=lambda v: v.pos)
        for v in self.vehicles:
            if v.pos > pos:
                return v if v.pos-pos<far else None
        # there is none in front in this lance
        # if the free lane in front is long enough or there is no next lane
        if self.length-pos>far or self.next is None:
            return None
        else:
            return self.next.inFront(0, far=far-(self.length-pos))

    def behind(self, pos, far=0):
        # make sure that the position of all cars is accurate
        # at this point in time
        for v in self.vehicles:
            v.updateOnly()
        # This time we sort in reverse order
        self.vehicles.sort(key=lambda v: v.pos, reverse=True)
        for v in self.vehicles:
            if v.pos < pos:
                return v if pos-v.pos<far else None
        # there is none behind in this lance
        # if the free lane in behind is long enough or there is no previous lane
        if pos>far or self.prev is None:
            return None
        else:
            return self.prev.behind(self.prev.length, far=far-pos)

    def enter(self, vehicle, pos=0):
        self.vehicles.insert(0, vehicle)
        vehicle.pos = pos
        vehicle.lane = self
        vehicle.rec.record(vehicle, event="enter lane")

    def leave(self, vehicle):
        vehicle.rec.record(vehicle, event="leave lane")
        vehicle.lane = None
        # in the meantime the vehicle may have have moved
        # to one of the next lane segments...
        lane = self
        while lane is not None:
            if vehicle in lane.vehicles:
                lane.vehicles.remove(vehicle)
                break
            else:
                lane = lane.next
```

Vehicles

In [6]:
```python
def isRunning(p):
    return p is not None and p.running

def isCrashed(p):
    return p is not None and p.crashed
```

In [7]:
```python
VEHICLE_ID = 0

class Vehicle:
    def __init__(self, env, rec,
                 startingLane=None, startingPos=0,
                 t0=0, x0=0, dx0=0, ddx0=0, dddx0=0,
                 t=[], v=[],
                Min_Time_Diff=1,Min_Speed_Test = 2,Car_Lenght = 4,
                 Far_Away_In_Front = 200,Far_Away_In_Back = 80,
                Lane_Change_time=3,a_min=-4,a_max=2.5):

        global VEHICLE_ID
        self.id = VEHICLE_ID
        VEHICLE_ID += 1


        self.Lane_Change_time = Lane_Change_time # [s]
        self.a_min = a_min # [m/s²]
        self.a_max = a_max # [m/s²] corresponds to 0-100km/h om 12s
        self.Min_Time_Diff = Min_Time_Diff
        self.Min_Speed_Test = Min_Speed_Test # [m/s] min speed diff to trigger overtaking
        self.Car_Lenght = Car_Lenght # [m]
        self.Far_Away_In_Front = Far_Away_In_Front # [m]  distance at which a car in front can be ignored
        self.Far_Away_In_Back = Far_Away_In_Back   # [m]  distance at which a car behind can be ignored

        self.env = env
        self.rec = rec

        self.startingLane = startingLane
        self.startingPos = startingPos
        self.lane = None
        self.pos = 0

        ## second lane reference during changing of lanes
        self.oldLane = None

        self.t0 = t0
        self.x0 = x0
        self.dx0 = dx0
        self.ddx0 = ddx0
        self.dddx0 = dddx0

        self.t = t
        self.v = v
        self.t_target = []
        self.v_target = []

        self.running = False
        self.crashed = False
        self.braking = False
        self.changingLane = False

        self.processRef = None
        self.env.process(self.process())

        ## this allows to trigger trace messages for
        ## the new feature Surround
        self.traceSurround = False
        self.traceOvertake = False
        self.traceBrake = False

    def __str__(self):
        return f"({self.id:d})"

    def isNotFasterThan(self, other):
        return True if other is None else self.dx0 <= other.dx0

    def isNotSlowerThan(self, other):
        return True if other is None else other.dx0 <= self.dx0

    def updateOnly(self):
        if self.crashed:
            return False
        t = self.env.now
        if t < self.t0:
            return False
        if self.running and t > self.t0:
            dt = t - self.t0
            ddx = self.ddx0 + self.dddx0*dt
            dx = round(self.dx0 + self.ddx0*dt + self.dddx0*dt*dt/2,4)
            Δx = self.dx0*dt + self.ddx0*dt*dt/2 + self.dddx0*dt*dt*dt/6
            x = round(self.x0 + Δx, 2)
            self.t0, self.x0, self.dx0, self.ddx0 = t, x, dx, ddx

            self.pos = round(self.pos+Δx, 2)
            # update lane information if necessary
            if self.pos >= self.lane.length:
                nextPos = self.pos - self.lane.length
                nextLane = self.lane.next
                self.lane.leave(self)
                if nextLane is None:
                    self.rec.record(self, event='end')
                    self.running = False
                    return False
                else:
                    nextLane.enter(self, pos=nextPos)
        return True

    def update(self):
        active = self.updateOnly()
        if not active:
            return False

        self.surround = Surround(self)

        ## instead of direct link, call method
        inFront = self.surround.front
        if (isRunning(inFront) or isCrashed(inFront)) \
                and inFront.x0 < self.x0 + self.Car_Lenght:
            self.crash(inFront)
            return True

        if inFront is not None and not self.braking and \
                self.dx0 > inFront.dx0 and \
                self.x0 + CRITICAL_TIME_TOLERANCE*self.dx0 > inFront.x0:
            Δt = max(self.Min_Time_Diff, (inFront.x0-self.x0)/self.dx0)
            self.setTarget(Δt, inFront.dx0)
            self.interruptProcess()
            return True

        ## new code: start overtaking maneuver by changing into fast lane
        if inFront is not None and \
                not self.braking and not self.changingLane and \
                self.dx0 > inFront.dx0 + self.Min_Speed_Test and \
                self.x0 + (self.Lane_Change_time+CRITICAL_TIME_TOLERANCE)*self.dx0 > inFront.x0 and \
                self.surround.rightLane is not None and \
                self.surround.right is None and \
                self.isNotFasterThan(self.surround.rightFront) and \
                self.isNotSlowerThan(self.surround.rightBack):
            if self.traceOvertake:
                print(f"t={self.t0:7,.1f}s Overtaking v{self.id:d} overtakes v{inFront.id:d} at x={self.x0:7,.1f}m")
            self.setTarget(self.Lane_Change_time, 'fast')
            self.interruptProcess()
            return True

        ## new code: end overtaking by returning to slow lane
        if self.surround.leftLane is not None and \
                not self.braking and not self.changingLane and \
                self.surround.left is None and \
                self.isNotFasterThan(self.surround.leftFront) and \
                self.surround.leftBack is None:
            if self.traceOvertake:
                print(f"t={self.t0:7,.1f}s Overtaking v{self.id:d} returns to slow lane at x={self.x0:7,.1f}m")
            self.setTarget(self.Lane_Change_time, 'slow')
            self.interruptProcess()
            return True

    def setTarget(self, Δt, v):
        self.t_target = [ Δt ] + self.t_target
        self.v_target = [ v ] + self.v_target

    def process(self):

        # delay start to the given time t-
        if self.t0>self.env.now:
            yield self.env.timeout(self.t0-self.env.now)
        self.t0 = env.now
        self.running = True
        self.rec.startRecording(self)
        self.startingLane.enter(self, pos=self.startingPos)

        while self.running:
            self.updateOnly()

            self.surround = Surround(self)

            inFront = self.surround.front
            if inFront is not None:

                # if the car in front is slower and we are a bit too near on its heals...
                if inFront.dx0 < self.dx0 and \
                        inFront.x0 < self.x0 + CRITICAL_TIME_TOLERANCE*self.dx0:
                    if self.traceBrake:
                        print(f"t={self.t0:7,.1f}s Braking v{self.id:d} v={self.dx0:4.4f}m/s to {inFront.dx0:4.4f}")


                    yield from self.emergencyBraking(inFront.dx0)
                    if not isZero(self.dx0-inFront.dx0):
                        # after emergency breaking adjust to the speed of the car in front...
                        Δt = 2
                        self.setTarget(Δt, inFront.dx0)
                    continue

            if len(self.t_target)==0:
                self.t_target = self.t.copy()
                self.v_target = self.v.copy()

            if len(self.t_target)>0:

                ## add code for explicit change of lane
                if type(self.v_target[0]) is str:
                    direction = normaliseDirection(self.v_target[0])
                    t = self.t_target[0]
                    self.t_target = self.t_target[1:]
                    self.v_target = self.v_target[1:]
                    if self.lane.getLane(direction) is not None:
                        yield from self.changeLane(direction, t)

                ## the rest is what was there before
                else:
                    v0 = self.dx0
                    v1 = self.v_target[0]
                    t = self.t_target[0]
                    self.t_target = self.t_target[1:]
                    self.v_target = self.v_target[1:]
                    if isZero(v1-v0):
                        yield from self.wait(t)
                    else:
                        yield from self.adjustVelocity(v1-v0, t)
            else:
                yield from self.wait(10)

        self.rec.stopRecording(self)

    def emergencyBraking(self, v):

        def emergencyBrakingProcess(v):
            self.rec.record(self, 'brake')
            minΔt = 0.2
            self.dddx0 = (self.a_min-self.ddx0)/minΔt
            yield self.env.timeout(minΔt)

            self.updateOnly()
            self.dddx0=0
            self.ddx0=self.a_min
            v = min(v, self.dx0-2)
                # the brake time estimate is for perfect timing for
                # autonomous cars. For manual driving leave out the
                # -minΔt/2 or use a random element.
            Δt = max(0.5, (v-self.dx0)/self.ddx0 - minΔt/2)
            yield self.env.timeout(Δt)

            self.updateOnly()
            self.dddx0 = -self.ddx0/minΔt
            yield self.env.timeout(minΔt)

            self.updateOnly()
            self.ddx0 = 0
            self.dddx0 = 0


        ## The 'braking' bit prevents the interruption of an emergency breaking process
        self.braking = True
        self.processRef = self.env.process(emergencyBrakingProcess(v))
        try:
            yield self.processRef
        except simpy.Interrupt:
            pass
        self.processRef = None
        self.braking = False

    ## make changeLane robust against interrupt:
    def changeLane(self, direction, Δt):

        # smoothly adjust velocity by Δv over the time Δt
        def changeLaneProcess(oldLane, newlane, Δt):
            self.updateOnly()
            self.rec.record(self, 'change '+direction)
            self.oldLane = oldLane
            newLane.enter(self, pos=self.pos)
            self.ddx0 = 1
            self.dddx0 = 0
            yield self.env.timeout(Δt)
            self.oldLane.leave(self)
            self.lane = newLane
            self.oldLane = None
            self.rec.record(self, 'done change '+direction)
            self.updateOnly()
            self.ddx0 = 0
            self.dddx0 = 0

        ## keep record of current lane, as in case of aborting
        ## the lane change
        ## when interrupted go back into original lane
        oldLane = self.lane
        newLane = self.lane.getLane(direction)
        self.changingLane = True
        try:
            self.processRef = self.env.process(changeLaneProcess(oldLane, newLane, Δt))
            yield self.processRef
            self.processRef = None
        except simpy.Interrupt:
            # if interrupted go quickly back into old lane
            # but this is not interruptible
            self.processRef = None
            self.env.process(changeLaneProcess(newLane, oldLane, Δt/4))
        self.changingLane = False

    def adjustVelocity(self, Δv, Δt):

        # smoothly adjust velocity by Δv over the time Δt
        def adjustVelocityProcess():
            self.updateOnly()
            minΔt = 0.1*Δt
            a = Δv/(Δt-minΔt)
            tt = Δt-2*minΔt

            self.dddx0 = (a-self.ddx0)/minΔt
            yield self.env.timeout(minΔt)

            self.updateOnly()
            self.dddx0 = 0
            self.ddx0 = a
            yield self.env.timeout(tt)

            self.updateOnly()
            self.dddx0 = -a/minΔt
            yield self.env.timeout(minΔt)

            self.updateOnly()
            self.dddx0 = 0
            self.ddx0 = 0

        self.processRef = self.env.process(adjustVelocityProcess())
        try:
            yield self.processRef
        except simpy.Interrupt:
            self.dddx0 = 0
            pass
        self.processRef = None

    def wait(self, Δt):

        def waitProcess():
            yield self.env.timeout(Δt)

        self.processRef = self.env.process(waitProcess())
        try:
            yield self.processRef
        except simpy.Interrupt:
            pass
        self.processRef = None

    def interruptProcess(self):
        if self.processRef is not None and self.processRef.is_alive:
            self.processRef.interrupt('change')

    def crash(self, other):

        def recordCrash(self):
            self.rec.record(self, 'crash')
            self.running = False
            self.crashed = True
            self.dx0 = 0
            self.ddx0 = 0
            self.dddx0 = 0

        if self.running:
            print(f"Crash p{self.id:d} into p{other.id:d} at t={self.t0:7.3f} x={self.x0:7.1f}")
            recordCrash(self)
            if other.running:
                recordCrash(other)
```

In [8]:
```python
class Surround:

    def __init__(self, vehicle):

        def s(vehicle):
            if vehicle is None:
                return " "
            elif type(vehicle) is list:
                if len(vehicle)==1:
                    return s(vehicle[0])
                else:
                    res = "["
                    for v in vehicle:
                        if len(res)>1:
                            res += ','
                        res+=s(v)
                    res += "]"
                    return res
            else:
                return f"{vehicle.id:d}"

        # For each of the directions None means that there is no
        # vehicle in the immediate vicinity.
        # We initialise to a 'safe' value which can be easily detected
        # if something goes wrong

        self.leftBack = vehicle
        self.left = vehicle
        self.leftFront = vehicle
        self.back = vehicle
        self.vehicle = vehicle
        self.front = vehicle
        self.rightBack = vehicle
        self.right = vehicle
        self.rightFront = vehicle

        lane = vehicle.lane
        pos = vehicle.pos
        if lane is not None:
            self.lane = lane
            self.front = lane.inFront(pos,vehicle.Far_Away_In_Front)
            self.back = lane.behind(pos,vehicle.Far_Away_In_Back)

            self.rightLane = lane.right
            if self.rightLane is not None:
                if vehicle.oldLane == lane.right:
                    # drifting left
                    self.right = vehicle
                    self.rightFront = self.rightLane.inFront(pos,vehicle.Far_Away_In_Front)
                    self.rightBack = self.rightLane.behind(pos,vehicle.Far_Away_In_Back)
                else:
                    right = self.rightLane.at(pos,-vehicle.Car_Lenght/2,vehicle.Car_Lenght/2)
                    if len(right)==0:
                        self.right = None
                    elif len(right)==1:
                        self.right = right[0]
                    else:
                        self.right = right

                    if self.right is None:
                        self.rightFront = self.rightLane.inFront(pos,vehicle.Far_Away_In_Front)
                        self.rightBack = self.rightLane.behind(pos,vehicle.Far_Away_In_Back)
                    else:
                        self.rightFront = None
                        self.rightBack = None

            self.leftLane = lane.left
            if self.leftLane is not None:
                if vehicle.oldLane == lane.left:
                    # drifting right
                    self.left = vehicle
                    self.leftFront = self.leftLane.inFront(pos,vehicle.Far_Away_In_Front)
                    self.leftBack = self.leftLane.behind(pos,vehicle.Far_Away_In_Back)
                else:
                    left = self.leftLane.at(pos,-vehicle.Car_Lenght/2,vehicle.Car_Lenght/2)
                    if len(left)==0:
                        self.left = None
                    elif len(left)==1:
                        self.left = left[0]
                    else:
                        self.left = left

                    if self.left is None:
                        self.leftFront = self.leftLane.inFront(pos,vehicle.Far_Away_In_Front)
                        self.leftBack = self.leftLane.behind(pos,vehicle.Far_Away_In_Back)
                    else:
                        self.leftFront = None
                        self.lefttBack = None

        if vehicle.traceSurround:
            print(f"surround t={self.vehicle.env.now:6.2f} " +
                  "|" +
                  ("" if self.leftLane is None else
                      f"|{s(self.leftBack):s}>{s(self.left):s}>{s(self.leftFront):s}") +
                 f"|{s(self.back):s}>{s(self.vehicle):s}>{s(self.front):s}|" +
                  ("" if self.rightLane is None else
                      f"{s(self.rightBack):s}>{s(self.right):s}>{s(self.rightFront):s}|") +
                  "|"
                 )
```

Recorder

In [9]:
```python
class SimpleRecorder:

    def __init__(self, env, startTime, stopTime, timeStep):

        global VEHICLE_ID, LANE_ID
        VEHICLE_ID = 0
        LANE_ID = 0

        self.env = env
        self.startTime = startTime
        self.stopTime = stopTime
        self.timeStep = timeStep
        self.vehiclesToTrace = []
        self.vehicles = []
        self.data = pd.DataFrame(columns=['t', 'x', 'v', 'a', 'id', 'lane', 'oldLane', 'pos', 'event'])

    # runs the simulation
    def run(self):
        self.env.process(self.process())
        self.env.run(self.stopTime+self.timeStep)

    def startRecording(self, p):
        self.vehicles.append(p)

    def stopRecording(self, p):
        self.vehicles.remove(p)

    def record(self, p=None, event='timer'):
        if p is not None:
            if p.updateOnly():
                laneId = None if p.lane is None else p.lane.id
                oldLaneId = None if p.oldLane is None else p.oldLane.id
                if p.running or event!='timer':
                    ix = len(self.data)
                    self.data.loc[ix]=[self.env.now, p.x0, p.dx0, p.ddx0, p.id, laneId, oldLaneId, p.pos, event]
                    if event=='timer':
                        p.update()
        else:
            for p in self.vehicles:
                self.record(p)

    def getData(self):
        return self.data.copy(deep=True)

    def getEvents(self):
        return self.data[self.data.event!='timer'].copy(deep=True)

    def process(self):
        yield self.env.timeout(self.startTime-self.env.now)
        while self.env.now <= self.stopTime:
            self.record()
            yield self.env.timeout(self.timeStep)

    def plot(self, x, y,
             vehicles=None,
             xmin=None, xmax=None, ymin=None, ymax=None):
        columns = ['t', 'x', 'v', 'a']
        labels = ['Time [s]', 'Position [m]', 'Velocity [m/s]', 'Acceleration [m/s²]']
        xindex = columns.index(x)
        yindex = columns.index(y)

        plt.figure(figsize=(6, 4), dpi=120)
        if xmin is not None and xmax is not None:
            plt.xlim((xmin, xmax))
        if ymin is not None and ymax is not None:
            plt.ylim((ymin, ymax))

        if vehicles is None:
            vehicles = list(self.data.id.unique())
        for id in vehicles:
            df = self.data[self.data.id==id]
            plt.plot(x, y, '', data=df)
            plt.xlabel(labels[xindex])
            plt.ylabel(labels[yindex])

            # use small circle to indicate emergency braking
            db = df[df.event=='brake']
            for i in range(len(db)):
                X = db.iloc[i, xindex]
                Y = db.iloc[i, yindex]
                plt.plot([X], [Y], 'ro')

            # use black 'x' as crash indicator
            dc = df[df.event=='crash']
            for i in range(len(dc)):
                X = dc.iloc[i, xindex]
                Y = dc.iloc[i, yindex]
                plt.plot([X], [Y], 'xk')

            # use black right pointing triangle
            # to indicate that a vehicle
            # was changing into the fast lane
            dc = df[df.event=='change fast']
            for i in range(len(dc)):
                X = dc.iloc[i, xindex]
                Y = dc.iloc[i, yindex]
                plt.plot([X], [Y], '>k')

            # use black left pointing triangle
            # to indicate that a vehicle
            # was changing into the slow lane
            dc = df[df.event=='done change slow']
            for i in range(len(dc)):
                X = dc.iloc[i, xindex]
                Y = dc.iloc[i, yindex]
                plt.plot([X], [Y], '<k')

            # use black diamond to indicate that
            # a vehicle ran out of track
            dc = df[df.event=='end']
            for i in range(len(dc)):
                X = dc.iloc[i, xindex]
                Y = dc.iloc[i, yindex]
                plt.plot([X], [Y], 'Dk')

        plt.grid(True)
```

In [10]:
```python
#def randomIntervals(cycles, length=100):
#    return [ max(0, random.normalvariate(length, length/3)) for i in range(cycles) ]
def randomSpeedVariation_1(vmax, cycles, cv=0.02):
    return [ vmax + (-1)**i*abs(random.normalvariate(0, vmax*cv)) for i in range(cycles) ]
```

In [11]:
```python
SLOW_CYCLE=100
def randomIntervals(cycles):
    # return [ random.expovariate(1.0/SLOW_CYCLE)+10 for i in range(cycles) ]
    return [ max(0, random.normalvariate(SLOW_CYCLE, SLOW_CYCLE/3)) for i in range(cycles) ]
#SPEED_VARIATION = 0.05
#def randomSpeedVariation(vmax, cycles):
#    return [ vmax + (-1)**i*abs(random.normalvariate(0, vmax*SPEED_VARIATION)) for i in range(cycles) ]
```

In [12]:
```python
#SLOW_CYCLE=100
#def randomIntervals(cycles):
#    return [ random.expovariate(1.0/SLOW_CYCLE)+10 for i in range(cycles) ]
#    #return [ max(0, random.normalvariate(SLOW_CYCLE, SLOW_CYCLE/3)) for i in range(cycles) ]
```

In [13]:
```python
random.seed(20)
```

```
In [14]: def random_speed(free_speed,quantiles):
             u = random.random() # generates uniformly distributed random number between 0 and 1
             for i in range(len(quantiles)):
                 if u<quantiles[i+1]:
                     p = (u-quantiles[i])/(quantiles[i+1]-quantiles[i])
                     return free_speed[i]*p+free_speed[i+1]*(1-p)


         def freeMotorwaySpeed(free_speed,quantiles):
             speeds = [ random_speed(free_speed,quantiles) for i in range(1200)]
             kernel = stats.gaussian_kde(speeds)

             vel = np.arange(30, 191)
             q = [ kernel.integrate_box_1d(30, i) for i in vel ]
             u = random.random() # generates uniformly distributed random number between 0 and 1
             for i in range(len(q)):
                 if u<q[i+1]:
                     p = (u-q[i])/(q[i+1]-q[i])
                     # return (free_speed[i+1]+free_speed[i])/2*p+(1-p)*(free_speed[i+1]+free_speed[i+2])/2
                     return vel[i]*p+vel[i+1]*(1-p)
         def randomSpeedVariation(vmax, cycles,free_speed,quantiles):
             return [math.floor(freeMotorwaySpeed(free_speed,quantiles)/3.6) for i in range(cycles)]
```

```
In [15]: VMAX = 120/3.6
         IAT=10
         CYCLES = random.randint(4, 8)
         #iat = [ random.uniform(IAT/10,IAT+10) for i in range(200) ]
         iat=[ random.expovariate(1.0/IAT) for i in range(10) ]
         iat
```

```
Out[15]: [3.0087194089698515,
          10.098485893089766,
          23.533069156129997,
          20.567440815540532,
          8.50832327511783,
          1.8558056615126446,
          5.3021754088476944,
          50.893559523783985,
          1.0897570917011172,
          3.8439732388604746]
```

```
In [53]: VMAX = 120/3.6
         N = 50 # number of points
         IAT = 30 # time difference between start
         random.seed(13)
         env = simpy.Environment()
         rec = SimpleRecorder(env, 0, 1500, 1)
         #iat = [ random.expovariate(1.0/IAT) for i in range(N) ]
         iat = [ random.uniform(IAT-4,IAT-6) for i in range(N) ]

         LANE_ID = 0
         l = Lane(2000, VMAX)
         r = l.widenRight()
         ll=l.widenLeft()
         l.extend(Lane(1000, VMAX))
         rr=r = l.widenRight()
         r = l.widenRight()
         print("left Lane: ", ll)
         print("centr Lane: ", l)
         print("Right Lane:", r)

         t0=0
         for i in range(N):
             CYCLES = random.randint(4, 8)
             times = randomIntervals(CYCLES)
             speed = randomSpeedVariation_1(VMAX, CYCLES)
             t0=i*iat[i]
             v=Vehicle(env, rec, startingLane=l, t0=t0, dx0=speed[-1], t=times, v=speed)
             v.traceOvertake=True
         rec.run()
```

```
left Lane:  [2 2000m R:0]
centr Lane:  [0 2000m L:2 R:6]-[3 1000m R:7]
Right Lane: [6 2000m L:0]-[7 1000m L:3]
t=    0.0s Overtaking v0 returns to slow lane at x=    0.0m
t=   25.0s Overtaking v1 returns to slow lane at x=   12.5m
t=   50.0s Overtaking v2 returns to slow lane at x=   24.3m
t=   73.0s Overtaking v3 returns to slow lane at x=    3.1m
t=  103.0s Overtaking v4 returns to slow lane at x=   15.7m
t=  128.0s Overtaking v5 returns to slow lane at x=   10.0m
t=  155.0s Overtaking v6 returns to slow lane at x=   25.2m
t=  179.0s Overtaking v7 returns to slow lane at x=    5.0m
t=  197.0s Overtaking v8 returns to slow lane at x=   25.1m
t=  232.0s Overtaking v9 returns to slow lane at x=   11.3m
t=  250.0s Overtaking v10 returns to slow lane at x=   20.8m
t=  282.0s Overtaking v11 returns to slow lane at x=   23.9m
t=  305.0s Overtaking v12 returns to slow lane at x=    2.4m
t=  327.0s Overtaking v13 returns to slow lane at x=    7.4m
t=  341.0s Overtaking v14 returns to slow lane at x=   14.9m
t=  372.0s Overtaking v15 returns to slow lane at x=    8.5m
t=  416.0s Overtaking v16 returns to slow lane at x=   15.5m
t=  433.0s Overtaking v17 returns to slow lane at x=   12.8m
t=  461.0s Overtaking v19 returns to slow lane at x=    3.5m
t=  463.0s Overtaking v18 returns to slow lane at x=    9.3m
t=  488.0s Overtaking v20 returns to slow lane at x=   12.9m
t=  513.0s Overtaking v21 returns to slow lane at x=   29.4m
t=  536.0s Overtaking v22 returns to slow lane at x=   12.3m
t=  564.0s Overtaking v23 returns to slow lane at x=    8.6m
t=  579.0s Overtaking v24 returns to slow lane at x=   19.6m
t=  611.0s Overtaking v25 returns to slow lane at x=   22.5m
t=  657.0s Overtaking v27 returns to slow lane at x=   29.8m
t=  663.0s Overtaking v26 returns to slow lane at x=   11.5m
t=  701.0s Overtaking v28 returns to slow lane at x=    8.7m
t=  711.0s Overtaking v29 returns to slow lane at x=   26.9m
t=  747.0s Overtaking v30 returns to slow lane at x=   28.0m
t=  780.0s Overtaking v31 returns to slow lane at x=   20.9m
t=  809.0s Overtaking v32 returns to slow lane at x=   10.1m
t=  830.0s Overtaking v33 returns to slow lane at x=   12.1m
t=  863.0s Overtaking v34 returns to slow lane at x=   11.3m
t=  877.0s Overtaking v36 returns to slow lane at x=    0.5m
t=  902.0s Overtaking v35 returns to slow lane at x=    7.1m
t=  903.0s Overtaking v37 returns to slow lane at x=    2.4m
t=  914.0s Overtaking v38 returns to slow lane at x=   30.2m
t=  961.0s Overtaking v39 returns to slow lane at x=   30.5m
t=  996.0s Overtaking v40 returns to slow lane at x=   11.4m
t=1,005.0s Overtaking v41 returns to slow lane at x=   11.9m
t=1,060.0s Overtaking v43 returns to slow lane at x=    7.0m
t=1,081.0s Overtaking v42 returns to slow lane at x=   11.1m
t=1,105.0s Overtaking v44 returns to slow lane at x=    0.6m
t=1,155.0s Overtaking v45 returns to slow lane at x=   29.9m
t=1,173.0s Overtaking v47 returns to slow lane at x=    4.5m
t=1,178.0s Overtaking v46 returns to slow lane at x=   21.2m
t=1,224.0s Overtaking v48 returns to slow lane at x=   10.7m
t=1,229.0s Overtaking v49 returns to slow lane at x=    0.9m
```

```
In [54]: randomSpeedVariation_1(VMAX, CYCLES)
         print(speed)

[33.65681275185505, 32.25989001197571, 33.579943693584745, 32.78739810032938, 33.42486294997936, 32.6
9204147538265]
```

```
In [55]: randomIntervals(CYCLES)
         print(times)

[141.70558028524465, 77.99114212312837, 111.79781247163538, 118.11546836024027, 69.14440147727251, 13
6.45763372491726]
```

```
In [56]: data = rec.getData()
         id_0 = data[data.id==39]
```

```
In [57]: data = rec.getData()
         data
```

Out[57]:

	t	x	v	a	id	lane	oldLane	pos	event
0	0	0	33.112566	0	0	0	None	0	enter lane
1	0	0	33.112566	0	0	0	None	0	timer
2	0	0	33.112566	0	0	0	None	0	change slow
3	0	0	33.112566	0	0	2	0	0	enter lane
4	1	33.61	34.112600	1	0	2	0	33.61	timer
...	...	...	...	...	...	...	...	...	...
3225	1284	1902.72	33.339900	-0.048896	49	2	None	1902.72	timer
3226	1285	1936.04	33.291000	-0.048896	49	2	None	1936.04	timer
3227	1286	1969.31	33.242100	-0.048896	49	2	None	1969.31	timer
3228	1287	2002.53	33.193200	-0.048896	49	2	None	2002.53	leave lane
3229	1287	2002.53	33.193200	-0.048896	49	None	None	2002.53	end

3230 rows × 9 columns

```
In [58]: rec.getEvents()
```

Out[58]:

	t	x	v	a	id	lane	oldLane	pos	event
0	0	0	33.112566	0	0	0	None	0	enter lane
2	0	0	33.112566	0	0	0	None	0	change slow
3	0	0	33.112566	0	0	2	0	0	enter lane
6	3	103.83	36.112600	1	0	2	0	103.83	leave lane
7	3	103.83	36.112600	1	0	2	None	103.83	done change slow
...	...	...	...	...	...	...	...	...	...
3128	1235	2012.07	33.690600	-0.0468289	46	None	None	2012.07	end
3219	1280	2011.31	34.815300	-0.0363275	48	2	None	2011.31	leave lane
3220	1280	2011.31	34.815300	-0.0363275	48	None	None	2011.31	end
3228	1287	2002.53	33.193200	-0.048896	49	2	None	2002.53	leave lane
3229	1287	2002.53	33.193200	-0.048896	49	None	None	2002.53	end

388 rows × 9 columns

```
In [59]: id_0.groupby(id_0['event']).nunique()
```

Out[59]:

	t	x	v	a	id	lane	oldLane	pos	event
event									
change slow	1	1	1	1	1	1	0	1	1
done change slow	1	1	1	1	1	1	0	1	1
end	1	1	1	1	1	0	0	1	1
enter lane	2	2	2	2	1	2	1	2	1
leave lane	2	2	2	2	1	1	1	2	1
timer	55	55	55	15	1	2	1	55	1

```
In [60]: ent_lane=id_0[id_0['event']=="enter lane"]
         ent_lane
```

Out[60]:

	t	x	v	a	id	lane	oldLane	pos	event
2516	960.108	0	34.188837	0	39	0	None	0	enter lane
2521	961	30.5	34.188700	-0.000383147	39	2	0	30.5	enter lane

```
In [61]: ent_lane.iloc[0]['t']

Out[61]: 960.1080332176876
```

```
In [62]: lev_lane=id_0[id_0['event']=="leave lane"]
         lev_lane
```

Out[62]:

	t	x	v	a	id	lane	oldLane	pos	event
2528	964	137.57	37.1887	1	39	2	0	137.57	leave lane
2631	1016	2020.01	34.9741	-0.0480496	39	2	None	2020.01	leave lane

```
In [63]: lev_lane.iloc[-1]['t']

Out[63]: 1016
```

```
In [116]: data = rec.getData()
          id_car=data.id.unique()
          #diff_time=[]
          end_time=[]
          for car in id_car:
              car_data=data[data.id==car]
              start_lane_1=car_data[car_data['event']=="enter lane"]
              end_lane_1=car_data[car_data['event']=="end"]
              if(len(end_lane_1.index)!=0):
                  end_time.append(end_lane_1.iloc[-1]['t']-start_lane_1.iloc[0]['t'])
          average_travelling_time=sum(end_time)/len(end_time)
          average_travelling_time

Out[116]: 66.68488973153885
```

```
In [118]: average_travelling_time*1.2

Out[118]: 80.02186767784661
```

```
In [113]: end_time

Out[113]: [57,
 56.370515985929075,
 56.73632767206444,
 58.09601696833958,
 59.48579339098988,
 57.30558608965468,
 56.76591901802101,
 57.15228109786957 6,
 57.74437763540436,
 58.16538409949547,
 56.62629503694038,
 56.70596567081827,
 57.0717620903207,
 58.221088538197534,
 57.45438229409234,
 58.25206443622858,
 56.26183657478691,
 56.37845303393135,
 59.10881970954068,
 61.281571589844134,
 57.389584448442406,
 54.85396719741004,
 56.360074966005186,
 56.25850702890159,
 54.56752400619041,
 57.68852753826036,
 57.89670669017369,
 57.34881477429224,
 57.25998760984453,
 56.79022337408924,
 57.84831591610077,
 57.633814063557566,
 57.308968014063566,
 57.36826987676727,
 55.835772876122974,
 57.01434232902977,
 57.11520354016545,
 59.071139148623274,
 56.91177010521017,
 55.89196678231235,
 57.338108665459686,
 58.36974229623877,
 56.206654598486466,
 55.327715940713006,
 58.019196027263206,
 57.897037285549004,
 56.10618601616193,
 57.641650144054665,
 56.31792857964933,
 58.02698431650333]
```

Throughput

```
In [67]: #THROUGHPUT
         l=len(rec.getData()[data.event=="end"])
         FirstE=rec.getData()[data.event=="end"].iloc[0]['t']
         LastE=rec.getData()[data.event=="end"].iloc[-1]['t']
         l/((LastE-FirstE)/3600)

Out[67]: 146.34146341463415
```

AVERAGE TRAVELING TIME

```
In [119]: #AVERAGE TRAVELLING TIME
          average_travelling_time=sum(end_time)/len(end_time)
          average_travelling_time

Out[119]: 66.68488973153885
```

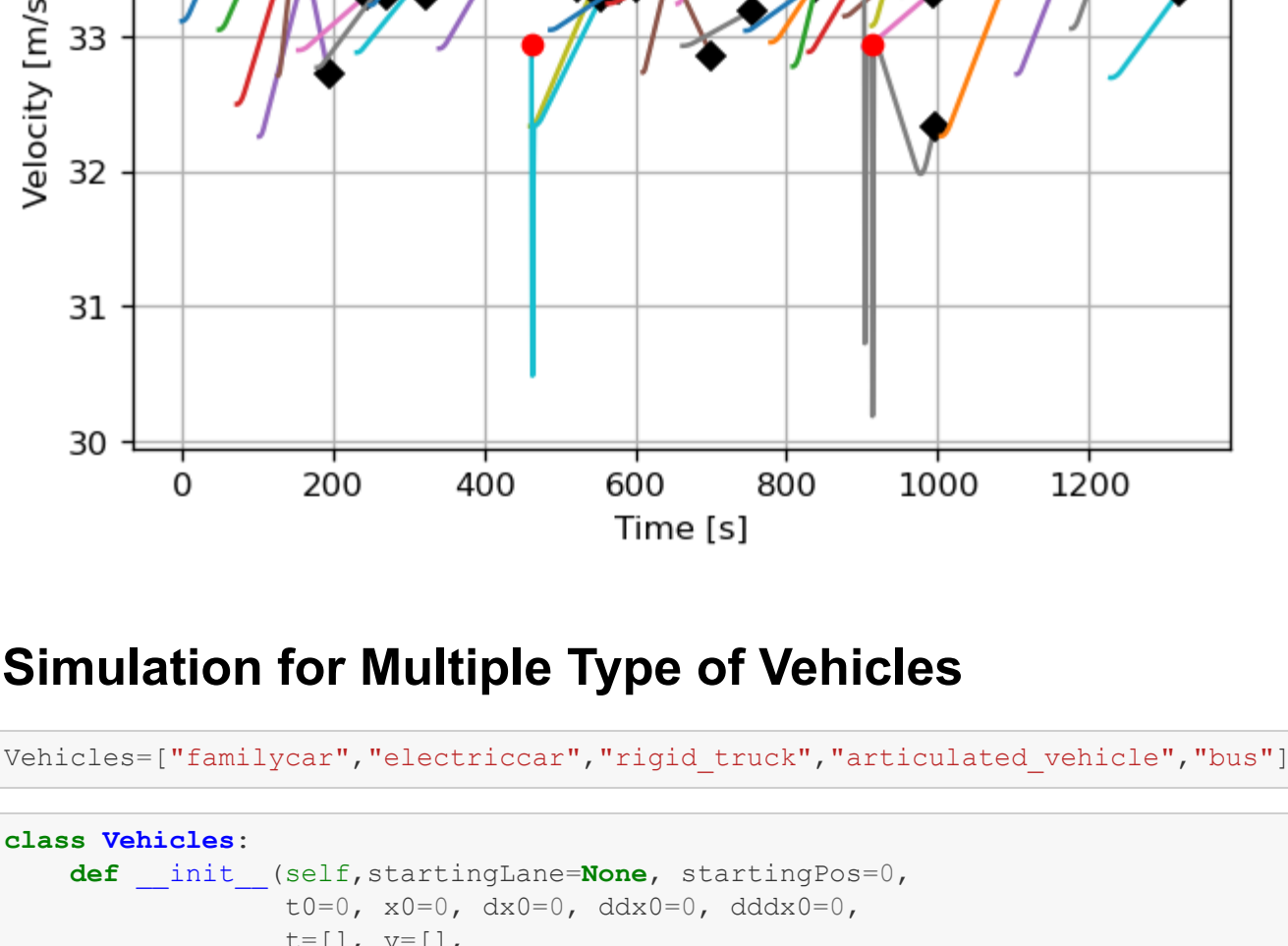
```
In [71]: def optimum_throughput(T_opt, t):
             t2 = []
             new_att = 1.2*T_opt
             for j in range(len(t)):
                 if t[j] >= new_att:
                     t2.append(t[j])
                 else:
                     break
             return t2
```

```
In [73]: #t22=optimum_throughput(avg,end_time)
         #ttt=sum(t22)/len(t22)
         #ttt= ttt/3600
```

```
In [74]: #N/ttt
```

Position vs Time Graph

```
In [69]: rec.plot('t','x')
```



Time vs Velocity

```
In [34]: rec.plot('t', 'v')
```

Simulation for Multiple Type of Vehicles

```
In [35]: Vehicles=["familycar","electriccar","rigid_truck","articulated_vehicle","bus"]
```

```
In [36]: class Vehicles:
             def __init__(self,startingLane=None, startingPos=0,
                          t0=0, x0=0, dx0=0, ddx0=0, dddx0=0,
                          t=[], v=[],
                         Min_Time_Diff=1,Min_Speed_Test = 2,Car_Lenght = 4,
                          Far_Away_In_Front = 200,Far_Away_In_Back= 80,
                         Lane_Change_time=3,a_min=-4,a_max=2.5,free_speed=[],quantiles=np.cumsum([])):


                 self.Lane_Change_time = Lane_Change_time # [s]
                 self.a_min = a_min # [m/s²]
                 self.a_max = a_max # [m/s²] corresponds to 0-100km/h om 12s
                 self.Min_Time_Diff = Min_Time_Diff
                 self.Min_Speed_Test = Min_Speed_Test # [m/s] min speed diff to trigger overtaking
                 self.Car_Lenght = Car_Lenght # [m]
                 self.Far_Away_In_Front = Far_Away_In_Front # [m]  distance at which a car in front can be ignor
         ed
                 self.Far_Away_In_Back = Far_Away_In_Back   # [m]  distance at which a car behind can be ignored
                 self.startingLane = startingLane
                 self.free_speed=free_speed
                 self.quantiles=quantiles
```

Family Car

```
In [76]: Lane_Change_time = 4# [s]
         a_min = -4 # [m/s²]
         a_max = 2.5 # [m/s²] corresponds to 0-100km/h om 12s
         Min_Time_Diff = 1
         Min_Speed_Test = 4 # [m/s] min speed diff to trigger overtaking
         Car_Lenght = 4 # [m]
         Far_Away_In_Front = 200 # [m]  distance at which a car in front can be ignored
         Far_Away_In_Back = 80
         free_speed = [ 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170 ]
         quantiles = np.cumsum([0, 0.003, 0.014, 0.052, 0.148, 0.27, 0.309, 0.143, 0.048, 0.01, 0.003])
         startingLane = 1


         familycar=Vehicles(Lane_Change_time=Lane_Change_time,a_min=a_min,Min_Time_Diff=Min_Time_Diff,Min_Speed_
         Test=Min_Speed_Test
                          ,Car_Lenght=Car_Lenght,Far_Away_In_Front=Far_Away_In_Front,Far_Away_In_Back=Far_Away_
         In_Back,startingLane=startingLane,
                          free_speed=free_speed,quantiles=quantiles)
```

Electric Car

```
In [77]: Lane_Change_time = 3 # [s]
         a_min = -4 # [m/s²]
         a_max = 2.5 # [m/s²] corresponds to 0-100km/h om 12s
         Min_Time_Diff = 1
         Min_Speed_Test = 3 # [m/s] min speed diff to trigger overtaking
         Car_Lenght = 4 # [m]
         Far_Away_In_Front = 150 # [m]  distance at which a car in front can be ignored
         Far_Away_In_Back = 60
         free_speed = [ 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170 ]
         quantiles = np.cumsum([0, 0.003, 0.025, 0.059, 0.226, 0.275, 0.409, 0.243, 0.148, 0.010, 0.003])
         startingLane = 1


         electriccar=Vehicles(Lane_Change_time=Lane_Change_time,a_min=a_min,Min_Time_Diff=Min_Time_Diff,Min_Spee
         d_Test=Min_Speed_Test
                          ,Car_Lenght=Car_Lenght,Far_Away_In_Front=Far_Away_In_Front,Far_Away_In_Back=Far_Away_
         In_Back,startingLane=startingLane,
                          free_speed=free_speed,quantiles=quantiles)
```

Rigid Truck

```
In [78]: Lane_Change_time = 7 # [s]
         a_min = -4 # [m/s²]
         a_max = 2.5 # [m/s²] corresponds to 0-100km/h om 12s
         Min_Time_Diff = 1
         Min_Speed_Test = 8 # [m/s] min speed diff to trigger overtaking
         Car_Lenght = 15 # [m]
         Far_Away_In_Front = 250 # [m]  distance at which a car in front can be ignored
         Far_Away_In_Back = 100
         #Quantiles has been changed according to RSA graph for rigid trucks on motorways
         free_speed = [ 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170 ]
         quantiles = np.cumsum([0, 0.008, 0.118, 0.711, 0.108, 0.027, 0.022, 0.19, 0.015, 0.010, 0.003])
         startingLane = 1


         rigid_truck=Vehicles(Lane_Change_time=Lane_Change_time,a_min=a_min,Min_Time_Diff=Min_Time_Diff,Min_Spee
         d_Test=Min_Speed_Test
                          ,Car_Lenght=Car_Lenght,Far_Away_In_Front=Far_Away_In_Front,Far_Away_In_Back=Far_Away_
         In_Back,startingLane=startingLane,
                          free_speed=free_speed,quantiles=quantiles)
```

Articulated Vehicles

```
In [79]: Lane_Change_time = 10 # [s]
         a_min = -4 # [m/s²]
         a_max = 2.5 # [m/s²] corresponds to 0-100km/h om 12s
         Min_Time_Diff = 1
         Min_Speed_Test = 10 # [m/s] min speed diff to trigger overtaking
         Car_Lenght = 20 # [m]
         Far_Away_In_Front = 270 # [m]  distance at which a car in front can be ignored
         Far_Away_In_Back = 120
         #Quantiles has been changed according to RSA graph for rigid trucks on motorways
         free_speed = [ 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170 ]
         quantiles = np.cumsum([0, 0.001, 0.003, 0.110,0.783, 0.103, 0.019, 0.015, 0.010,0.002, 0.003])
         startingLane = 1


         articulated_vehicle=Vehicles(Lane_Change_time=Lane_Change_time,a_min=a_min,Min_Time_Diff=Min_Time_Diff,
         Min_Speed_Test=Min_Speed_Test
                          ,Car_Lenght=Car_Lenght,Far_Away_In_Front=Far_Away_In_Front,Far_Away_In_Back=Far_Away_
         In_Back,startingLane=startingLane,
                          free_speed=free_speed,quantiles=quantiles)
```

Bus

```
In [80]: Lane_Change_time = 6 # [s]
         a_min = -4 # [m/s²]
         a_max = 2.5 # [m/s²] corresponds to 0-100km/h om 12s
         Min_Time_Diff = 1
         Min_Speed_Test = 9 # [m/s] min speed diff to trigger overtaking
         Car_Lenght = 14 # [m]
         Far_Away_In_Front = 230 # [m]  distance at which a car in front can be ignored
         Far_Away_In_Back = 90
         free_speed = [ 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170 ]
         quantiles = np.cumsum([0, 0.003, 0.014, 0.052, 0.348, 0.870, 0.409, 0.143, 0.048, 0.01, 0.003])
         startingLane = 1


         bus=Vehicles(Lane_Change_time=Lane_Change_time,a_min=a_min,Min_Time_Diff=Min_Time_Diff,Min_Speed_Test=M
         in_Speed_Test
                          ,Car_Lenght=Car_Lenght,Far_Away_In_Front=Far_Away_In_Front,Far_Away_In_Back=Far_Away_
         In_Back,startingLane=startingLane,
                          free_speed=free_speed,quantiles=quantiles)
```

Task 3

Created Diffirent class for vechiles and trying simulation

```
In [102]: VMAX = 120/3.6
          N = 400 # number of points
          IAT = 30 # time difference between start
          random.seed(13)
          env = simpy.Environment()
          rec = SimpleRecorder(env, 0, 1000, 1)
          #iat = [ random.expovariate(1.0/IAT) for i in range(N) ]
          iat = [ random.uniform(IAT-4,IAT-6) for i in range(N) ]
          lane_m=3000 # total distance of lane

          LANE_ID = 0
          l = Lane(2000, VMAX)
          r = l.widenRight()
          ll=l.widenLeft()
          l.extend(Lane(1000, VMAX))
          rr=r = l.widenRight()
          r = l.widenRight()
          print("left Lane: ", ll)
          print("centr Lane: ", l)
          print("Right Lane:", r)

          t0=0
          for i in range(N):
              CYCLES = random.randint(4, 8)
              choose_vehicle = random.randint(0, 4)
              if choose_vehicle == 0:
                  vec = familycar
              elif choose_vehicle == 1:
                  vec=electriccar
              elif choose_vehicle == 2:
                  vec=rigid_truck
              elif choose_vehicle == 3:
                  vec=articulated_vehicle
              else:
                  vec=bus
              #print(choose_vehicle)
              times = randomIntervals(CYCLES)
              speed = randomSpeedVariation(VMAX, CYCLES,vec.free_speed,vec.quantiles)
              t0=i*iat[i]
              v=Vehicle(env, rec, startingLane=l, t0=t0, dx0=speed[-1], t=times, v=speed,
                      Lane_Change_time=vec.Lane_Change_time,a_min=vec.a_min,Min_Time_Diff=vec.Min_Time_Diff,Min_
          Speed_Test=vec.Min_Speed_Test
                           ,Car_Lenght=vec.Car_Lenght,Far_Away_In_Front=vec.Far_Away_In_Front,Far_Away_In_Back=v
          ec.Far_Away_In_Back)
              v.traceOvertake=True
          rec.run()
```

```
left Lane:  [2 2000m R:0]
centr Lane:  [0 2000m L:2 R:6]-[3 1000m R:7]
Right Lane: [6 2000m L:0]-[7 1000m L:3]
t=    0.0s Overtaking v0 returns to slow lane at x=    0.0m
t=   25.0s Overtaking v1 returns to slow lane at x=   10.4m
t=   50.0s Overtaking v2 returns to slow lane at x=   18.4m
t=   73.0s Overtaking v3 returns to slow lane at x=    1.9m
t=  103.0s Overtaking v4 returns to slow lane at x=   13.6m
t=  128.0s Overtaking v5 returns to slow lane at x=    7.3m
t=  155.0s Overtaking v6 returns to slow lane at x=   22.2m
t=  179.0s Overtaking v7 returns to slow lane at x=    2.9m
t=  197.0s Overtaking v8 returns to slow lane at x=   18.6m
t=  232.0s Overtaking v9 returns to slow lane at x=    8.9m
t=  250.0s Overtaking v10 returns to slow lane at x=   14.4m
t=  282.0s Overtaking v11 returns to slow lane at x=   19.1m
t=  305.0s Overtaking v12 returns to slow lane at x=    1.7m
t=  327.0s Overtaking v13 returns to slow lane at x=    6.4m
t=  341.0s Overtaking v14 returns to slow lane at x=   14.5m
t=  372.0s Overtaking v15 returns to slow lane at x=    8.1m
t=  416.0s Overtaking v16 returns to slow lane at x=   15.2m
t=  433.0s Overtaking v17 returns to slow lane at x=   11.0m
t=  461.0s Overtaking v19 returns to slow lane at x=    2.6m
t=  463.0s Overtaking v18 returns to slow lane at x=    6.8m
t=  465.0s Overtaking v17 overtakes v16 at x=1,201.7m
t=  488.0s Overtaking v20 returns to slow lane at x=   12.5m
t=  513.0s Overtaking v21 returns to slow lane at x=   21.4m
t=  536.0s Overtaking v22 returns to slow lane at x=    7.9m
t=  564.0s Overtaking v23 returns to slow lane at x=    6.5m
t=  579.0s Overtaking v24 returns to slow lane at x=   17.6m
t=  611.0s Overtaking v25 returns to slow lane at x=   20.7m
t=  657.0s Overtaking v27 returns to slow lane at x=   24.2m
t=  695.0s Overtaking v26 returns to slow lane at x=1,053.5m
t=  701.0s Overtaking v28 returns to slow lane at x=    6.0m
t=  711.0s Overtaking v29 returns to slow lane at x=   18.2m
t=  747.0s Overtaking v30 returns to slow lane at x=   19.5m
t=  780.0s Overtaking v31 returns to slow lane at x=   19.0m
t=  809.0s Overtaking v32 returns to slow lane at x=    9.0m
t=  830.0s Overtaking v33 returns to slow lane at x=    8.1m
t=  863.0s Overtaking v34 returns to slow lane at x=    8.7m
t=  877.0s Overtaking v36 returns to slow lane at x=    0.5m
t=  902.0s Overtaking v35 returns to slow lane at x=    5.4m
t=  905.0s Overtaking v37 returns to slow lane at x=   56.4m
t=  914.0s Overtaking v38 returns to slow lane at x=   23.7m
t=  961.0s Overtaking v39 returns to slow lane at x=   20.5m
t=  996.0s Overtaking v40 returns to slow lane at x=    9.5m
```

```
In [103]: data_2 = rec.getData()
          data_2
```

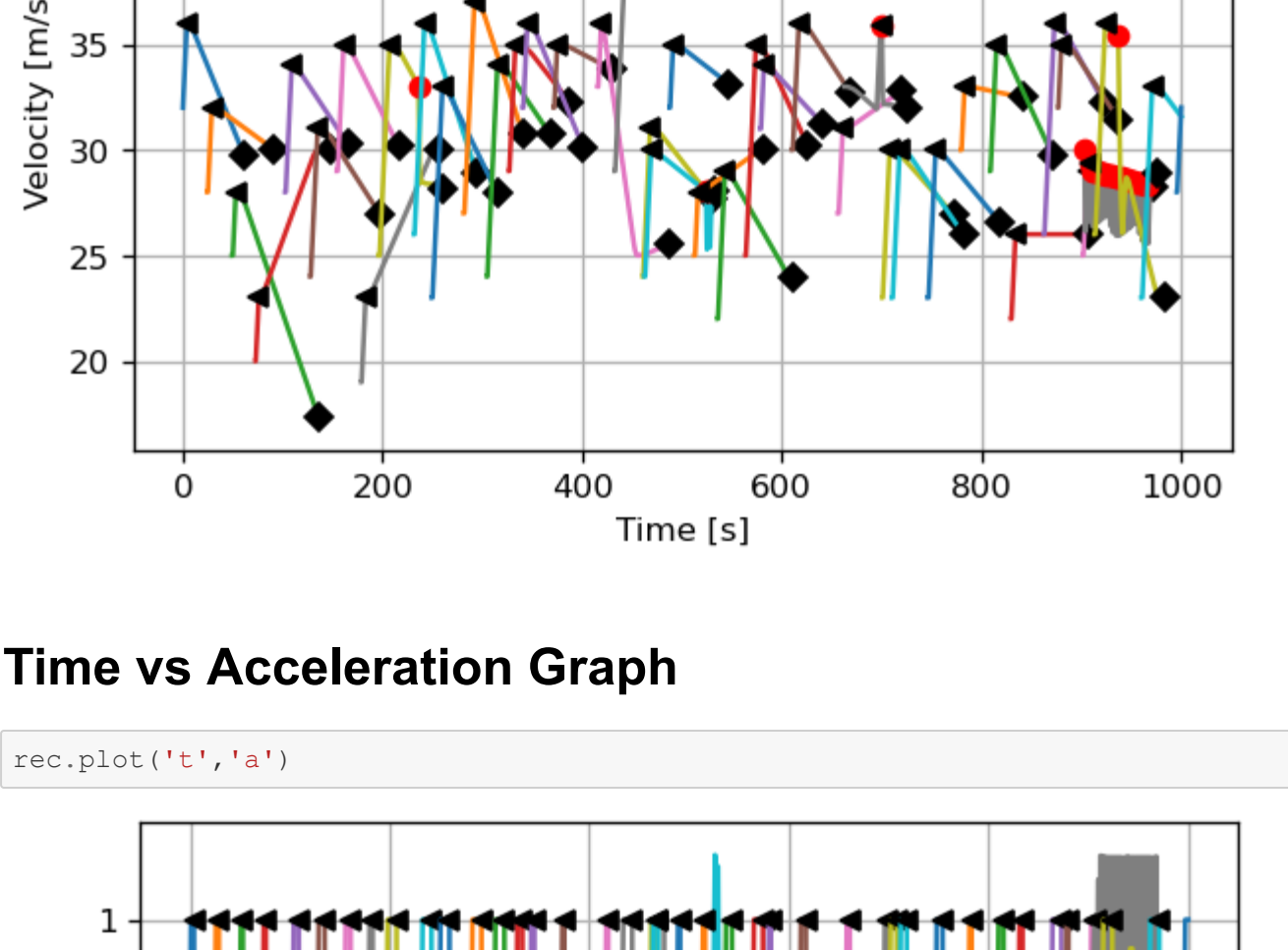
Out[103]:

	t	x	v	a	id	lane	oldLane	pos	event
0	0	0	32	0	0	0	None	0	enter lane
1	0	0	32	0	0	0	None	0	timer
2	0	0	32	0	0	0	None	0	change slow
3	0	0	32	0	0	2	0	0	enter lane
4	1	32.5	33	1	0	2	0	32.5	timer
...	...	...	...	...	...	...	...	...	...
2940	998	67.47	29.9999	1	40	2	0	67.47	timer
2941	999	1209.46	31.6417	-0.0625313	39	2	None	1209.46	timer
2942	999	97.97	30.9999	1	40	2	0	97.97	timer
2943	1000	1241.07	31.5792	-0.0625313	39	2	None	1241.07	timer
2944	1000	129.47	31.9999	1	40	2	0	129.47	timer

2945 rows × 9 columns

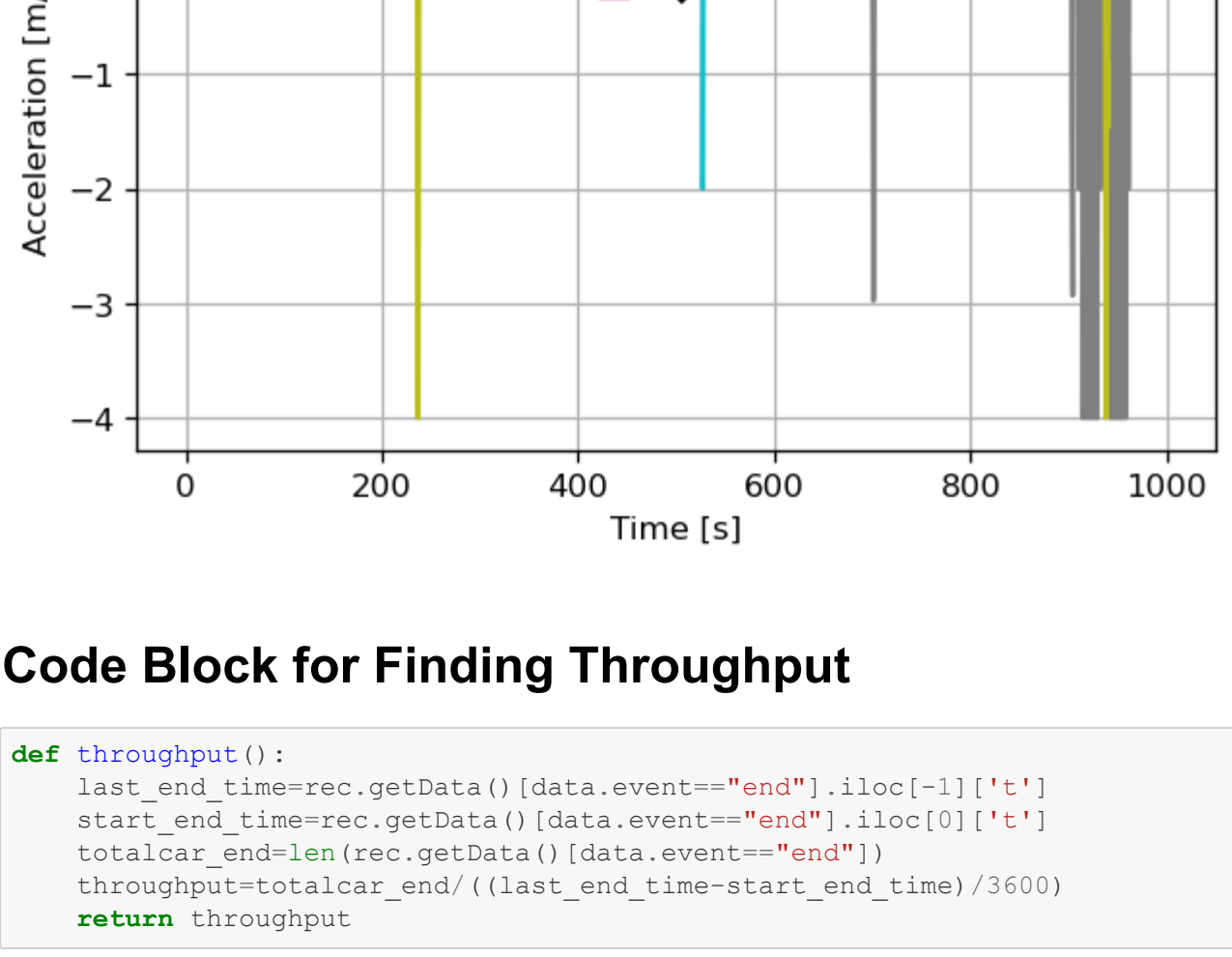
Time Vs Position Grpah

```
In [104]: rec.plot('t','x')
```



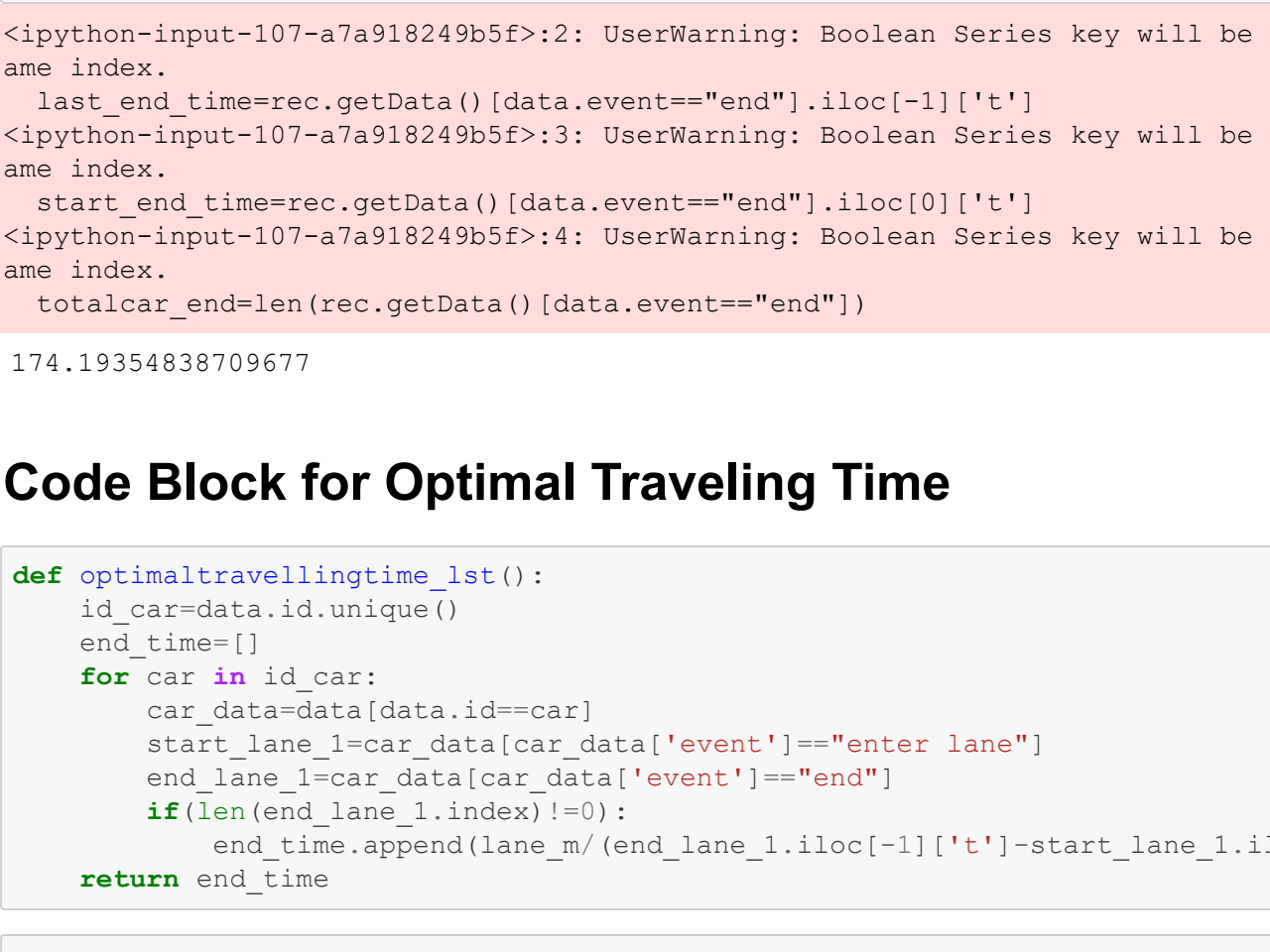
Time Vs Velocity Graph

```
In [105]: rec.plot('t','v')
```



Time vs Acceleration Graph

```
In [106]: rec.plot('t','a')
```



Code Block for Finding Throughput

```
In [107]: def throughput():
              last_end_time=rec.getData()[data.event=="end"].iloc[-1]['t']
              start_end_time=rec.getData()[data.event=="end"].iloc[0]['t']
              totalcar_end=len(rec.getData()[data.event=="end"])
              throughput=totalcar_end/((last_end_time-start_end_time)/3600)
              return throughput
```

```
In [108]: throughput_val=throughput()
          throughput_val

<ipython-input-107-a7a918249b5f>:2: UserWarning: Boolean Series key will be reindexed to match DataFr
ame index.
  last_end_time=rec.getData()[data.event=="end"].iloc[-1]['t']
<ipython-input-107-a7a918249b5f>:3: UserWarning: Boolean Series key will be reindexed to match DataFr
ame index.
  start_end_time=rec.getData()[data.event=="end"].iloc[0]['t']
<ipython-input-107-a7a918249b5f>:4: UserWarning: Boolean Series key will be reindexed to match DataFr
ame index.
  totalcar_end=len(rec.getData()[data.event=="end"])

Out[108]: 174.19354838709677
```

Code Block for Optimal Traveling Time

```
In [109]: def optimaltravellingtime_lst():
              id_car=data.id.unique()
              end_time=[]
              for car in id_car:
                  car_data=data[data.id==car]
                  start_lane_1=car_data[car_data['event']=="enter lane"]
                  end_lane_1=car_data[car_data['event']=="end"]
                  if(len(end_lane_1.index)!=0):
                      end_time.append(lane_m/(end_lane_1.iloc[-1]['t']-start_lane_1.iloc[0]['t']))
              return end_time
```

```
In [110]: car_data=data[data.id==0]
          car_data[car_data['event']=="end"]
```

Out[110]:

	t	x	v	a	id	lane	oldLane	pos	event
112	57	2024.31	34.8716	-0.0262407	0	None	None	2024.31	end

Optimal Traveling Time

```
In [88]: lst=optimaltravellingtime_lst()
         optimaltravellingtime=sum(lst) / len(lst)
         optimaltravellingtime

Out[88]: 52.43448145449667
```

Density

In [111]:
```
density = throughput_val/optimaltravellingtime
density
```
Out[111]: 3.322118261782835