EMERGENCY VENTILATION OF A RAILWAY TUNNEL
BY JET FANS

J.P. Kunsch
Institute of Fluidodynamics
Department of Mechanical Engineering, ETH - Zurich

ABSTRACT
In case of a fire in a long railway tunnel, an emergency stop of a passenger train at an arbitrary location in the tunnel cannot be excluded. In tunnel systems with two single-track tubes, corresponding to the system adopted by the NEAT in Switzerland, passengers can escape through the cross-passages connecting both tubes. The ventilation of the cross-passages, which are opened for escape, by jet fans installed in the portal regions is an interesting option to be discussed in general. Attention has been focused on the time duration required to obtain full ventilation power in the open cross-passage. The influence of the ventilation effect of the traffic is also discussed. A simplified model has been developed to estimate the air-flow rate in the cross-passage opened for escape.

Key words: cross-passage, tunnel fire, critical velocity, smoke control

1. INTRODUCTION

Emergency situations in long railway tunnels, such as tunnel fires, represent important challenges to the tunnel ventilation. The tunnel system chosen for the long railway tunnels of the NEAT (Neue Eisenbahn Alpentransversale) in Switzerland consists of two parallel single-track tubes. The risk of collisions is thereby removed and the risk of derailments is substantially reduced, because the use of points is restricted to the multipurpose stations or emergency stops dividing the tunnel into two or three main sections. At the location of these stations, crossovers or tunnel switches allow the trains to change the tunnel tube. The discussion on the installation of gates in the crossovers is not yet completely closed. The arguments in favour of an aerodynamic decoupling of both tubes by means of the gates prevail over those related to costs, maintenance and operation of the gates.

Detailed risk assessment studies have shown that the probability for a burning or damaged passenger train to be able to leave the tunnel or to reach an emergency stop is high. This scenario is therefore a requirement within modern regulations concerning passenger transport through long railway tunnels (see e.g. Schneider, 1997). For this reason, efforts are focused on the installation of an emergency ventilation in the emergency stations. The emergency stops are part of multipurpose sectors containing rooms with technical installations. These rooms, which are ventilated by fresh air under overpressure, are used as safe-haven areas in case of an emergency.

An emergency stop of a train at an arbitrary location within the tunnel, however, cannot be ruled out. In case of a fire, for example, the passengers will evacuate the contaminated tube through escape shafts (e.g. originally used for the construction of the tunnel) when the overburden is small or through cross-passages, which interconnect the two parallel single-track tubes at uniform distances. These rescue and escape passages ought to be safe-haven areas, where temperature and concentrations of fire gases or toxic materials should be as low as possible. The cross-passages not used for escape remain closed, except small ventilation openings. A major requirement is to generate sufficient fresh-air current through the open cross-passages to ensure an appropriate climate for survival and escape and to prevent the fire gases from entering the sound tube.

One possibility to cope with these problems is to generate a fresh air current in the open cross-passage by means of the ventilation installed in the emergency stations. This is achieved by generating overpressure in the sound tube and underpressure in the contaminated tube, if needed. A major objective is to obtain critical or supercritical velocities for the air flow in the cross-passages preventing backlayering of smoke, i.e. contamination of the sound tube (see e.g. Kunsch, 2002). The possibility to support the ventilation of the cross-passages, in particular those close to the portals, by jet fans installed in the portal regions can be envisaged. The time required to
reach the steady-state regime, where full ventilation power is obtained, is an important parameter to be estimated. It is required in the planning of escape and rescue scenarios.

In order to analyse these problems, a simplified model of an idealized tunnel system with two single track tubes is proposed to simulate the unsteady tunnel aerodynamics including the ventilation by jet fans.

2. VENTILATION BY JET FANS AND BY TRAFFIC: basic flow model

In order to illustrate the ventilation effect of jet fans and train traffic in a tunnel, a momentum balance of a single-track tube with length \( L \) can be given as

\[
\rho L \frac{du}{dt} = \Delta p_{ve} + \Delta p_F - \Delta p_R .
\]

The different pressure contributions on the RHS of eq. (1) are discussed in what follows.

The pressure loss \( \Delta p_R \) includes the losses at the entrance portal

\[
\Delta p_e = (1 + \zeta_e) \frac{L/2 \rho u_v^2}{D}
\]

and the losses by wall friction

\[
\Delta p_w = \lambda \frac{L}{D} \left( \frac{\rho u_v^2}{2} \right)
\]

i.e.,

\[
\Delta p_R = \Delta p_e + \Delta p_w = a \frac{L/2 \rho u_v^2}{D} \quad \text{with} \quad a = 1 + \zeta_e + \lambda \frac{L}{D}. \quad (1c)
\]

The friction coefficient \( \lambda \) is roughly equal to 0.030 for the types of tunnels considered here.

The pressure increase by the jet fans can be estimated by means of an integral momentum balance formulated for the control volume in Fig. 1 (see e.g. Meidinger, 1964 or Plaskowski, 1973)

\[
\Delta p_{ve} = p_3 - p_1 = \rho u_v^2 \phi \left( \frac{L}{D} - \psi \right) \quad \text{with} \quad \phi = F_v/F_s \quad \text{and} \quad \psi = u_v/u_s . \quad (1d)
\]

The piston effect exerted by trains on the air in the tunnel is described by means of

\[
\Delta p_F = b \frac{L/2 \rho (\omega - \psi)^2}{D} = b \frac{L/2 \rho u_v^2 (\omega - \psi)^2}{D} , \quad (1e)
\]

where \( \omega = v/u_s \) is the dimensionless velocity of a train travelling with velocity \( v \). \( b \) depends on the geometry of the train and the tunnel, i.e. on the obstruction of the cross-sectional area of the tunnel by the train and the wetted area relevant for friction (see e.g. Gaillard (1973)). For a cross-sectional area of the tunnel \( F_v = 47m^2 \) and a length of the train \( L = 300m \), an estimate of \( b \) yields a value of \( b = 2.4 \).

![Fig. 1: Tunnel section with jet fan.](image)

**Steady-state solution**

When the traffic does not vary with time (and when the jet fans are operating steadily) a steady-state ventilation regime is reached after the initial transients. The steady-state velocity is obtained when the RHS of eq. (1) is set equal to zero, i.e.,
\[ \psi_2 = u/c = \frac{-\phi - \omega b + \sqrt{(\phi + \omega b)^2 + (a - b)(2\phi + b\omega^2)}}{a - b}. \]  

(2)

The velocity induced by traffic only (no jet fans, i.e., \( \phi = 0 \)) is

\[ \psi_{2B} = \frac{\omega}{1 + \sqrt{a/b}}. \]  

(2B)

When, on the other hand, the jet fans operate without traffic present in the tunnel (i.e. \( b = 0 \)), we obtain

\[ \psi_{2C} = \frac{-\phi + \sqrt{2a\phi}}{2a} \approx \sqrt{\frac{2\phi}{a}} \left( \frac{1}{2} - \frac{1}{4} \frac{\phi}{a} \right). \]  

(2C)

The simplified expression \( \psi_{2C} = \sqrt{2a/\phi} \) will be used in what follows because the expression in the brackets is very close to unity.

Transient solution with jet fans and residual flow in the tunnel \( (\psi = \psi(t = 0) \geq 0) \)

Even when the train has left the tunnel, a residual flow with velocity \( u_o \) (i.e. \( \psi_o = u_o/u_s \)) has to be taken into account. The flow \( \psi \) in the tunnel starts with \( \psi = \psi_o \) and converges towards the steady-state regime defined by \( \psi_2 = u_s/c = \sqrt{2a/\phi} \) (eq. (2C)), i.e.,

\[ \psi = \frac{I + A\exp(-t/c_i)}{1 - A\exp(-t/c_i)} \]  

(3)

with

\[ c_i = \frac{L}{u_s\sqrt{2a/\phi}} \quad \text{and} \quad A = \frac{\psi_o - \psi_2}{\psi_o + \psi_2}. \]

This expression can be rewritten for two distinct cases

(I) \( \psi_o < \psi_2 \)

\[ \psi = \psi_2 \tanh \left[ \frac{1}{2c_i} (t + \Delta t) \right] \]  

(4A)

(II) \( \psi_o > \psi_2 \)

\[ \psi = \psi_2 \coth \left[ \frac{1}{2c_i} (t + \Delta t) \right] \]  

(4B)

with

\[ \Delta t = -c_i \ln |A|. \]

Special cases

1. The acceleration in case (I) is given by

\[ \frac{d\psi}{dt} = \frac{\psi_2}{2c_i} \left[ 1 - \tanh^2 \left[ \frac{1}{2c_i} (t + \Delta t) \right] \right]. \]  

(5)

When the flow starts from rest (\( \psi_o = 0 \), i.e. \( \Delta t = 0 \)), the initial acceleration is

\[ \frac{d\psi}{dt} = \frac{\psi_2}{2c_i} \frac{\phi u_o}{L} \quad \text{or} \quad \frac{du}{dt} = \frac{\Delta p_{Fv}}{\rho LFv} = \text{force of fan/mass of air in tunnel} \]  

(5A)

The last expression could be obtained at once from eq. (1) by neglecting frictional effects (i.e., \( \Delta p_{Fv} = 0 \)). This result clearly shows that the initial flow is dominated by inertia. The mass of air to be accelerated in a tunnel with a length of 20 km amounts to about 1000 tons.

2. When the active flow components such as trains or jet fans are removed, a residual velocity \( u_o = \psi \mu \) decreases until the air comes to rest. The decrease of the velocity can be obtained from eq. (1), where \( \Delta p_{Fv} \) is the only term on the RHS.

\[ \frac{u}{u_o} = \frac{1}{1 + (u_o a/2L)t} \]  

(6)
When the tunnel is long, the last term in \( a = 1 + \zeta_e + \lambda L/D \) dominates, i.e., \( a \approx \lambda L/D \). In this case, eq. (6) yields
\[
\frac{u}{u_o} = \frac{1}{1 + (u_\lambda/2D)t}.
\]
This means that the decrease does not depend on the length of the tunnel!

3. VENTILATION SYSTEM; PRESENT CONFIGURATION

A system similar to that presented in the Introduction will be considered next. The analysis is focused on the aerodynamics of the portal regions of the two single-track tubes shown in Fig. 2. It is assumed that one cross-passage connecting both tubes is opened for escape of the tunnel users in case of a tunnel fire. Reversible jet fans are installed close to the tunnel portals, in order to generate a fresh-air current in the cross-passage, which ensures a climate for survival and escape and which prevents the smoke gases from entering the sound tube. The fans generate overpressure in the sound tube and underpressure in the contaminated tube, if needed. The flow velocities indicated by the arrows in Fig. 2 correspond to a scenario where the upper tube is contaminated. In order to simplify the analysis and to emphasize the effect of the jet fans, the influence of the ventilation of the emergency stops has been neglected.

\[\text{Fig. 2: Tunnel system with two parallel single-track tubes.}\]

3.1 Ventilation by jet fans; influence of traffic

The air velocity generated by a jet fan in a tunnel can be estimated by means of eq. (2C). When the tunnel is characterized by \( L = 20\, \text{km} \) and \( F_\alpha = 47\, \text{m}^2 \) and the jet fan by \( u_\alpha = 38\, \text{m/s} \) and \( F_\beta = 0.6\, \text{m}^2 \), the velocity of the air flow amounts to \( u_o = 0.63\, \text{m/s} \). The same air velocity could be obtained by the piston effect of a train travelling with a speed of \( v = 16.5\, \text{km/h} \) (see eq.(2B)). A train with speed \( v = 140\, \text{kn/h} \) would induce an air flow velocity of \( u_v = 5.4\, \text{m/s} \).

This result clearly shows that the piston effect of a train travelling at realistic speeds, generally exceeding \( 100\, \text{kn/h} \), dominates over the effect of jet fans.

A major result of this estimate is that the jet fans are not effective in presence of traffic in a tunnel. It can be concluded that the installation of jet fans should be considered for tunnels with short to medium lengths only; in this case the train would be able to leave the tunnel before the emergency ventilation by jet fans starts.

When the train has left the tunnel, however, the residual air flow still present in the tunnel will decrease until a steady-state regime is reached. This regime is defined by the pressure rise of the jet fan in equilibrium with the pressure losses due to wall friction etc. (see eq. (2C)). The ventilation by jet fans becomes effective only after the time delay corresponding to this decrease.
3.2 Ventilation by jet fans; no railway traffic in the tunnel

3.2.1 Model
The ventilation by jet fans is effective when the jet fans start operating in a quiescent environment. This case will be discussed in this section.

The present model describes the tunnel system shown in Fig. 3. The cross-passages interconnecting both tunnel tubes are assumed to be closed, except for the passage used for escape in case of emergency. In order to keep the analysis as simple as possible, the air-flow rate through the small ventilation openings in the doors in the cross-passages will be neglected in a first approximation.

The ventilation power of the jet fans not only must be high enough to prevent contaminated or smoke gases from entering the sound tube, but also has to be available after a reasonably short time period. One objective of the present study is to estimate how long it will take for the flow velocity in the open cross-passage to reach its maximum value. This time could be relevant for rescue scenarios.

Fig. 3: Short-circuit flow through the open cross-passage.

The tunnel configuration to be studied is shown in Fig. 3. It is assumed that only the cross-passage, which is used for escape, is open. The short circuit flow through the cross-passage (velocity \( u_a \)) corresponds to the operation of the jet fans shown in Fig. 2.

Fig. 4: Cross-passage with door modeled as a flow component with bifurcation and constriction.

The open cross-passage with a door or a gate can be modeled as a combining and dividing junction with additional constriction (see Fig. 4).

The loss of total pressure for dividing flows can be written e.g.

\[
\Delta H_s = \left( p_1 + \frac{1}{2} \rho u_s^2 \right) - \left( p_2 + \frac{1}{2} \rho u_s^2 \right) = \zeta_{ps}^{\prime} \frac{1}{2} \rho u_s^2 \quad \text{(side branch)} \quad (8A)
\]

\[
\Delta H_r = \left( p_1 + \frac{1}{2} \rho u_s^2 \right) - \left( p_2 + \frac{1}{2} \rho u_s^2 \right) = \zeta_{pr}^{\prime} \frac{1}{2} \rho u_r^2 \quad \text{(through flow)} \quad (8B)
\]
Analogous expressions are used for the flow junction. The corresponding loss coefficients can be found e.g. in Miller (1990).

When the configuration of Fig. 3 is considered, a momentum balance analogous to eq. (1), has to be formulated for every section, i.e. for, \( L_1 + L_2 \) and \( L_3 \) in both single-track tubes.

Due to the open cross-passage connecting both tunnel tubes, a system of four coupled ordinary differential equations is obtained, which can be solved by means of a Runge-Kutta integration procedure.

### 3.2.2 Results and discussion

The first objective of the present study is to estimate the time period necessary to build up full ventilation power and the flow velocity in the open cross-passage when the jet fans close to the portals operate.

Because the ventilation of the passages close to the portals is a major concern, the distance \( x = L_1 + L_2 \) of the open cross-passage from the portal will be a main parameter in the study. The jet fans are mounted at a distance \( L_1 \) from the portals. In order to check the general validity of the results, the influence of the remaining tunnel system is roughly taken into account by varying the length \( L_3 \) of the tunnel section behind the cross-passage. Values similar to those found in realistic railway tunnels are used for the other dimensions such as the cross-sectional area of the tubes and of the cross-passages, and the distance of the jet fans from the portals. Each portal is equipped with two jet fans with a ventilation power of 40 to 50 kW each. The velocity of the jet is assumed to be as high as \( u_s \approx 38 \text{ m/s} \).

![Fig. 5: Time history of the velocities \( u_v \), \( u_{v,3} \) and \( u_a \) in the sections \( L_1 + L_2 \), \( L_3 \) and the cross-passage, respectively.](BILD5.EPS)

The flow velocity \( u_v \) in the section between the portal and the open cross-passage, the velocity \( u_{v,3} \) in section \( L_3 \) and the flow velocity \( u_a \) in the cross-passages are shown in Fig. 5 as a function of time. One part of the volume flow rate produced by the jet fans (velocity \( u_s \)) is diverted through the cross-passages (velocity \( u_a \)) in order to form a short-circuit flow from portal to portal in the adjacent tube. It can be observed that the acceleration of the air (gradient of \( u_v \)) in the section \( L_1 + L_2 \) between portal and cross-passages dominates over the acceleration of the air (gradient of \( u_{v,3} \)) in the remaining section \( L_3 \) of the tunnel, for reasons of mass inertia of the air in \( L_3 \). This temporary blockage by mass inertia of the air in section \( L_3 \) is responsible for the rapid increase of the
velocity \( u_a \) of the short-circuit flow diverted through the cross-passages. It even results in an overshooting of the flow velocity \( u_a \) in the cross-passages, before a steady-state regime is attained. The time \( t_{90\%} \) needed for the flow velocity to reach 90\% of its final steady-state value is marked by the circular symbols for the three sections considered, i.e., \( L_1 + L_2, L_3 \) and the cross-passage. The final steady-state values are marked by the symbols [ ].

The distance \( x \) of the open cross-passage from the portal has been varied in the study documented in Fig. 6. The total length \( L \) of the tunnel is a parameter. The variation of \( L \) shows the influence of additional flow resistance and inertia in section \( L_3 \). In a broader sense, the variation of the total length also illustrates how sensitive the results are to an uncertainty in the description of the flow components behind the cross-passage. The distance of the open cross-passage from the portal has been varied from the location of the jet fan towards the midst of the tunnel, i.e. \( L_1 < x < L_2 \). (So \( x \) varies from \( L_1 \) to 5000 m for a total length of 10000 m, etc.). The steady-state value of the velocity \( u_a \) and the time interval \( t_{90\%} \) found for the configuration treated in Fig. 5 are indicated in Fig. 6 by the same symbols as in Fig. 5. The velocity in the open cross-passage \( u_a \) and the velocity \( u_p \) in the door or opening in the cross-passage (see Fig. 4) are shown in Fig. 6 (a).

---

Fig. 6: (a) Steady-state values of the velocity \( u_a \) in the open cross-passage and of the velocity \( u_p \) in the door in the cross-passage.

(b) Time period \( t_{90\%} \) required to obtain 90\% of the steady-state values of \( u_a \) and \( u_p \).

(\( x \) is the distance of the open cross-passage from the portal, the parameter \( L \) is the total length of the tunnel.)

Influence of the total length \( L \) and the location of the cross-passage \( x \)
It can be observed that the flow velocity in the cross-passage decreases with increasing distance of the cross-passage from the jet fans.

A variation of the total tunnel length $L$ has an interesting effect on the velocities: the velocity through the cross-passages increases with increasing length of the tunnel when $x$ is kept constant. This can be explained by the blockage effect due to mass inertia in section $L_3$ behind the open cross-passage.

The time delay $t_{90\%}$ required to obtain 90% of the final steady-state velocities (Fig. 6(b)) increases with increasing distance $x$ and increasing total length of the tunnel. In particular, it can be observed that the time periods $t_{90\%}$ are of the order of one minute when the open cross-passage is located within a distance of 3 km from the portal. Within this range of distances, the velocity $u_p$ in the door of the open cross-passage is larger than 6 m/s. So the velocity $u_p$ will be supercritical, i.e. the fresh air current will be able to prevent backlayering of the smoke gases (see e.g. Kunsch, 2002). The resulting short time intervals required to build up full ventilation power in the cross-passages and the corresponding supercritical ventilation rates would support the choice of jet fans close to the tunnel portals, when the air flow induced by traffic is neglected.

3.3 Ventilation by jet fans; no railway traffic but residual velocity in the tunnel

In order to discuss the operation of jet fans in presence of residual air flow due to traffic, a configuration comprising a single track-tube with a side passage, opened to the free atmosphere, is chosen (Fig. 7).

![Fig. 7: Tunnel with side-passage.](image)

The two different cases considered here are illustrated in Fig. 8.

1. The jet fan starts operating in a quiescent tunnel environment. The time histories of $u_v$, $u_{v3}$ and $u_a$ are plotted as solid lines. The velocity $u_a$ of the flow diverted through the side passage increases quickly for reasons of mass inertia in the tunnel segment $L_3$, as already explained in section B.

2. When the jet fan starts operating, the train has left the tunnel, but the residual flow induced by the piston effect is still present ($t = 0$: $u_v = u_{v3} = 3 \text{ m/s}$ in Fig. 8). (In order to simplify the analysis, the same direction has been chosen for the residual flow and the flow generated by the jet fan.) The decrease of $u_v$ and $u_{v3}$ is illustrated by the dashed lines and the velocity in the side passage by the dash-dotted line. It can be observed that the flow rate in the side passage increases much more slowly than in the first case without residual flow. This can be explained by the fact that the blockage effect of segment $L_3$ due to mass inertia is not relevant in this case.

It can be concluded that the time intervals $t_{90\%}$ required to reach 90% of the full ventilation power in the cross-passage connecting two single-track tubes (see Fig. 6 in section B) have to be
augmented considerably when residual air flow is present. The values for $t_{90\%}$ given in Fig. 6(b) should be considered as lower bounds valid for an initially quiescent tunnel atmosphere. The conditions for an effective use of jet fans can be identified only after a careful analysis of the planned ventilation scenario.
Remark

Influences, which are not completely understood, or meteorologic pressure differences between the tunnel portals have not been taken into account. They could reduce the effectiveness of the jet fans, so that a power reserve must be recommended. Note that compressibility effects have been neglected in the present study. This simplification is motivated by the low Mach numbers of the flow. The present results are quite accurate when compared to calculations taking compressibility effects into account, even when the rapid transients of the present application are considered.

File Name: BILD8.EPS;2
Creator: EGM2.10M

Fig. 8: Time history of the velocities $u_x$, $u_y$, and $u_z$

in the sections $L_1 + L_2$, $L_3$ and the side-passage, respectively.

Continuous lines: no residual velocity due to traffic (case 1).
Dashed and dash-dotted lines: residual velocity due to traffic (case 2).

4. CONCLUSIONS

The present analysis deals with a tunnel system consisting of two long single-track tubes, which are connected by cross-passages used for escape and rescue in case of a tunnel fire. The installation of jet fans in the portal regions supporting the emergency ventilation in the cross-passages close to the portals, is an option discussed here. The present analysis shows that the jet fans are only effective under special conditions.

- When trains are present in the tunnel, the traffic-induced flow dominates over the flow generated by jet fans, so that jet fans are not effective. This situation can generally be encountered in long railway tunnels.
- In medium-sized tunnels, trains can leave the tunnel, but there may still be some residual traffic induced flow, when the jet fans start operating. In this case jet fans can contribute to the emergency ventilation after a time delay, when the traffic-induced flow has decreased.
- Jet fans are quite effective in an initially quiescent tunnel environment. Only short time intervals are required to reach full ventilation power in the cross-passages. In particular, a short-circuit flow through the cross-passages close to the portals is quickly established.

It can be concluded that the benefit of jet fans installed close to the tunnel portals is limited in the presence of traffic induced flow. The corresponding ventilation scenarios have to be analysed...
carefully before considering the installation or use of jet fans. In the light of these results, the more costly alternative of an emergency ventilation by jet fans installed in the cross-passages themselves could be envisaged.
References

Gaillard; M.(1973)  "Zur Aerodynamik der Zugbegegnung im Tunnel und auf offener Strecke"
Diss. ETHZ Nr. 4874

Kunsch; J.P.(2002)  "Simple model for control of fire gases in a ventilated tunnel"

Meidinger; U.(1964)  "Längslüftung von Autotunneln mit Strahlgebläsen"

Miller; D.S.(1990)  "Internal Flow Systems"
BHRA (Information Services)
The Fluid Engineering Centre, Cranfield, Bedford, UK
1990, 2nd edition

Plaskowski; Z.(1973)  "Zur Möglichkeit aerodynamischer Verfeinerungen von Strahlaggregaten für Tunnellüftung"

Schneider; J. (1997)  "Personensicherheit beim Betrieb langer Eisenbahntunnel"
Diskussion von Konzepten für die Betriebsphase
Fachtagung, IBK - ETH Zürich, 17. Okt. 1997
Leitung J. Schneider
$u_{v3}, u_v, u_a \ [m/s] \ \ \ \ u_{v3}, u_v, u_a \ [m/s]$

$u_{v3}, u_v, u_a \ [m/s] \ \ \ \ u_{v3}, u_v, u_a \ [m/s]$

$t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s]$

$t_{90\%} \ [s] \ \ \ \ t_{90\%} \ [s] \ \ \ \ t_{90\%} \ [s]$

$u_a, u_p \ (stat.) \ [m/s] \ \ \ \ u_a, u_p \ (stat.) \ [m/s]$

$x[m] \ \ \ \ x[m] \ \ \ \ x[m] \ \ \ \ x[m]$

$6 \ (a) \ \ \ \ 6 \ (a) \ \ \ \ 6 \ (b) \ \ \ \ 6 \ (b)$

$u_{v3}, u_v, u_a \ [m/s] \ \ \ \ u_{v3}, u_v, u_a \ [m/s]$

$t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t[s] \ \ \ \ t