SPECIAL OFF-ROAD VEHICLES - SELECTED CHARACTERISTICS

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Abstract

Special off-road vehicles capable of use in difficult terrain conditions are employed in the military, agriculture, forestry, civil engineering, exploration and mining, earthworks, and other operations. Similar principles apply to all these vehicles in terms of the mechanics of movement and the interaction of the vehicle with the terrain. The authors deal only with selected problems including a brief passage about the mechanics of movement in the terrain, environment and its characteristics, obstacles, trafficability as well as the basics of autonomous vehicles.

Keywords: off-road vehicle, terrain characteristics, trafficability, autonomous vehicle

1 Introduction

An off-road vehicle is a vehicle for driving on unpaved surfaces. It is characterized by special chassis, tires and shock absorbers, all-wheel drive and differential locking mechanism [1]. The off-road vehicles can be also equipped with tracks. Special off-road vehicles are used in the military (HMMWV, Land Rover Defender, Honker, Toyota Hilux, Perun, Iveco LMV, Dingo 2 ATF, etc.), as utility vehicles for agriculture, forestry, exploration and mining, earthworks, military and similar purposes or in motorsport. SUVs (Sport Utility Vehicles), adapted for both road and off-road use, often suitable for recreation, are also common. The European Directive 2007/46 /EC defines an off-road vehicle as: category M vehicles (passenger car) and category N1 vehicles (lorry) not exceeding 2 tonnes if they satisfy the following conditions:

- at least one front and at least one rear axle designed to be driven simultaneously including vehicles where the drive can be disconnected,
- at least one differential locking mechanism or a mechanism having similar effect is fitted,

    - the front approach angle shall be at least 25°,
    - the rear departure angle shall be at least 20°,
    - the ramp angle shall be at least 20°,
    - the ground clearance under the front axle shall be at least 180 mm,
    - the ground clearance under the rear axle shall be at least 180 mm,
    - the ground clearance between the axles shall be at least 200 mm.

Category M3 vehicles whose maximum mass exceeds 12 tons or N3 vehicles if all their axles are driven simultaneously including vehicles where one powered axle can be disengaged. Or if they satisfy the following conditions [1]:

- at least one half of the axles is driven,
- there is at least one differential locking mechanism or a mechanism having similar effect,
- they are able to climb at least a 25° gradient as solo vehicle,
- they satisfy at least four out of the following six requirements:
    - the front approach angle shall be at least 25°,
    - the rear departure angle shall be at least 25°,
    - the ramp angle shall be at least 25°,
    - the ground clearance under the front axle shall be at least 250 mm,
    - the ground clearance between axles shall be at least 300 mm,
    - the ground clearance under the rear axle shall be at least 250 mm.

The off-road vehicles compared to road vehicles are generally characterized by a special construction and equipment, e.g.:

- higher number and range of gears,
- all-wheel drive,
- differential locks, or their higher aligment,
- higher ground clearance and approach angle,
- special tires (tread pattern for optimum off-road traction), puncture resistance, underinflation and inflation of tires during driving, self-cleaning effect, etc.

2 Terrain characteristics

Terrain is an undeveloped or dry part of the Earth's surface (land) formed by terrain relief covered by objects such as vegetation, water, roads, structures and technical installations. It is therefore any part of the Earth's surface with all its obstacles, inequalities, created by natural forces or artificially, with all objects and phenomena found on the Earth's surface [2].

The terrain is based on terrain relief characterized by the horizontal and vertical segmentation of the Earth's surface. The second part of the terrain are terrain objects, which include all objects of natural and artificial origin, found on the relief. Depending on the segmentation of the terrain relief and the occurrence of terrain objects, different types of terrain can be distinguished on the Earth's surface, e.g. dry and hard, boggy, muddy, slushy, loose, sandy, stony, gravelly, bouldery, cohesive, incoherent, eroded, sedimentary, etc. The geometry of the possible position of an off-road vehicle on a slope is shown in Fig. 1. An important characteristic of the terrain is the slope gradient, Fig. 2, denoted by the angle of inclination S_α of climb/descent in % or degrees; then.

$$S_\alpha = 100 \cdot \frac{a}{l_1} = 100 \cdot tg\alpha \quad [\%] \tag{1}$$

and

$$\alpha = arctg(\frac{S_\alpha}{100}). \tag{2}$$

An example of conversion of the slope angle, incline, or absolute ratio is shown in Fig. 3 and Table 1 [3].

If the off-road vehicle centre line is inclined by an angle β from the slope, the slope (vehicle inclination) for the vehicle shall be reduced to α_y according to the formulas:

$$sin\alpha_y = sin\alpha \cdot cos\beta, \tag{3}$$

but its transverse slope α_x increases according to the relation

$$sin\alpha_x = sin\alpha \cdot \cos(90 - \beta) = sin\alpha \cdot sin\beta. \tag{4}$$

Note: On the contour line ($\beta = 90^o$) $\alpha_y = 0;\ \alpha_x = \alpha$.

Based on the equations, it is possible to exclude the angle β and express the angle α, then

$$sin\alpha = \sqrt{sin^2\alpha_x + sin^2\alpha_y}. \tag{5}$$

In this way we can indicate the slope angle α for off-road vehicles, using mutually perpendicular sensors that detect partial inclinations $\propto_{x,y}$.

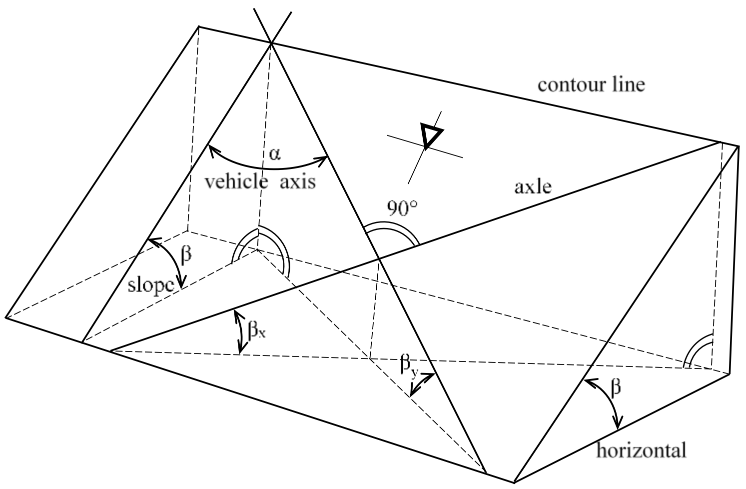

Fig 1 *Geometry of off-road vehicle position on slope*

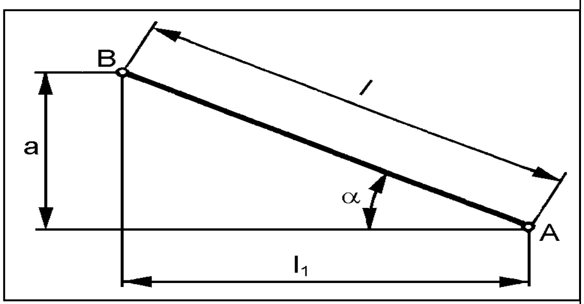	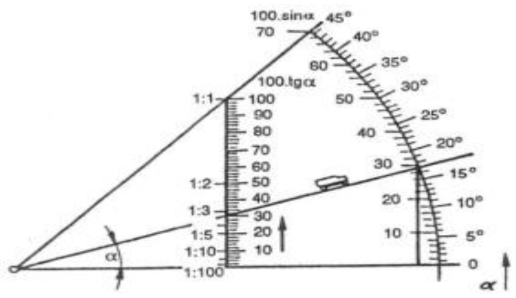
Fig. 2 *Ascent / descent slope diagram (a - elevation; I - distance A - B; l_1 - plan view of distance A - B*	***Fig. 3*** *Dependence of longitudinal slope (angle) of ascent / descent*

Fig. 2 Ascent / descent slope diagram (a - elevation; I - distance A - B; l1 - plan view of distance A - B
Fig. 3 Dependence of longitudinal slope (angle) of ascent / descent

An important feature of the terrain is the soil resistance to burying, Fig. 4 and 5, which shows the relationship between soil pressure p and soil deformation z described by the so-called pressure deformation characteristic and approximately holds $p=k \cdot z^n$ where n is the experimentally determined soil constant.

The obstacles are generally determined by length, height and angular dimensions; the shape (profile) is often simplified by a series of intersecting planar surfaces, Fig. 6. The basic types of obstacles are shown in Fig. 7 [4]. An important element of off-road vehicles are tires, which fulfill the functions of the supporting elements, the moving and guiding device and the spring element. In difficult terrain conditions, special tires are used (tactical, wide-profile, curved, cylindrical, etc.). Examples of special tires are shown in Fig. 8. The specific tire pressure is shown in Fig. 9.

Table 1 *Conversion of slope angle of ascent/descent to % and ratio*

Ascent/descent in %	0	10	20	40	67	80	100
Slope angle [°]	0	5,7	11,3	21,8	33,7	38,7	45
Ascent/descent abs.	0	1:10	1:5	2:5	2:3	4:5	1:1

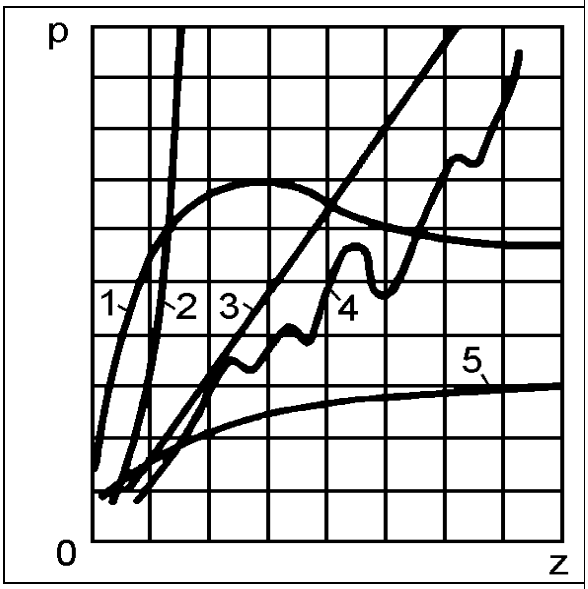

Fig. 4 *Soil resistance against burying*

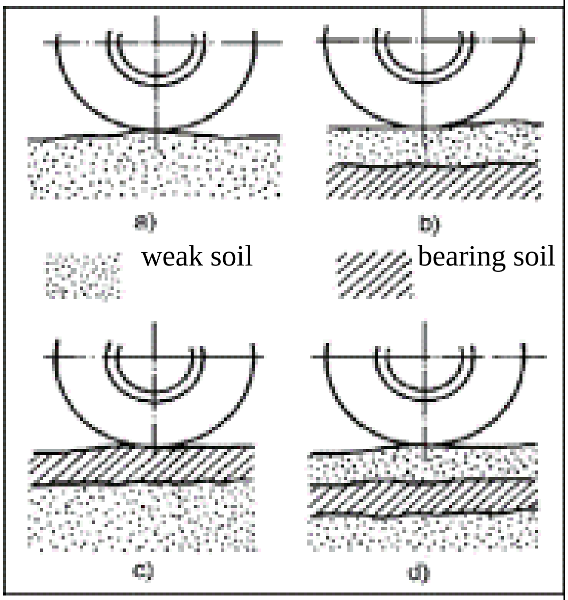

Fig. 5 *Unsurfaced terrain - soil homogeneity*

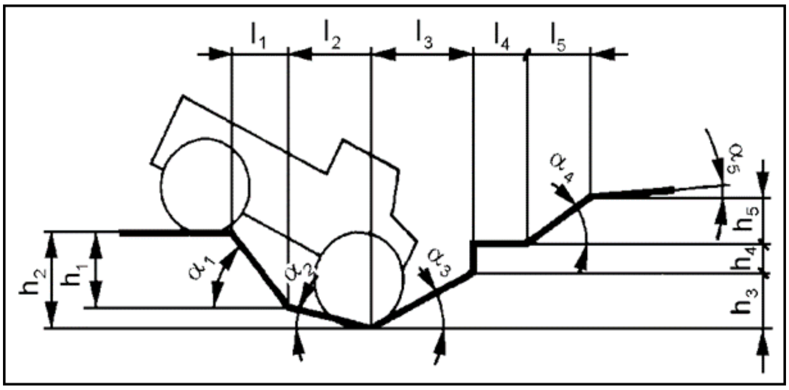

Fig. 6 *Geometry of terrain surface (obstacles)*

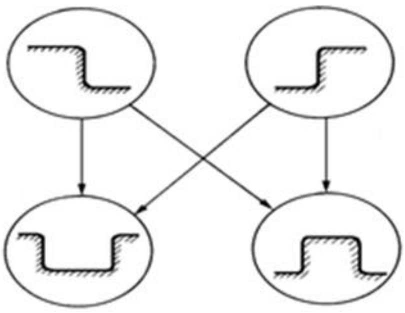

Fig. 7 *Basic types of artificial obstacles*

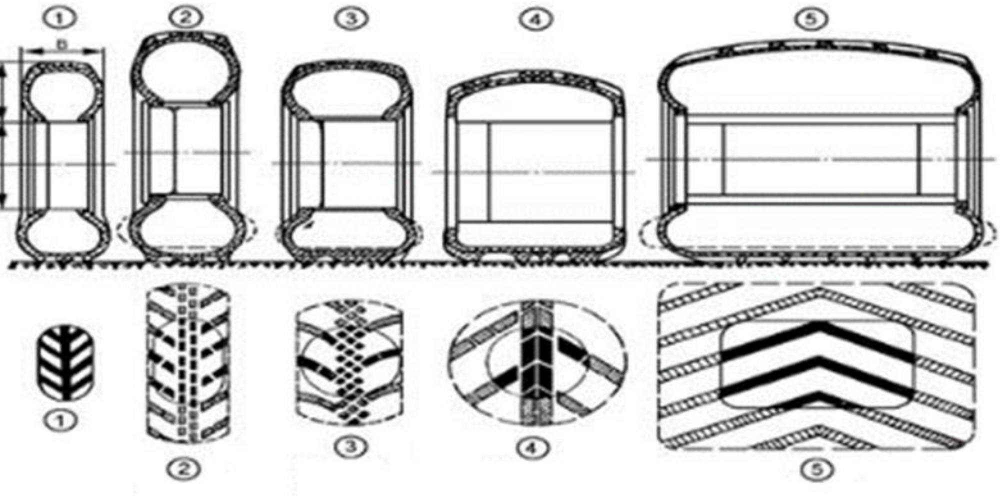

Fig. 8 Special off-road tires

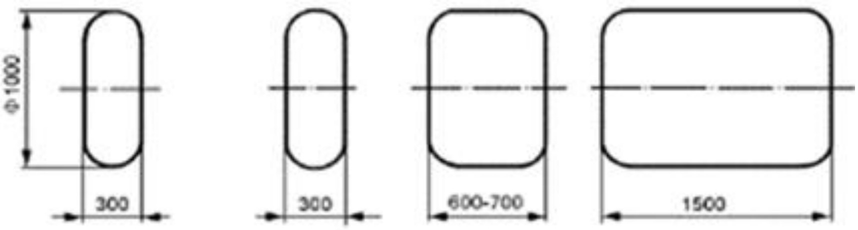

Fig. 9 *Specific pressure in the track of off-road vehicles* [4]

3 Distribution of off-road vehicle mass and its consequences

An important role in defining the off-road trajectory is the use of a 3D coordinate system that is tied to the terrain. The basic concepts include the vehicle's centre of gravity, or the centre of gravity of a loaded vehicle, or with carried load, or also a partial centre of gravity of the tilting parts without sprung masses (axles). The centre of gravity is the point of gravity acting on the body in a homogeneous gravity field (the resulting moment of the applied forces is zero at the centre of gravity). The position of the centre of gravity is given by the distribution of the substance in the body. Generally, the coordinates of the centre of gravity are denoted $\boldsymbol{x_T, y_T, z_T}$ and are calculated from the equilibrium of static moments of partial masses $\boldsymbol{m_i}$ to the respective planes, e.g. $\boldsymbol{x_T} = \frac{\sum m_i \cdot x_{Ti}}{\sum m_i}$ to the plane (y, z) or $\boldsymbol{z_T} = \frac{\sum m_i \cdot z_{Ti}}{\sum m_i}$ to the plane (x, y). For a two-axle off-road vehicle, the total mass can be divided into two masses above the axles $\boldsymbol{m_1 = \frac{x_T}{L} \cdot m}$ and $\boldsymbol{m_2 = (1 = \frac{x_T}{L}) \cdot m}$ or to the partial centres of the tilting front part $\boldsymbol{x_f}$ and $\boldsymbol{x_r}$ (these distances are known). Then

$$\boldsymbol{m_f \cdot \left(L - x_f - x_i\right) = (x_t - x_r) \;\rightarrow\; m_f} \;, \tag{6}$$

$$\boldsymbol{m_f \cdot \left(L - x_f - x_i\right) = (x_t - x_r) \;\rightarrow\; m_f} \;, \tag{7}$$

$$\boldsymbol{m_r \cdot \left(L - x_f - x_i\right) = (L - x_t - x_f) \rightarrow\; m_r} \;, \tag{8}$$

$$\boldsymbol{m_r = m - m_f} \;. \tag{9}$$

The following applies for the centre of gravity heights in the front and rear $\boldsymbol{h_f, h_r}$ tilting part

$$\boldsymbol{h_f \cdot m_f + h_r \cdot m_r = h \cdot m} \;. \tag{10}$$

When solving the dynamics of an off-road vehicle, its mass can be divided into three parts with partial weights $\boldsymbol{m'_1}$, $\boldsymbol{m'_2}$, $\boldsymbol{m'_3}$ of which the first two are above the axles and the third is at the centre of gravity of the off-road vehicle. This is defined by equations

$$\boldsymbol{m'_1} + \boldsymbol{m'_2} + \boldsymbol{m'_3} = \mathrm{m} \;, \tag{11}$$

$$\boldsymbol{m'_1 (L - x_T) - m'_2 \cdot x_T = 0} \;, \tag{12}$$

$$\boldsymbol{m'_1 \cdot (L - x_T)^2 + m'_2 \cdot x_T = J_{Ty}} \;. \tag{13}$$

where $\boldsymbol{J_{Ty}}$ is the moment of inertia of the off-road vehicle to the y′ axis passing through the centre of gravity, then $\boldsymbol{x'_1 = \frac{J_{Ty}}{L\cdot(L-x_T)}}$, $\boldsymbol{x'_2 = \frac{J_{Ty}}{L\cdot x_T}}$ and $\boldsymbol{m'_3 = m - \frac{J_{Ty}}{(L-x_T)\,.\,x_T}}$

4 Vehicle control systems

The issue of autonomous (self-driving) vehicles is a highly topical issue of the present time together with efforts to massively reduce the carbon footprint of vehicles, for example by electromobility, etc. At present, the automotive community of SAE (Society of Automotive Engineers) defines 6 levels of automation, ranging from non-automated vehicles where the system only warns of the danger but does not control the vehicle, to full automation where the system drives the vehicle to any legit destination and the driver only enters this destination. Logically, this issue does not concern passenger and transport vehicles only, but intensive research is ongoing in the field of off-road and special vehicles. In the field of autonomous vehicle technology, it is generally about obtaining, evaluating and processing information in and around the control system in order to achieve the desired driving objective. The complexity of the issue can be illustrated by the following very simplified example [7]. A combustion engine, or in our case, an electric motor is expressed, if the armature inductance is neglected, by the first-order state differential equation, which describes the dynamic behaviour of the DC motor

$$\frac{RJ}{k}\frac{d\omega}{dt} + k\omega = u - \frac{R}{k}M_z\,, \qquad (14)$$

where, R … resistance, J … armature current, k … proportionality constant, ω … angular speed, u … armature voltage, M_z … load torque.

The state variables for the combustion engine are torque and angular velocity; for the electric motor it is the armature current and angular velocity, thus $x_1 = i$ and $x_2 = \omega$; using these variables we get a substitution, e.g. electric motor equations in matrix form

$$\begin{bmatrix}\dot{\boldsymbol{x}}_1\\ \dot{\boldsymbol{x}}_2\end{bmatrix} = \begin{bmatrix}-\frac{R}{L} & \frac{K}{L}\\ \frac{K}{J} & \boldsymbol{0}\end{bmatrix}\cdot\begin{bmatrix}\boldsymbol{x}_1\\ \boldsymbol{x}_2\end{bmatrix} + \begin{bmatrix}\frac{1}{L} & \boldsymbol{0}\\ \boldsymbol{0} & -\frac{1}{J}\end{bmatrix}\cdot\begin{bmatrix}u\\ m_z\end{bmatrix} \qquad (15)$$

and

$$\boldsymbol{\omega} = [\boldsymbol{0}\ \boldsymbol{1}]\cdot\begin{bmatrix}\boldsymbol{x}_1\\ \boldsymbol{x}_2\end{bmatrix}. \qquad (16)$$

The output, i.e. the angular speed ω is equal to one state variable. A simplified state model of an off-road vehicle driven by front wheel steering is shown in Fig. 10. The state variables in this case are: the distance of the vehicle centre of gravity y_0 from the reference level, i.e. from the lane axis, the instantaneous direction of the longitudinal axis of the vehicle φ, directional deviation ε (difference between the desired direction φ_p and the actual direction φ), the angle of turning the vehicle wheels relative to its actual axis δ (not shown in Fig. 10).

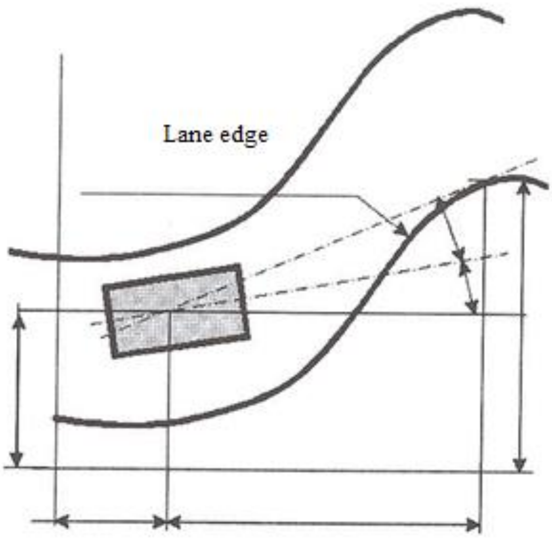

Fig. 10 *State quantities describing the dynamics of an off-road vehicle during transverse motio*

5 Conclusion Trafficability based on design parameters

The relatively complex criteria below are used primarily to compare vehicles in terms of terrain trafficability. These include traction and dynamic parameters, geometrical and design parameters described in the previous chapters. Further we can include:

a) Vehicle climbing ability - expressed as a percentage of the largest longitudinal slope of the road, which a fully laden vehicle can overcome by its own force and uniform speed.

b) Ascending ability - the ability of a fully laden vehicle to overcome the right-angled rigid step with its front wheels touching it. The step height is the ascent ability.

c) Exceedability - indicated by the width of a ditch with vertical rigid walls in a horizontal road, which is a fully laden vehicle, standing by the front wheels on the edge of the ditch, able to overcome without momentum and any adjustments.

d) Fordability - the vehicle's ability to overcome water obstacles. It is given by the depth of still water with a fixed bottom, in which a fully laden vehicle can stand for 10 minutes without affecting the start of the engine and from which it can exit by itself.

e) Maximum permissible depth of burying wheels - characterizes the vehicle's ability to cross an unsurfaced terrain.

f) Lateral inclination – is expressed as the greatest lateral gradient of the road that the vehicle can overcome without rollover.

For the purpose of vehicle trafficability comparison, four basic methods are most commonly used, namely order, directive parameters, estimation of weights (Saaty) from expert estimates and index of mobility [4].

6 Conclusion

This paper presents selected information about general principles of off-road vehicles movement. The solution is being applied in practice, but also seems to be perspective for further development of off-road vehicles in various sectors. The text lacks special chapters about vehicles on tracked chassis, the issues of driving dynamics in the field, efficiency, suspension, etc. Much attention is currently paid to the issue of autonomous vehicles, although the actual driving remains the domain of manual driving, but with the massive use of assistance systems (ABS - Anti-lock Braking System, ESP - Anti-skid Braking System, PEBS - Predictive Emergency Braking System, adaptive cruise control, tailback assistant, slope descent assistant, cornering assistant, slope start assistant, lane driving assistant, e-Call - emergency call in an accident, etc.). The absence of mechanical connection between the steering and braking elements is becoming more and more massive. In this case, all movements of the control elements are transmitted to the controlled elements by means of special control circuits - servomechanisms, manufacturers switch to systems "drive by wire". In the foreseeable future, according to the authors of this paper within five years, the transition to autonomous systems with high automation or with full automation will occur. An example of the use of an autonomous or robotized and automated, special off-road, unmanned, self-driving vehicle in the US Army is a Humvee (High Mobility Multipurpose Wheeled Vehicle, code-named Wingman, already deployed successfully in missions (Iraq, Somalia, Afghanistan). The technical and technological problems of autonomous vehicles have been almost resolved, but the relatively complicated legal aspects of liability, social and ethical issues, transport and digital infrastructure, security issues and spatial data acquisition remain to be solved.

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