A Study on Automatic Passenger Mover Envelope Gauge

Y ji , L Ren , Y Song

Institute of Rail Transit, Tongji University, Shanghai 201804, China
jiyuanjin@tongji.edu.cn

Abstract. Based on structural feature of running gear of APM and referring to research achievement, the method of calculating APM envelope gauge is discussed and an example is illustrated. A reference for drawing up the standard of APM envelope gauge is provided.

Introduction

Envelope gauge is a basic technical guideline for rail transit system construction. Rail transit envelope gauge can be divided into vehicle, equipment and construction, and vehicle envelope gauge is the basis of the others [1]. Vehicle envelope gauge restricts vehicle size shape and relates to internal contours of all kinds of buildings, having a significant impact on construction scale of rail transit system and its economic benefit. At present, Standard of Metro Gauges [2] (CJJ96—2003) and Code for Design of Straddle Monorail Transit [3] (GB 50458—2008) have been formulated.

With the diversified development of rail transit demand, automatic passenger mover (APM) vehicle with single-axle tire running gear has been applied in Guangzhou and Beijing. General Technical Specification for Automated Guideway Transit Tire Vehicles [4] has been compiled but no vehicle gauge calculation method has been formed for APM. Therefore APM vehicle gauge calculation has practical engineering value.

1. APM vehicle and its running gear

1.1. Construction of APM vehicle and its running gear

Single-axle tire running gear is usually used in APM vehicle. The running gear includes 2 driving wheels and 4 guiding wheels. Driving wheels with high pressure nitrogen (0.1 MPA) drive on top surface of the track and bear all the weight. Guiding wheels filled with solid rubber is horizontal installed on the guide frame and contact with the side of the I section to guide the vehicle along the track.

Axis bridge and guide frame rigidly connect by bolts as a rigid body. Carbody is located on the front and rear turn tables and longitudinal damper is set between wheel and carbody to resist shaking. Turn table is connected to the axis bridge through the air spring, hydraulic damper is set between turn table and axis bridge which is often inclined installed to provide


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vertical and lateral damping at the same time. Between turn table and axis bridge, upper and lower traction rods are set to transfer longitudinal traction and braking force and resist nod movement of axis bridge. Traction motor is installed on the guide frame, transferring power to left and right driving wheels through the coupling and the differential gear train. To prevent capsizing after tire burst, steel wheels are set on both driving and guiding wheels.

1.2. Compared with wheel/rail vehicle and straddle monorail vehicle

APM vehicle is very different from wheel/rail vehicle in running gear structure. The running gear of wheel/rail vehicle is often in the form of two-axle bogie, its wheelsets act as both direction and guiding roles. While APM vehicle is often in the form of single-axle tire running gear with two kinds of tires namely driving and guiding wheel which realize guiding and bearing respectively. Multidirectional flexibility of inflatable rubber tire replace first suspension devices between frame and wheels of APM vehicle. Because of elasticity of guide wheel, the form of link is normally used in lateral connection between frames and carbody, the lateral rigidity of suspension device is much bigger than metro vehicle.

There are many similarities in running gear structure between straddle monorail vehicle and APM vehicle which both use tire running gear with driving and guiding wheels, and use tires instead of traditional first suspension devices. The difference is that steady wheel is set in straddle monorail vehicle to provide enough ability to resist rolling, its guiding and steady wheels is tightly holding track [5]. While lateral span of driving wheels of APM vehicle is big, so steady wheel is not necessary, and there set aside a certain gap between guide wheel and track [6]. APM vehicle and straddle monorail vehicle both travel on the concrete road surface.

2. Gauge calculation method

APM vehicle is similar to straddle monorail vehicle on structure, based on structural feature of APM vehicle, gauge calculation method is discussed referring to Code for Design of Straddle Monorail Transit.

2.1. Calculation principle

Following principles should be complied with when APM vehicle gauge calculating:

(1)Vehicle gauge calculation should take the train on the straight line with rated speed as the basic conditions. Gauge is divided into two basic types, ground and underground condition according to the different line environment.

(2)Additional factors of curve should be considered in equipment gauge rather than vehicle gauge.

(3)According to probability, calculation parameter on vehicle gauge is divided into two categories, namely random and nonrandom factors. Nonrandom factors combine linearly, random factors combine with mean square root, finally add those two categories to form a vehicle the offset.

(4)Ground and underground vehicle gauge both use the unified calculation formula. Calculation parameter should be reasonably selected according to external conditions

2.2. Calculation elements

Following elements should be considered when APM vehicle gauge calculating:

(1)Guide wheel is in the most unfavorable position on track.
(2)Geometric deviation (including maintenance limits) and elastic deformation.
(3)Horizontal and vertical manufacturing error (AW0) in different parts of the vehicle and maintenance limits.
(4)All kinds of vibration (including vibration acceleration) under the normal operation of the vehicle.
(5)Change of deflection of empty and heavy vehicle.
(6)Vehicle deflection because of passengers partial load.
(7)Influence of lateral wind load.

2.3. Calculation formula

APM vehicle gauge is got by adding horizontal and vertical offset to each point coordinates of vehicle contour, the calculation formula is divided into two parts of the body and frame.

2.3.1. Parameters and its significance of calculation. Part of parameters and its significance of calculation is shown as Table 1. Main parameters refer to General Technical Specification for Automated Guideway Transit Tire Vehicles [4].

Table 1 Part of Parameters and Its Significance of Calculation

Num.	Symbol	Significance	Parameter
1	Δl	Lateral span of left and right driving wheel	1400 mm
2	S	Additional gravity angle coefficient	0.22
3	Δb	Carbody center of gravity offset	80mm
4	h_{sw}	Height between windage area centroid and rail surface when ground vehicle	1950mm
5	h_{sc}	Height between carbody mass center and rail surface when ground vehicle	1900mm
6	ΔM_{BX}	Horizontal manufacturing error of carbody	±15mm
7	ΔM_{qc}	Hanging up/down for pin outer of carbody	3mm
8	ΔM_{tX}	Horizontal manufacturing error of frame	±3mm
9	Δc	Lateral deviation of center line of guide rail	±25mm
10	δ_c	Vertical deviation of rail surface	+30 /-15mm
11	Δe	Horizontal elastic deformation of guide rail	3mm
12	δ_e	Horizontal elastic deformation of rail surface	5mm
13	δ_w	Abrasion value of driving wheel	18mm
14	f_1	Deflection change of empty and heavy vehicle of driving wheel	17mm
15	Δf_p	Vertical dynamic deflection driving wheel	5mm

2.3.2. Offset calculation of car body.

The maximum deflection position should be considered when calculating. Cross section outside the pin whose distance from center pin acts as calculation section for deducing offset formula. The maximum deflection position of cross section outside the pin is that two pairs of

guide wheels of different running gears press close to different side faces of rail, Fig.2 shows that carbody is under maximum deflection position when dynamic lateral displacement of guide rail relative to frame (ΔX_{dw}) and lateral deformation of second suspension (ΔW) simultaneously act[7].

Carbody offset formula can be summarized by geometrical relationship in Fig.1, that is $E=\left(d+\Delta X_{\mathrm{dw}}+\Delta W\right)\dfrac{2n+a}{a}$.

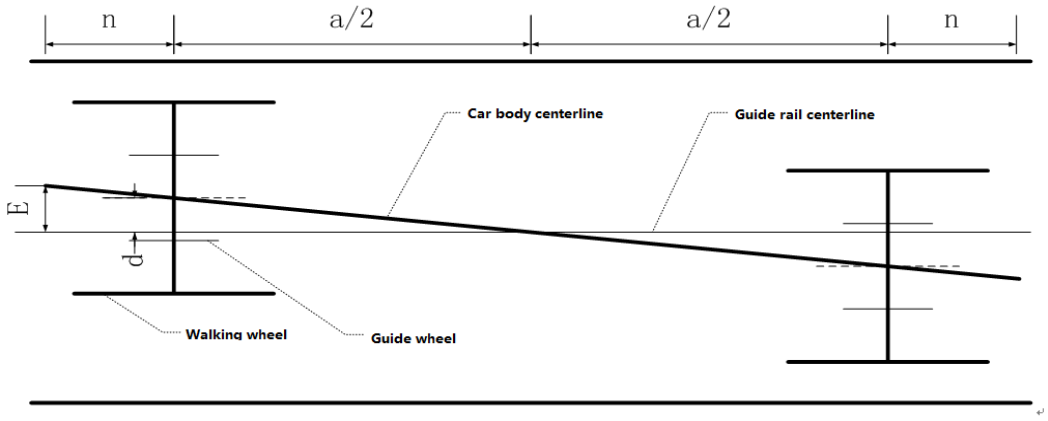


Fig.1 Maximum deflection position

（1）Lateral offset of car body

$$\Delta X_{\mathrm{BP}}=\left(d+\Delta X_{\mathrm{dw}}+\Delta W\right)\frac{2n+a}{a}+\Delta e+\frac{\Delta h_{\mathrm{c2}}}{\Delta l}Y\left(1+S\right)+\Delta b\cdot m_{\mathrm{z}}g\left(1+S\right)\left(\frac{\left|Y-h_{\mathrm{cp}}\right|}{k_{\varphi\mathrm{p}}}+\frac{\left|Y-h_{\mathrm{cs}}\right|}{k_{\varphi\mathrm{s}}}\right)$$
$$+\Delta M_{\mathrm{BX}}+\sqrt{\Delta c^{2}+\left[\frac{\Delta h_{\mathrm{c1}}}{\Delta l}Y\left(1+S\right)\right]^{2}+\left[A_{\mathrm{w}}P_{\mathrm{w}}\left(1+S\right)C_{\mathrm{h}}\right]^{2}+\left[m_{\mathrm{B}}a_{\mathrm{B}}\left(1+S\right)C_{\mathrm{h}}^{'}\right]^{2}} \quad (1)$$

Above：

$$C_{\mathrm{h}}=\left|Y-h_{\mathrm{cp}}\right|\cdot\frac{h_{\mathrm{sw}}-h_{\mathrm{cp}}}{k_{\varphi\mathrm{p}}}+\left|Y-h_{\mathrm{cs}}\right|\cdot\frac{h_{\mathrm{sw}}-h_{\mathrm{cs}}}{k_{\varphi\mathrm{s}}}$$

$$C_{\mathrm{h}}^{'}=\left|Y-h_{\mathrm{cp}}\right|\cdot\frac{h_{\mathrm{sc}}-h_{\mathrm{cp}}}{k_{\varphi\mathrm{p}}}+\left|Y-h_{\mathrm{cs}}\right|\cdot\frac{h_{\mathrm{sc}}-h_{\mathrm{cs}}}{k_{\varphi\mathrm{s}}}$$

Significance of part of parameters is shown in table 1 and significance of subkeys in table 2.

Table 2 Significance of subkeys in lateral offset of car body

Symbol	**Significance**
$\left(2n+a\right)/a$	Coefficient of skewness of car body vertical centerline
$\left(\Delta h_{\mathrm{c2}}/\Delta l\right)Y\left(1+S\right)$	Lateral offset generated from inclination angle caused by elastic variation between two rail surface
$\Delta b\cdot m_{\mathrm{z}}g\left(1+S\right)\left\|Y-h_{\mathrm{cp}}\right\|/k_{\varphi\mathrm{p}}$	Lateral offset generated from inclination angle caused by partial load torque ($\Delta b\cdot m_{z}g$) on mass center of axis bridge because of asymmetry calculation passenger weight (m_z)
$\left(\Delta h_{\mathrm{c1}}/\Delta l\right)Y\left(1+S\right)$	Lateral offset generated from inclination angle caused by error between two rail surface

$A_{\mathrm{w}} P_{\mathrm{w}} (1+S)\left\|Y-h_{\mathrm{cp}}\right\|\left(h_{\mathrm{sw}}-h_{\mathrm{cp}}\right)/k_{\varphi \mathrm{p}}$	Lateral offset generated from inclination angle $(A_w P_w(1+S)(h_{sw}-h_{cp})/k_{\varphi p})$ on mass center of axis bridge from moment in roll $(A_w P_w(h_{sw}-h_{cp}))$ caused by wind
$m_{\mathrm{B}} a_{\mathrm{B}} (1+S)\left\|Y-h_{\mathrm{cp}}\right\|\left(h_{\mathrm{sc}}-h_{\mathrm{cp}}\right)/k_{\varphi \mathrm{p}}$	Lateral offset generated from inclination angle $(\frac{m_B a_B(1+S)(h_{sc}-h_{cp})}{k_{\varphi p}})$ on mass center of axis bridge from moment in roll $(m_B a_B(h_{sc}-h_{cp}))$ caused by lateral vibration inertia force

（2）Upward offset of car body

$$\Delta Y_{\mathrm{BPu}} = \Delta M_{\mathrm{BY}} + f_2 + \Delta M_{\mathrm{qc}} + \frac{\Delta h_{\mathrm{c2}}}{\Delta l} X(1+S) + \Delta b \cdot m_{\mathrm{z}} g(1+S) X\left(\frac{1}{k_{\varphi \mathrm{p}}} + \frac{1}{k_{\varphi \mathrm{s}}}\right) + \sqrt{\begin{array}{l}\delta_{\mathrm{c}}{}^2 + \left(\Delta f_{\mathrm{p}} \cdot \dfrac{2n+a}{a}\right)^2 + \left(\Delta f_{\mathrm{s}} \cdot \dfrac{2n+a}{a}\right)^2 + \left[\dfrac{\Delta h_{\mathrm{c1}}}{\Delta l} X(1+S)\right]^2 \\ + \left[A_{\mathrm{w}} P_{\mathrm{w}} (1+S) X\left(\dfrac{h_{\mathrm{sw}}-h_{\mathrm{cp}}}{k_{\varphi \mathrm{p}}} + \dfrac{h_{\mathrm{sw}}-h_{\mathrm{cs}}}{k_{\varphi \mathrm{s}}}\right)\right]^2 + \left[m_{\mathrm{B}} a_{\mathrm{B}} (1+S) X\left(\dfrac{h_{\mathrm{sc}}-h_{\mathrm{cp}}}{k_{\varphi \mathrm{p}}} + \dfrac{h_{\mathrm{sc}}-h_{\mathrm{cs}}}{k_{\varphi \mathrm{s}}}\right)\right]^2\end{array}} \quad (2)$$

（3）Plummet offset of car body

$$\Delta Y_{\mathrm{BPd}} = \Delta M_{\mathrm{BY}} + f_1 + f_2 + \delta_{\mathrm{e}} + \delta_{\mathrm{w}} + \frac{\Delta h_{\mathrm{c2}}}{\Delta l} X(1+S) + \Delta b \cdot m_{\mathrm{z}} g(1+S) X\left(\frac{1}{k_{\varphi \mathrm{p}}} + \frac{1}{k_{\varphi \mathrm{s}}}\right) + \sqrt{\begin{array}{l}\delta_{\mathrm{c}}{}^2 + \left(\Delta f_{\mathrm{p}} \cdot \dfrac{2n+a}{a}\right)^2 + \left(\Delta f_{\mathrm{s}} \cdot \dfrac{2n+a}{a}\right)^2 + \left[\dfrac{\Delta h_{\mathrm{c1}}}{\Delta l} X(1+S)\right]^2 \\ + \left[A_{\mathrm{w}} P_{\mathrm{w}} (1+S) X\left(\dfrac{h_{\mathrm{sw}}-h_{\mathrm{cp}}}{k_{\varphi \mathrm{p}}} + \dfrac{h_{\mathrm{sw}}-h_{\mathrm{cs}}}{k_{\varphi \mathrm{s}}}\right)\right]^2 + \left[m_{\mathrm{B}} a_{\mathrm{B}} (1+S) X\left(\dfrac{h_{\mathrm{sc}}-h_{\mathrm{cp}}}{k_{\varphi \mathrm{p}}} + \dfrac{h_{\mathrm{sc}}-h_{\mathrm{cs}}}{k_{\varphi \mathrm{s}}}\right)\right]^2\end{array}} \quad (3)$$

2.3.3. Offset calculation of frame.

1）Lateral offset of frame

$$\Delta X_{\mathrm{t}} = d + \Delta X_{\mathrm{dw}} + \Delta b \cdot m_{\mathrm{z}} g(1+S)\frac{\left|Y-h_{\mathrm{cp}}\right|}{k_{\varphi \mathrm{p}}} + \frac{\Delta h_{\mathrm{c2}}}{\Delta l}\left|Y-h_{\mathrm{cp}}\right|(1+S) + \Delta M_{\mathrm{tX}} + \sqrt{\left[\frac{\Delta h_{\mathrm{c1}}}{\Delta l} Y(1+S)\right]^2 + \left[A_{\mathrm{w}} P_{\mathrm{w}} (1+S)\left(Y-h_{\mathrm{cp}}\right)\frac{h_{\mathrm{sw}}-h_{\mathrm{cp}}}{k_{\varphi \mathrm{p}}}\right]^2 + \left[m_{\mathrm{B}} a_{\mathrm{B}} (1+S)\left(Y-h_{\mathrm{cp}}\right)\frac{h_{\mathrm{sc}}-h_{\mathrm{cp}}}{k_{\varphi \mathrm{p}}}\right]^2} \quad (4)$$

（2）Upward offset of frame

$$\Delta Y_{\mathrm{tu}} = \Delta M_{\mathrm{tY}} + \frac{\Delta h_{\mathrm{c2}}}{\Delta l} X(1+S) + \Delta b \cdot m_{\mathrm{z}} g(1+S)\frac{X}{k_{\varphi \mathrm{p}}} + \sqrt{\Delta f_{\mathrm{p}}{}^2 + \left[\frac{\Delta h_{\mathrm{c1}}}{\Delta l} X(1+S)\right]^2 + \left[A_{\mathrm{w}} P_{\mathrm{w}} (1+S) X\left(\frac{h_{\mathrm{sw}}-h_{\mathrm{cp}}}{k_{\varphi \mathrm{p}}}\right)\right]^2 + \left[m_{\mathrm{B}} a_{\mathrm{B}} (1+S) X\left(\frac{h_{\mathrm{sc}}-h_{\mathrm{cp}}}{k_{\varphi \mathrm{p}}}\right)\right]^2} \quad (5)$$

（3）Plummet offset of frame

$$\Delta Y_{\mathrm{td}} = \delta_{\mathrm{w}} + f_1 + \Delta M_{\mathrm{tY}} + \frac{\Delta h_{\mathrm{c2}}}{\Delta l} X\left(1+S\right) + \Delta b \cdot m_{\mathrm{z}} g\left(1+S\right)\frac{X}{k_{\varphi \mathrm{p}}} + \sqrt{\Delta f_{\mathrm{p}}{}^2 + \left[\frac{\Delta h_{\mathrm{c1}}}{\Delta l} X\left(1+S\right)\right]^2 + \left[A_{\mathrm{w}} P_{\mathrm{w}}\left(1+S\right) X\left(\frac{h_{\mathrm{sw}} - h_{\mathrm{cp}}}{k_{\varphi \mathrm{p}}}\right)\right]^2 + \left[m_{\mathrm{B}} a_{\mathrm{B}}\left(1+S\right) X\left(\frac{h_{\mathrm{sc}} - h_{\mathrm{cp}}}{k_{\varphi \mathrm{p}}}\right)\right]^2} \quad (6)$$

3. Example

Carbody contour coordinates of an APM vehicle is given in table 3, width of carbody is 2654 mm, height of car body is 3368 mm, height of ground is 890 mm.

Table 3 Carbody contour coordinates （mm）

Num.	1	2	3	4	5	6	7	8	9
X	0	630	856	1078	1327	1299	1327	1327	0
Y	3423	3390	3158	3125	1662	944	922	890	890

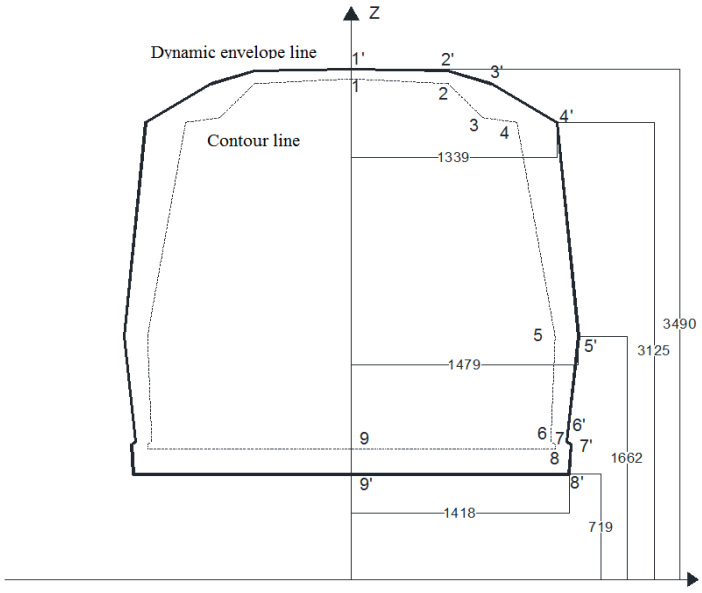


Fig.2 Dynamic envelope line of carbody basic outline upon ground （mm）

4. Conclusion

Gauge is basic technical specifications in rail transit construction. The lager the gauge margin, the safer, but work amount more. Based on structure feature of APM vehicle and Design of Straddle Monorail Transit, calculation method is discussed, considering running status, rail characteristics and kinds of error and deformation. Further example is exhibited. Such a method provides reference on APM vehicle envelop gauge.

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