Chapter 2
System Model

2.1 VANET Scenario

Consider a connected VANET on a multi-lane highway with no on or off ramps. This brief focuses on a single lane with lane changes implicitly captured in the adopted mobility model. A single lane from a multi-lane highway is chosen instead of a single-lane highway, in order to be more realistic in a highway scenario. A vehicle can overtake a slower leading vehicle, if possible, and accelerate towards its desired speed.[1] Assume that the highway is in a steady traffic flow condition defined by a time-invariant vehicle density. Let D denote the vehicle density in vehicle per kilometer. Three levels of D are considered: low, intermediate, and high vehicle densities as in Table 1.1. However, in this research the case when the vehicle density is changing among the three levels is not considered. Additionally, this work does not consider the case of increasing/decreasing vehicle density within the same level of density. The system model focuses only on a single direction traffic flow. All the vehicles have the same transmission range, denoted by R. Any two nodes at a distance less than R from each other are one hop neighbors. The set of vehicles, that are within the coverage range R of a vehicle, is referred to as *vehicle's one-hop neighborhood* as illustrated in Fig. 2.1a. The length of a hop is defined as the distance to the furthest node within the transmission range of a reference node, which is upper bounded by R as illustrated in Fig. 2.1b. The furthest node within the transmission range of a reference vehicle is referred to as *hop edge node*. Let H denote the hop length with respect to a reference node. Assume that the transmission range is much larger than the width of the highway such that a node can communicate with any node within a longitudinal distance

[1] In a single-lane highway, the vehicle traffic gradually converges into a number of platoons lead by the slower vehicles on the highway [1].

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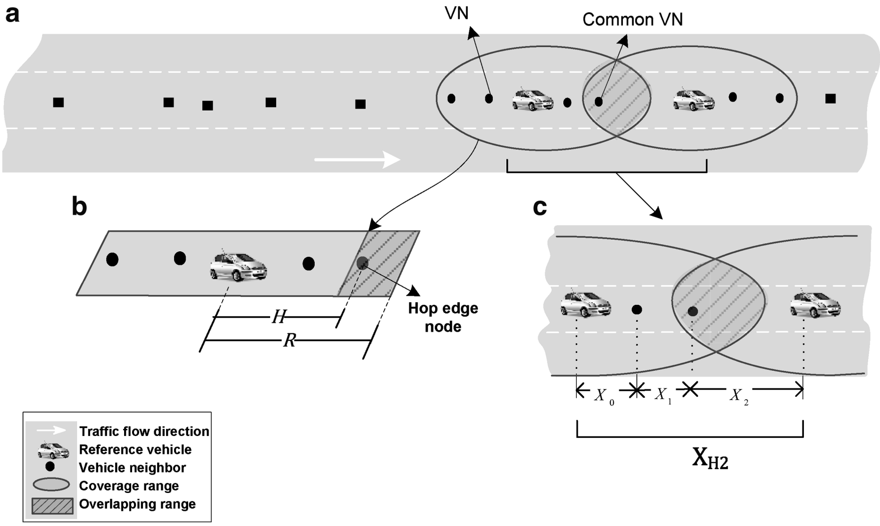

Fig. 2.1 Illustration of the system model under consideration

of R from it.[2] Time is partitioned with a constant step size. Let X_i be the distance headway between node i and node $i+1$, $i = 0, 1, 2, \ldots$. The distance headway is the distance between two identical points on two consecutive vehicles on the same lane. Define $X_i = \{X_i(m), m = 0, 1, 2 \ldots\}$ to be a discrete-time stochastic process of the ith distance headway, where $X_i(m)$ is a random variable representing the distance headway of node i at the mth time step. At any time step, $X_i(m) \in [\alpha, X_{\max}]$ for all $i, m \geq 0$, where α and $X_{\max}$ is the minimum and maximum distance headway, respectively. Furthermore, assume that the distance headways (X_i for all $i \geq 0$) are independent with identical statistical behaviors. For notation simplicity, the index i from X_i is omitted when referring to an arbitrary distance headway. In this analysis, the 0th time step refers to the time when the network has just established. A two-hop neighborhood between two reference vehicles is the set of vehicles between two reference vehicles that are connected via two-hop connection. Let $\mathbb{X}_{H2}$ denote the sequence of distance headways between two reference vehicles that are two-hop apart as illustrated in Fig. 2.1c. The set of nodes between the two-hop vehicles is referred to as *vehicle's two-hop neighborhood*. The vehicles are assumed to be distributed on the highway according to a stationary probability distribution of the distance headways when the network is first established. Let μ and σ be the mean and the standard deviation of the distance headway in meters, respectively, where $\mu = 1000/D$ and σ are constant system parameters

[2]Typically, the transmission range covers a circular area with a radius R centred at the node. However, since the transmission range is much larger than the width of the road, the area covered by the transmission range can be approximated by a rectangular area with length $2R$.

and take different values according to the vehicle density. Throughout this brief, $F_Y(y), P_Y(y), f_Y(y), Q_Y(y)$, and $E[Y]$ are used to denote the cumulative distribution function (cdf), the probability mass function (pmf), the probability density function (pdf), the probability generating function, and the expectation of random variable Y, respectively.

2.2 Node Mobility

This research focuses on the distance headway and the spatial distribution of vehicles along the road. Therefore, the adopted vehicular mobility model is used to describe the distance headway. Unless otherwise mentioned, on a macroscopic level, three different traffic flow conditions are studied separately: uncongested, near-capacity, and congested. Each traffic flow condition corresponds to a range of vehicle densities according to Table 1.1 [2]. The uncongested, near capacity, and congested traffic flow conditions correspond to low, intermediate, and high vehicle densities, respectively. Furthermore, each traffic flow condition corresponds to a unique microscopic and a unique mesoscopic distance headway model. On a microscopic level, the time variations of the distance headway is modeled by a discrete-time finite-state Markov chain. Details of the microscopic model are given in Chap. 3.

2.2.1 Mesoscopic Mobility Model

The literature of mesoscopic models focuses on the time-headway, which is the elapsed time of the passage of identical points on two consecutive vehicles [2]. For an uncongested traffic flow condition, the exponential distribution has been shown to be a good approximation for the time headway distribution [2]. With a low vehicle density, interactions between vehicles are very low and almost negligible. As a result, vehicles move independently at a maximum speed [2]. It is reasonable to assume that, over a short time interval of interest, vehicles move at constant velocity and do not interact with each other [3, 4]. Therefore, for a low vehicle density, it is assumed that the distance headway has the same distribution as the time headway with parameters properly scaled. The distance headways at any time step are independent and identically distributed (i.i.d.) with an exponential probability density function (pdf)

$$f_{X_i}(x) = \frac{1}{\mu} e^{-\frac{x}{\mu}}, \quad x \geq 0. \tag{2.1}$$

In this case, the mean and the standard deviation of the distance headway are equal ($\mu = \sigma = \frac{1000}{D}$). According to the distribution, $P(X_i \leq \alpha) > 0$; however, for simplicity, the effect of this probability is ignored.[3]

In the literature, the Gaussian distribution is used to model the time headway for a congested traffic flow condition [2]. Although the time headway is almost constant for a high vehicle density, driver behaviors cause the time headway to vary around that constant value. Therefore, the Gaussian distribution model for the time headway characterizes the driver attempt to drive at a constant time headway [2]. With the same argument, a distance headway is assumed to vary around a constant value with a Gaussian distribution. The pdf of the distance headway is approximately given by

$$f_{X_i}(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \quad x \geq 0. \tag{2.2}$$

The standard deviation σ for a high vehicle density is given by[4] $\sigma = \frac{(\mu-\alpha)}{2}$.

For a near-capacity traffic flow condition, empirical pdfs for inter-vehicle distances show that neither an exponential nor a Gaussian distribution is a good fit [5]. Hence, the inter-vehicle distances are assumed to follow a general distribution, Pearson type III, that was originally proposed for time headways [2]. With an intermediate vehicle density, the pdf of the distance headway is approximately given by

$$f_{X_i}(x) = \frac{\lambda^z}{\Gamma(z)} (x-\alpha)^{z-1} e^{-\lambda(x-\alpha)}, \quad x \geq \alpha \tag{2.3}$$

where λ and z are the scale and shape parameters of the general Pearson type III distribution, respectively, and $\Gamma(z) = \int_0^\infty u^{z-1} e^{-u} du$ is the gamma function. The parameters λ and z are related to μ and σ according to the following relations [2]

$$\lambda = \frac{\mu-\alpha}{\sigma^2}, \quad z = \frac{(\mu-\alpha)^2}{\sigma^2}. \tag{2.4}$$

[3] $P(X_i \leq \alpha) = 1 - e^{-D\alpha}$. For example, for $D = 6$ veh/km and $\alpha = 6.7$ m [2], $P(X_i \leq \alpha) = 0.04$. The probability $P(X_i \leq \alpha)$ increases with D.

[4] The guidelines used for calculating the variance of time headway are given in [2]. With $\sigma = \frac{(\mu-\alpha)}{2}$, $P(X_i > \alpha) = 0.977$ [2]. For a congested traffic flow condition (i.e., $D \geq 42$ veh/km) and $\alpha = 6.7\,m$ [2], $P(X_i \leq 0) \leq 2.8 \times 10^{-3}$.

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